Mine Closure 2018

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Editors

Carsten Drebenstedt

Technical University Bergakademie Freiberg, Germany

Friedrich von Bismarck

Germany

Andy Fourie

The University of Western Australia, Australia

Mark Tibbett

University of Reading, United Kingdom

Technical University Bergakademie Freiberg
Institute of Mining and Special Civil Engineering
Gustav-Zeuner-Straße 1A
09599 Freiberg, Germany
Phone: +49 3731 39 3373
Fax: +49 3731 39 3581

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Review

The dedicated efforts of the peer reviewers have resulted in the high quality of the technical programme and the papers compiled for this publication. The editors thank the technical reviewers (page 6) who contributed their time and expertise as reviewers of manuscripts for the proceedings of the 12th International Conference on Mine Closure held in Leipzig, Germany. A technical and critical review of most paper was undertaken by a minimum of two reviewers for the production of this volume.

Patron's Statements

The Technical University Bergakademie Freiberg as organizers of the Mine Closure 2018 is proud to have two leading personalities, Peter Altmaier Federal Minister for Economic Affairs and Energy and Michael Kretschmer Prime Minister Free State of Saxony, as patrons for the 12th international conference on mine closure.

"This conference picks up a very important topic of our time. The mining has brought prosperity to Germany. Due to the long history of mining we gained a lot of experience in closing and rehabilitation mining, knowledge we want to share internationally.

That's why I like to take the patronage for this year's conference in Leipzig. I wish you a very successful conference!"

Peter Altmaier

Federal Minister for Economic Affairs and Energy

Welcome to the Free State of Saxony! Centuries of mining here gave rise to the saying "Everything comes from the mines". Ore mining and metallurgy created enormous wealth, because they set manufacturing and science on an ascending trajectory. Until this very day, the centuries of mining impact the economic development of our country. The world's oldest scientific mining institution, the Bergakademie Freiberg, has been transformed into The University of Resources. Its research powers Saxony's advanced manufacturing businesses e.g. in the semiconductor industry.

While most mining activities in the Ore Mountains have ceased, this region is today Saxony's industrial heartland. In a similar fashion, the end of open-cast lignite mining after the depletion of coal fields has been the starting point of post-industrial development in the Leipzig and Lusatia regions. The moonscapes left by the mining industry have been transformed into beautiful seascapes that attract tourists and water sports enthusiasts from far and near, giving rise to a burgeoning tourism industry.

So Saxony has amassed a great wealth of knowledge and experience in managing the structural change from a mining-centered economy toward high-tech and service sector businesses. We heavily draw on these experiences when we now tackle the task of transforming the economy of the Lusatia region while the end of open-cast lignite mining there is still decades away. In managing this complicated process, the Saxon government receives support from the federal government and the EU and commits to develop a concept for a low carbon yet economically viable regional economy. Moreover, our knowledge of how to remediate former mining sites and spur new economic development is in great demand elsewhere. The Mine Closure conference is coming to Leipzig, Saxony is for me a sign of this keen interest in our experience. I therefore send my best wishes for a successful conference as well as insightful lectures and excursions to the Leipzig Lake District.

Glück auf!

Michael Kretschmer

Prime Minister Free State of Saxony

Australian Centre for Geomechanics

The Australian Centre for Geomechanics was formally established in 1992 as a University of Western Australia research centre in order to promote research excellence and continuing education in geomechanics, with particular emphasis on its application to the mineral and energy extraction sections of Australia's resources industry. In 2017 the ACG celebrated 25 years of providing research, training and education to industry in the geomechanics disciplines.

The Australian Centre for Geomechanics is an unincorporated Joint Venture involving:

- CSIRO Mineral Resources
- The University of Western Australia — Civil, Environmental and Mining Engineering

The ACG draws together staff knowledge, experiences and expertise from within the two groups forming the Centre and facilitates a multi-disciplinary approach to research and education in geomechanics. Research undertaken by the ACG attracts both national and global support and the outcomes of the projects are utilised to promote safer mining and environmental geomechanics practices, operating efficiencies and to meeting community expectations for sustainable mining practices.

With the guidance of strong industry representation on the Board of Management, and close collaboration with senior representatives of the mining industry, research, training and further education activities are tailored directly to the needs of industry. The ACG Board expects the Australian Centre for Geomechanics to be the focal point for industry on geomechanics issues and to address the needs of industry through a collaborative interdisciplinary approach.

Accessing geomechanical excellence

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ACG AUSTRALIAN CENTRE FOR GEOMECHANICS
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Since 2005, the ACG has published conference papers across the geotechnical mining spectrum, including: underground and open pit mining, paste and thickened tailings and mine closure. To make many of these papers more accessible for industry and academia, in 2017 the ACG launched the Online Repository of Conference Proceedings. This repository aims to provide the mining geomechanics fraternity with open access, peer-reviewed conference papers that may assist readers to maintain and develop their skills, knowledge and capabilities.

Setting a high standard for technology transfer and accessibility, this valuable online resource will continue to develop and grow with future ACG geomechanical mining events.

papers.acg.uwa.edu.au

Mine Closure 2019

The Australian Centre for Geomechanics, in collaboration with the University of Reading, looks forward to hosting the 13th International Conference on Mine Closure in Australia in 2019.

www.mineclosure2019.com

The University of Reading

The University of Reading was established in 1892 and is now ranked in the top 1% of universities worldwide with a world-class reputation for the quality of our research, teaching and links to business. The university's School of Agriculture, Policy and Development is ranked amongst the top 20 universities globally for agriculture and forestry and aims to provide graduates the knowledge to address the major challenges and opportunities in our sector for the 21st Century. Research within the school focuses on, and integrates aspects of, food production, the sustainability of agro-ecosystems, soil science, restoration ecology, food security, adaptation and mitigation to climate change, food chains and health, animal welfare and behaviour, poverty alleviation, international development, and consumer behaviour and choice.

Research in the area of soil and land remediation mainly takes place within the Centre for Agri-Environmental Research (CAER). CAER was founded in 2000, a move that integrated the university's strengths in agricultural and environmental research, resulting in a facility that consists of the wide ranging set of disciplines that are necessary to address issues related to sustainable agriculture.

The Centre carries out high-quality scientific research with the aim of reconciling the often conflicting demands of land use and environmental protection, as well as developing partnerships with researchers, funding agencies, industry, policy makers, users and stakeholders that enable the application of knowledge and expertise to the design of sustainable agricultural landscapes. CAER enjoys state-of-the-art facilities, with laboratories and teaching facilities in addition to the University's own farm and farm-based research sites that occupy more than 850 ha. This creates a variety of opportunities to link agricultural production and environmental research. The School's Analytical Laboratory provides facilities for a wide range of analyses of soil, plant and animal materials.

Other related work also occurs within the wider remit of the cross-faculty Soil Research Centre (SRC). The SRC is built on a long legacy of soil research at the University of Reading over the last 100 years. Our expertise includes land rehabilitation, biogeochemistry, ecology, hydrology, plant sciences, microbiology, palaeoecology, archaeology, geography, earth observation, modelling, economics and social sciences. This diversity reflects the multiple challenges of understanding the dynamic processes within the Earth's critical zone. Soil is part of Earth's natural capital, where interactions between climate, geology, plants, organisms, water and humans control the supply of ecosystem goods and services, such as food, water and climate regulation, which make human life possible.

The University of Reading has a diverse and thriving postgraduate community in a wide range of environmental topics, including land remediation and ecosystem services and offers an MSc in Environmental Pollution and BSc and MSc in Environmental Management.

http://www.reading.ac.uk/apd

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University of Reading

Technical University Bergakademie Freiberg

Reclamation is an important and inseparable part of mining and compensates for the unavoidable impact of mining activities on nature, landscape and the society. Without this compensation, mining is not possible, neither from the perspective of the approval procedures nor considering the acceptance of society. Unfortunately, this is not a practice in worldwide mining, even in developed countries.

The increasing demand for raw materials is more and more affecting the environment and thus has an effect on living conditions of people around the world. Already in the early stages of mine planning, the future needs and requirements of the post mining landscape must be taken into account. Reclamation starts with the first works of exploration and digestion, and the mining ends not until the successful recultivation is finally ensured. The work of reclamation goes far beyond the simple design of embankments and greenery. The creation of new cultural landscapes, which must be stable and safe once returned to the natural and economic cycle, is necessary. The restoration of existing landscapes and uses or completely new ones is possible.

Reclamation is an interdisciplinary topic, dealing with particular technical questions, e.g. soil, water resources, vegetation and wildlife, handling of contaminations and brownfields, geotechnical safety and geochemical processes in tipping, heaps and tailings ponds. Specific features of legal, financial and organizational issues should also be mentioned. The conference will give an overview of the complex interrelations and specific recultivation issues.

In Germany there exists an extensive knowledge in closing ore, spat, salt and coal mines, which has been going on for about 25 years, and which determines standards of active mining. The results of the recultivation depend on many factors, in particular on the social, geological and natural environment. MINECLOSURE2018 brings together various sectors, such as active large and small scale mining, abandoned mines, marine mining or illegal mining.

The Bergakademie Freiberg, founded in 1756, is the oldest existing montane educational institution in the world. With over 250 years of tradition, today the Bergakademie Freiberg is a resource university with the principle of sustainable development in research and teaching in order to promote responsible handling and production of natural resources.

In co-operation with the Australian Centre for Geomechanics, the Bergakademie Freiberg as the host of the Mine Closure 2018 in Leipzig welcomes many experts from authorities, planning companies, universities, as well as companies active in mining and reclamation. In addition to the presentations and posters, there will be numerous opportunities for professional exchange and insights into successful mining and reclamation in Germany.

With kind regards and Glückauf!

Professor Carsten Drebenstedt
Professor of Surface Mining,
Technical University
Bergakademie Freiberg

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Friedrich Carl Benthaus
Lausitzer- und Mitteldeutsche Bergbau-Verwaltungsgesellschaft Senftenberg, Germany

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Friedrich von Bismarck Berlin, Germany

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Andy Fourie The University of Western Australia, Australia

Juliane Günther TU Bergakademie Freiberg, Germany

Alexander Hesse EIT RawMaterials Regional Centre Freiberg, Germany

Nils Hoth TU Bergakademie Freiberg, Germany

Nora Loose TU Bergakademie Freiberg, Germany

Michael Paul WISMUT GmbH, Germany

Peter Schmidt WISMUT GmbH, Germany

Robert Sieland WISMUT GmbH, Germany

André Simon TU Bergakademie Freiberg, Germany

Mark Tibbett University of Reading, United Kingdom

Stefanie Walter TU Bergakademie Freiberg, Germany

Preface

The Bergakademie Freiberg, as the host of the Mine Closure 2018 in Leipzig, is pleased to welcome many experts from authorities, planning companies, universities as well as companies active in mining and reclamation. In addition to the presentations and posters, the conference presents numerous opportunities for professional exchange and insights into successful mining and reclamation in Germany. Our conference themes are:

1. Legal, financial, socio-economical and organizational aspects
2. Planning, modelling and monitoring
3. Case studies for mine closure
4. Mine closure and mining infrastructure
5. Mine flooding, balancing of groundwater deficits and pit lakes
6. Hydrogeochemistry, acid mine drainage and treatments
7. Geotechnical aspects
8. Biodiversity and ecological aspects
9. Handling of contamination and soil formation
10. Aftercare, marketing, reorganization of land, geotourism

Past International Conferences on Mine Closure were held:

2006	1st Seminar	13-15 September 2006	Perth	Australia
2007	2nd Seminar	16-19 October 2007	Santiago	Chile
2008	3rd Seminar	14-17 October 2008	Johannesburg	South Africa
2009	4th Conference	9-11 September 2009	Perth	Australia
2010	5th Conference	23-26 November 2010	Viña del Mar	Chile
2011	6th Conference	18-21 September 2011	Alberta	Canada
2012	7th Conference	25-27 September 2012	Brisbane	Australia
2013	8th Conference	18-20 September 2013	Cornwall	England
2014	9th Conference	1-3 October 2014	Johannesburg	South Africa
2015	10th Conference	1-3 June 2015	Vancouver	Canada
2016	11th Conference	15-17 March 2016	Perth	Australia
2018	***12th Conference***	***3-7 September 2018***	***Leipzig***	***Germany***

With kind regards and Glückauf!

Professor Carsten Drebenstedt
Professor of Surface Mining
Technical University Bergakademie Freiberg

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Keynotes

Words, Words, Words: But What Is the Matter, My Closure Lords

C Grant *Anglo American, Australia*

H Lacy *Mine Closure Management Services, Australia*

K Ferguson *AngloGold Ashanti, Australia*

J Heyes *BHP, Australia*

Abstract

The Cambridge dictionary defines closure as 'the fact of a business, organization, etc. stopping operating'. Historically, when this meaning of the word closure was applied to mining operations it was probably quite close to the intended final result. However, closure planning and implementation have progressed significantly over the past three decades and most mining houses now have the objective of leaving a post-mining legacy with a sustainable land-use. The concept of closure planning is now from 'cradle to cradle' and not 'cradle to grave' as it was 30 years ago, reflective of the stronger understanding that mining is and should be treated as a temporary land-use. The stigma and emotion associated with using the term closure still remains, and both internal and external stakeholders can become disengaged at even approaching a discussion on mine closure. We propose that as closure professionals we should attempt to transform the language in our field of expertise and, in doing so, shift the existing paradigms.

We will present a range of alternative terminology to replace the commonly used phrases in our field. For example, we propose that 'closure planning' should be replaced with 'integrated life of mine planning'. This new terminology resonates internally with key enablers such as mine planners, mining engineers, finance staff and general managers. There has been an increasing focus on 'social closure' in the past five years, but the term itself does not represent what is trying to be achieved. We propose that a phrase such as 'social transition' is much more appropriate and likely to be attractive to external stakeholders. Similarly, the phrase 'license to operate' is common industry parlance; what would change if we instead require a 'license to transition'? We believe that a project management approach to closing an operation is critical to a successful outcome. We propose a new term 'Back-End Loading' (BEL) to replicate the existing project development terminology of 'Front-End Loading' (FEL). This language is more relevant to key internal stakeholders such as project managers and mining engineers, and will assist in emphasizing the importance of the project management approach when an operation permanently ceases production.

International standards are currently being developed in the field of mine closure and we will attempt to align our proposed new terminology with that process wherever possible. It is likely to take time to make such a significant change in the language of our profession, but we believe the size of the prize is large. We believe our ability to engage and collaborate with both internal and external stakeholders will be enhanced and that this new language is more indicative of what we are trying to achieve today through integrated life of mine planning. A journey of a thousand miles begins with one step.

Keywords: *closure planning, integrated life of mine planning, Front-End Loading, Back-End Loading, social transition, licence to transition*

1 Introduction

Polonius: What do you read, my lord?

Hamlet: Words, words, words

Polonius: What is the matter, my lord?

Hamlet: Between who?

Polonius: I mean, the matter that you read, my lord.

Hamlet: Slanders, sir: for the satirical rogue says here that old men have grey beards…

Polonius: (Aside) Though this be madness, yet there is method in it

Hamlet, Act II, Scene ii (Shakespeare 1600)

There are many interpretations of this famous scene from Shakespeare's play Hamlet. Some believe that it is Hamlet snidely dismissing Polonius, while others believe it is Hamlet, a lover of words, expressing how serious his crisis is that his cherished words no longer matter. Another interpretation is that Hamlet is expressing that words are never just words: words can hurt a great deal more than physical actions.

Hamlet was published in 1603 and it is interesting that in 2018, nothing much has changed. US Senator Jeff Flake in February this year took to the Senate floor to respond to President Donald Trump's calling some Democrats who did not applaud during the State of the Union address 'treasonous' and 'un-American'. In a moving speech, Senator Flake emphasised that 'words matter' and terms such as treason should not be used lightly, nor be dismissed by arguably the most powerful person in the world as being 'a joke'. Equally, words can be transformational and inspirational such as those uttered by the late Dr Martin Luther King, Jr.'s 'I Have a Dream'. We propose to harness that inspiration by recognising that "Speech is the great medium through which human co-operation is brought about" (De Laguna).

The philosopher Korzybski stated "We do not realize what tremendous power the structure of a habitual language has…the structure which a language exhibits, and impresses upon us unconsciously, is automatically projected upon the world around us" (Korzybski 1933). It would also be remiss of us not to mention Orwell's 'Newspeak' as identified in the novel 1984…a language of restricted grammar and limited vocabulary, a linguistic design meant to limit the freedom of thought, a language characterised by a continually diminishing vocabulary; complete thoughts reduced to simple terms of simplistic meaning (Wikipedia 2018). There are many recent examples of newspeak; "regime change" - overthrow an existing govenment, "healthy forests" - program logging of protected wilderness areas, "clear skies" - initiative removing the restrictions on businesses which pollute the air (Politics and Language 2009). More recently the Trump Administration has been influencing all its Departments in denial of the effects of anthropomorphic climate change. For instance, the US Dept of Agriculture are requested to alter their documentation and use "intense weather events" to replace "extreme weather events brought on by climate change", and use "weather extremes" to replace "climate change" wherever this is written (Climate Dialogue 2018; The Guardian 2017)

So, what does this have to do with the discipline of mine closure? In this paper, we propose that 'words matter' in our discipline, as much as they do in literature and politics. Johnson stated 'Language is the only instrument of science, and words are but the signs of ideas' (Johnson 1755). Terms such as 'closure' are highly emotive and reflective of a time when mines ceased production and were literally abandoned. The Cambridge dictionary defines closure as 'the fact of a business, organization, etc. stopping operating'. Words such as 'closure' are disengaging to external stakeholders and are misaligned with other messages we are delivering relating to sustainable livelihoods beyond the active mining cycle. We have come a long way in our discipline, however many of the words or phrases we use today do not reflect our vision of leaving a positive post-mining legacy with sustainable land-uses. In the following section, we emphasise further the importance of language and propose that who controls the language, controls the narrative. We then propose the application of some 'new, revised or re-purposed terminology' (words and phrases) and associated definitions, and encourage all closure practitioners to take on the challenge of embracing a change in narrative in their professional pursuits.

2 Who Controls the Language Controls the Narrative

There are existing examples where language has been changing in our industry, and that gradual transformation changes the way our industry looks at its operations, impacts and business. At times we clearly adopt words that initiate cultural change in a positive way, but like with many human endeavours we also have a tendency to try to hide uncomfortable truths and realities. Then we sometimes employ 'new' words that can at times cause consternation for stakeholders. 'Sustainability' for instance is used by the industry in endorsement of the principals of the 1987 concept, and the Sustainable Development Goals (Bruntland 1987. UN 2015). The industry endeavours to follow the principals this powerful word entails, while understanding ore deposit themselves are not inherently sustainable, when what the industry is actually seeking to garner from its stakeholders is its "sustainability" for its shareholders.

Most industries when threatened employ techniques to develop the most effective words to attempt to control the narrative. This was recently well demonstrated within the current Government of Australia, where senior ministers during a parliamentary session derided those in opposition with the term 'Clean Coal' while tossing a piece of the mineral around the parliamentary benches. A perfect example of a government attempting to seize the narrative with words, provided by the currently threatened coal industry and twisting the issue by using a 'tag line' in denial of all the science that demonstrates the burning of coal to be deleterious to the environment. There is equal denial by parts of the green movement that coal fired power stations around the world can be switched off tomorrow with no impact on human livelihoods.

There is tendency to manipulate language with scientific jargon, deliberately creating confusion or uncertainty, to shield us individually and our industry. The use of jargon inside industries or specific communities can be seen as contrived, dishonest or just silly by those outside, and does not garner respect and trust, but often tends to do the opposite. With our responsibility as professional representatives of the mining industry – we must guard against this tendency in our use of words and in control of the narrative.

The same approach regarding the shift in words, language and narrative, can be employed as we change the dialogue to our post production activities. This is very similar to the safety paradigm; with investment and effort around use of language and narrative during the 'life of mine' cycle, the paradigm shift can occur. If we develop clear unequivocal language that is endorsed by mining leaders, integrated through mining organisations (via policy and dialogue), and made accessible to all stakeholders we can indeed shift the current mine closure paradigm.

A recent demonstration where language has been used to encourage a paradigm shift and facilitate open consultative dialogue is shown in Figure 1, and can be found within the latest Australian Leading Practice Series Guide for Mine Closure. This diagram, 'The Minerals Resource Legacy', illustrates the prime relationships in the discovery and utilisation of minerals, between mining companies, local communities, and government, and lists and describes these activities using verbs. At the interface of these three primary relationships is the resources legacy (Australian Government 2016). The diagram can be employed in the interests of fostering understanding via a simple narrative in the development, processing and closure of minerals deposits. The words can provide a common and understood dialogue between company employees, local communities, regional stakeholders, shareholders, company managers, non-government organisations and society as a whole (Lacy and Bennett, 2015).

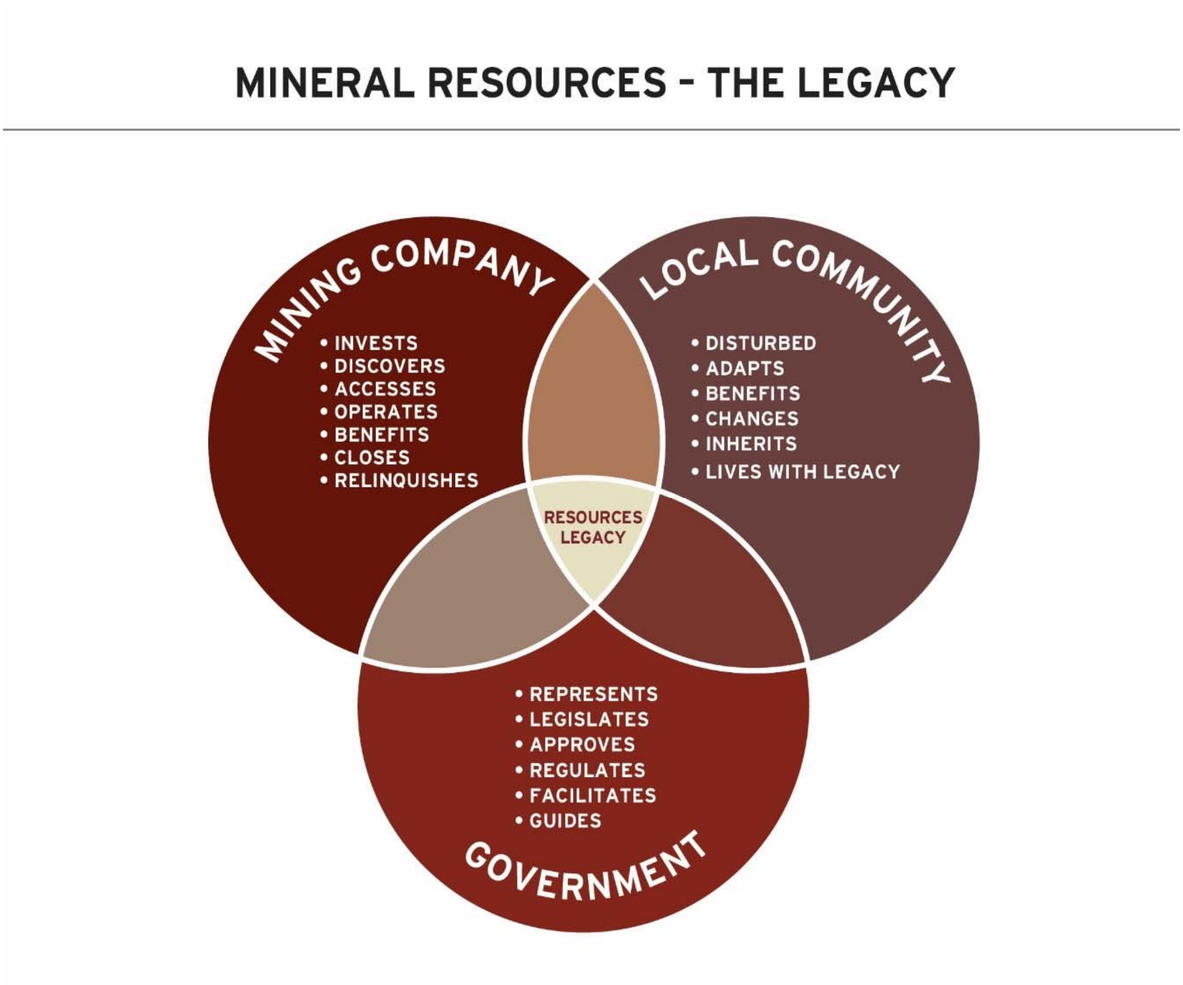

Figure 1 The Minerals Resource Legacy (after Lacy and Bennett 2015)

3 Proposed Terminology

A number of new and replacement terms for the mine closure dialogue are proposed below (Table 1). A brief explanatory paragraph is provided for each to explain the reasoning behind the proposed change.

'Integrated Life of Mine Planning' is the proposed term to replace 'closure planning'. The reasoning behind this is two-fold. Firstly, to remove the stigma associated with the term closure and to more accurately reflect the continuation of the disturbed area through the post-mining phase to meet identified land-uses. Secondly, to emphasise the importance of integration of 'closure planning' with all aspects of mine planning from short-term to Life of Mine planning. There are significant opportunities through the life of a mine to decrease risk in the transition phase to the post-mining land-use. There are a great many examples in the physical realm through progressive rehabilitation, backfilling of voids and capping of tailings facilities with waste, and also in the socio-economic realm with community benefits, improved health and education, and initiation of post closure industries. Through realisation of these opportunities, the closure liability can be optimised throughout the life of the mine, leading to positive legacy being the main outcome that communities experience post mine closure.

Table 1 Original and proposed mine closure terminology and associated definitions

Original Term	Proposed Term	Definition
Closure Planning	Integrated Life of Mine Planning	The process of integrating closure planning with Life of Mine planning to manage risk and realise opportunities throughout the operational life to optimise required activities when operations cease to meet the identified post-mining land-uses. Infers implementation of plans.
Social Closure	Social Transition	The process of transitioning communities from the operational mining phase to the post-mining phase through the collaborative establishment of sustainable livelihoods where practicable.
New	Back-End Loading	The various stage gates that the project associated with the transitioning of an operation must pass through to ensure optimal implementation and project management.
New	Licence to Transition	The intangible right that operations earn through their operating cycle through stakeholder engagement to cease operations and relinquish leases to be used for the identified post-mining land-uses.
Mine Closure	Mine Transition	The transition of a mine from the operating phase to its post-mining land-use.
Cradle to Grave	Cradle to Cradle	The process of developing a mine from exploration through to its post-mining land-use.
New	Opportunities Analysis	A formal analysis involving all relevant internal stakeholders to examine opportunities to integrate planning across the entire life of the mine.
Waste Dumps	Mine Waste Landforms	Structures and features as a result of mining that need quality design, construction and rehabilitation applied if they are to function and blend effectively into the pre-existing environment.
New	Integrated Waste Landforms (IWL)	Integrates, in immediate proximity, different waste materials generated by a mining operation within multiple facilities in a single landform or structure.
New	Resources Legacy	The legacy that is created by the mining process recognising this can be positive or negative depending on one's point of view.
New	Beneficial Legacy	A gift handed down (Oxford on Line), with an overall beneficial effect as a result of mining.
Closure Liability	Asset Value	The full remaining value of an asset including net present value minus the closure liability.
New	Comparative Analysis	Comparison of mine transition options that compares the overall beneficial effect across relevant considerations (i.e. Environment, Societal and Economic)

'Social transition' is the proposed term to replace 'social closure'. As for closure planning, the primary driver for the change is to remove the word closure which has a stigma associated with it and is not reflective of the objective to establish sustainable communities post-mining. The word 'transition' was chosen to acknowledge that there are likely to be significant changes to the social structure and composition of communities from pre-mining and throughout the operation to when the mine ceases operation. It also recognises that there may be another phase involving the new community structure and composition centred on post-mining land use. A similar explanation exists for the proposal to replace 'mine closure' with 'mine transition'.

'Cradle to Cradle' is the proposed term to replace 'Cradle to Grave'. While this change was proposed a number of years ago, it has not been embraced across the entire profession. The first cradle in the term relates to the importance of commencing planning for the end of the mine as early as possible, generally in the exploration phase but certainly through the Front-End Loading (FEL) project stage gates. The reasoning for the second cradle is to reflect the rebirth of the mine in a new form reflective of the identified sustainable post-mining land-uses.

Back-end Loading (BEL) is a new term that is being proposed. This term is being proposed to summarise the stage gates that transitioning mines need to go through to ensure a project management approach is being taken to deliver optimal implementation. Historically, the transition of a mine into closure was largely the domain of environmental professionals with little planning or implementation through the mine cycle. It is important to recognise that end of mine transitioning ideally requires the involvement of people with project management experience with teams similar to FEL projects being formed. This would involve personnel with expertise in fields such as project management, planning, scheduling, finance, safety and health, human resources, environment, legal, document control and administration. It is important to note that the senior leadership personnel at a mine during its operating phase are not necessarily the best people to be involved in the transition phase. There is, of course, a trade-off between site knowledge and required skills in the transition phase, but a combination of project people and site people often achieves the best results.

'Licence to Transition' is a new term that is being proposed. Clearly, this term is derived from the widely used term 'Social Licence to Operate'. 'Social License' has been defined as existing when a project has the ongoing approval within the local community and other stakeholders, broad social acceptance and, most frequently, as ongoing acceptance. The historical focus has been on the operating phase, but we propose that the meaning of the phrase should be extended to beyond the cessation of mining operations. The ultimate objective is the achievement of the sustainable post-mining land-use and robust sustainable communities as applicable.

'Resources Legacy' and 'Beneficial Legacy' is the movement to transition terminology from mining's general reputation of 'legacy' assumed in a negative context, to an understanding that minerals themselves are a positive legacy to humankind, and the action of mining and production itself produces a range of legacies. The purpose is to create a reasonable expectation that the mining of the mineral and the interaction and collaboration of the industry and stakeholders must be to create a positive legacy.

'Mine Waste Landform' terminology has been increasing in use in Australia for some time; evolving from 'Waste Dumps' to 'Waste Landforms' to 'Mine Waste Landform's and including 'Integrated Waste Landforms' (DME 1996; Lacy 1998). These changes in terminology are a very relevant example of creating a change in narrative and, internal culture, that results in a change in design, construction, rehabilitation and closure of this important component of mine waste management from open cut mining.

'Integrated Waste Landform (IWL)' is a terminology that elegantly describes the combination of mine waste rock, tailings, and other waste material within one structure. IWL's have been defined as "integrates, in immediate proximity, different waste materials generated by a mining operation within multiple facilities in a single structure" (Landform Solutions 2006). IWL's provides early opportunities for the application of the concept of progressive rehabilitation to outer surfaces of the IWL early in the mine life providing benefits (both economic and environmental) that are considerable (Lacy and Barnes 2006; Lacy and Lane 2007*)*.

'Closure Liability' refers to the negative cash spend and associated risks related to the closure (or end LoM transitioning) requirements of a mine. This definition results in this concept often being left for the end of LoM. By transforming this to an 'Asset Value' conversation, the broader value of a company's asset is considered among the portfolio and a more business oriented approach is applied. This may result in high liabilities and risks being addressed sooner in the mine life.

‘Comparative Assessment’ is the comparison of mine transition options that compares the overall beneficial effect across relevant considerations. This concept has also been referred to as the ‘net benefit’ approach. This changed nomenclature to a formal assessment has recently been adopted in the Western Australia, “*A comparative assessment approach should be used to identify the best decommissioning options for specific assets. Evaluation should include an assessment of complexity and associated technical risk, risks to personnel, environmental impact, effect on safety of navigation, other users, and full social and economic considerations*” (DMIRS 2017). Extension of this formal approach to the mining industry is likely given the discussions in this paper on Beneficial Legacy.

The mine closure industry has matured to an extent that the International Standards Organisation (ISO 2016) has establish a Steering Committee to develop a draft “Mine Closure and Reclamation Management Planning Standard”. Subsequently the terminology aspect to support commonly used words and phrases in mine closure, restoration and reclamation management, is required for the main standard. A Working Group has been established to collate and formulate a draft “Terminology Standard” hence this is a most appropriate time to consider the influence of terminology. Participating (~10) and observing (~8) countries during 2018-19, will be engaged and required to soon commence reviews of this important and influential work. Inclusion of the terminology outlined in this paper will be encouraged by the two co-authors involved in this process.

4 Conclusion

We have proposed in this paper that ‘Words Matter’ and the outdated and sometimes now inappropriate language that has been used in closure planning does not adequately engage critical internal and external stakeholders. We therefore encourage all closure practitioners to embrace the proposed new terminology and continue to develop it. We believe there is a compelling case for this change and that it will lead to better engagement and collaboration with stakeholders. A journey of a thousand miles begins with one step. We are asking that we all take this important first step starting at this conference and ‘maintain the rage’ moving forward.

Acknowledgement

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Source Assessment to Support Closure Designs for the Western and Central Development Areas at a Site in Central Laos

CM Linklater *SRK Consulting (Australasia) Pty Ltd, Australia*

JT Chapman *SRK Consulting (Australasia) Pty Ltd, Australia*

A Hendry *SRK Consulting (Australasia) Pty Ltd, Australia*

A Watson *SRK Consulting (Australasia) Pty Ltd, Australia*

J Rowntree *MMG Limited, Australia*

D Noonan *MMG Limited, Australia*

Abstract

SRK Consulting (Australasia) Australia Pty Ltd (SRK) are currently assisting with the development of closure plans for the Western and Central Development Areas at a site in Central Laos. These areas include more than 40 pits, some backfilled, and 13 waste rock dumps. To support closure planning, it is important to identify which pits and dumps represent significant contaminant sources, and to understand how effectively contaminant release can be mitigated as part of the closure design.

Available information for the site included drill-hole data, geological block models, current topographic surfaces, future pit and dump designs, outcomes from geochemical characterisation studies, surface and groundwater water quality monitoring data.

Conceptual models of the distribution of reactive materials and contaminant sources within key pits and dumps were developed. Post-closure, the most significant ongoing sources of solute production are expected to be related to oxidising sulfide minerals present within unsaturated materials in:

- *Above ground dumps*
- *Pit backfill located above the long-term water table and*
- *Pit walls that remain exposed after closure, i.e. are not covered by backfill, or remain above the long-term pit lake levels.*

Field-scale solute production rates (inferred from laboratory column test results) were combined with water flows to calculate water chemistry at source and downstream following mixing with other water sources. A companion paper describes development of a site water balance, including representation of surface and groundwater flows at the site.

The water quality calculations were used to examine the range of possible impacted water chemistries for (i) base case flows and solute loadings – to reflect the condition of the site prior to implementation of active closure measures, and (ii) post-closure design conditions – to examine the effect of closure measures, such as emplacement of low infiltration covers on dumps.

Using the site-wide water and solute load balance approach it was possible identify the optimal closure measures in terms of mitigation of water quality impacts to downstream receptors (drinking water resources).

Keywords: *geochemistry, water quality, sulfide oxidation, acid mine drainage*

1 Introduction

The subject mine (the site) is an open cut gold and copper mining operation located in central Laos. Mining operations comprise several gold and copper open pit operations, with the gold operations currently in care and maintenance. Figure 1 shows the site layout comprising open pits, waste rock dumps, and water management structures. Mining intersected sulfidic lithologies, and acid mine drainage (AMD) is occurring at various locations across the site. AMD is associated with oxidising pit wall rocks, and potentially acid forming (PAF) rock contained in some of the waste rock dumps.

For the purposes of closure planning, the operations have been separated into three distinct areas:

- Western and Central Development Areas
- Khanong mining area in the east
- Two tailings storage facilities (TSF1 and WTSF)

The current paper describes a geochemical assessment conducted to quantify the potential for dumps and pits to represent ongoing sources of contaminants, post-closure, for the Western and Central Development Areas. These areas include more than 40 pits and 13 waste rock dumps.

The assessment formed part of a multi-disciplinary approach to support development of overall closure designs (the overall approach is described in a companion paper, Chapman et al. 2018).

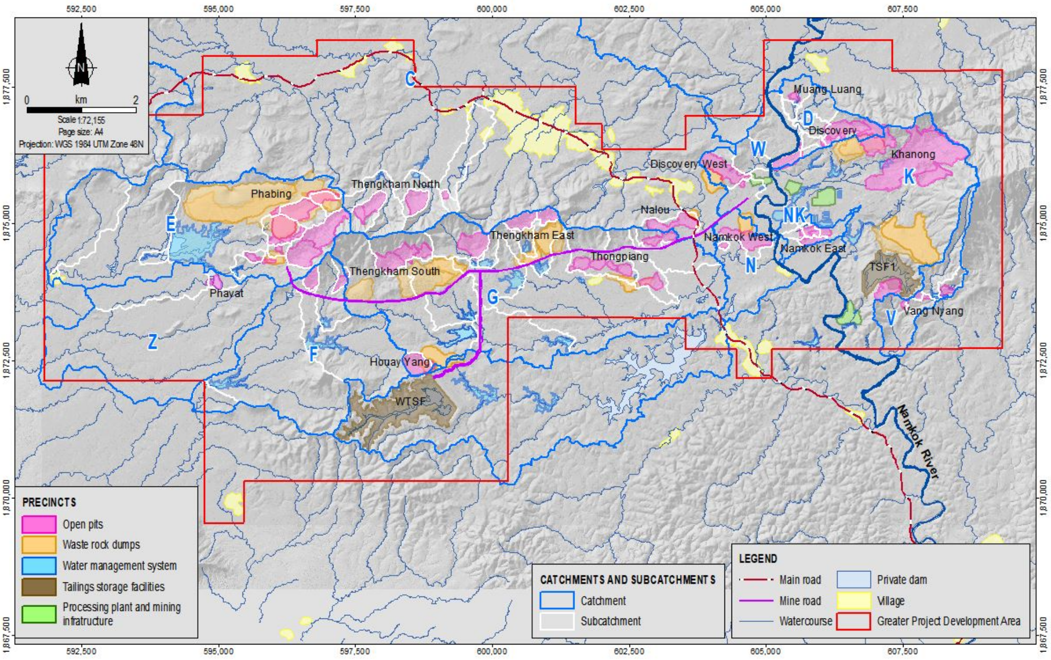


Figure 1 General layout of the subject mine site

2 Conceptual Models

Solute production at the site has been conceptualised based on the distribution of sulfidic materials within unsaturated materials exposed by mining activities. Air and water ingress to such materials results in sulfide oxidation and associated solute production. Post-closure, the main sources of ongoing solute production are expected to be sulfidic materials present in:

- Above ground dumps
- Backfill placed in pits that will remain above the long-term water table and
- Pit walls that remain exposed after closure (i.e. are not sufficiently covered by backfill, or remain above the long-term pit lake levels).

The operation manages mineralised waste rock according to a sulfur cut-off threshold (independent of acid neutralising capacity, ANC) to infer the acid generation potential. Material with total sulfur content above the threshold is classed as PAF whilst material with a sulfur content below this cut-off is classed as non acid forming (NAF). Typically, the sulfur threshold value used at site was 0.3% total sulfur.

Geological block models, pitshells, and mine scheduling information were used to estimate quantities, and distributions, of PAF and NAF materials within dumps and on pit walls. As an example, Figure 2 shows a 'map' of the distribution of NAF (green) and PAF (red) on the walls of one of the Thengkham pits. The PAF/NAF maps generated from the block models were found to be in agreement with field observations (as shown in the photographic image below the figure).

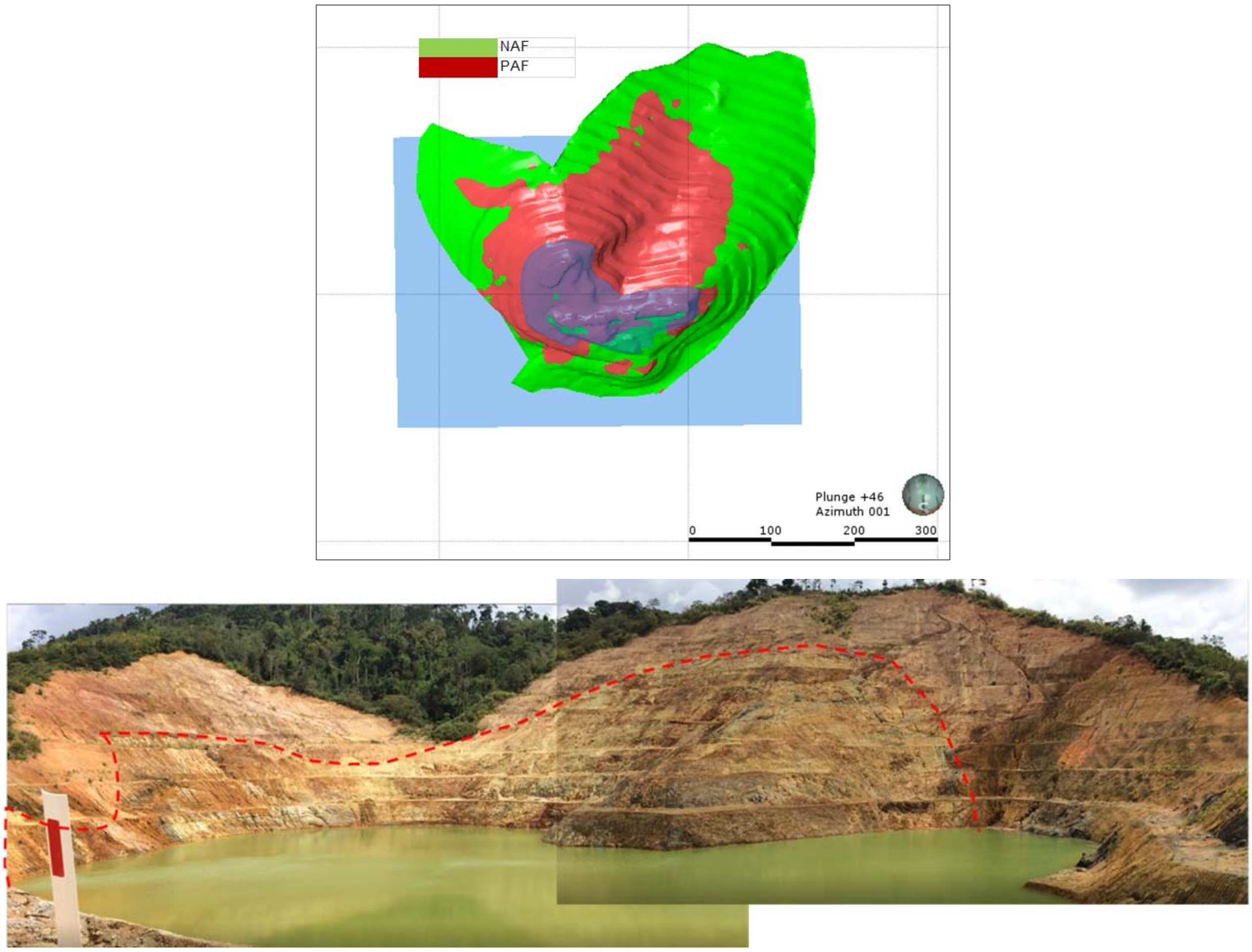


Figure 2 Distribution of PAF and NAF-classed materials on pit walls, Thengkham South D

3 Source Term Development

3.1 General Principles

Solute source terms were developed using a combination of:

- Laboratory data – the site's geochemical database included data from small-scale free-draining column tests. Trends in the datasets were used to determine solute production rates and controls. Laboratory-derived rates were extrapolated or 'scaled' to field conditions as discussed below.
- Site-based observations and water quality monitoring results. Seep survey and water quality monitoring results proximal to AMD sources provided the range of solute concentrations that occur at site.

3.2 Solute Production Rates and Controls

The site's geochemical database included data from eight small-scale free-draining columns conducted on waste rock. Average long-term solute production rates were calculated using leachate chemistries observed from Week 40 to 52 of testing (i.e. towards the end of the tests). Trends in the dataset were used to infer solute production rates and controls as follows

- Sulfate release rates did not correlate well with sulfur content – possibly a reflection of complex sulfide mineralogy within the samples. For example, mineralogical descriptions suggest that samples contain combinations of pyrite (FeS2) and chalcocite (Cu2S) which would be expected to oxidise at different rates.
- Leachate pH during testing was largely consistent with sample classification; seven of the eight samples were classed as PAF, and leachates were acidic (average pH ranging between 2 and 4). The one NAF sample tested gave an average pH of 6.
- Ca and Mg release rates were relatively high from the NAF sample, consistent with neutralisation by Ca- and Mg-bearing carbonate minerals. Mn release was concurrently high, possibly indicating that carbonate minerals may represent a source of Mn in rocks. This inference was supported by site observation – relatively high dissolved Mn (greater than 10 mg/L) concentrations occur in neutral seepage from the Thengkham South waste dump, and in neutral pit lake water in the Namkok East area.
- Some minor and trace element release rates are positively correlated with sulfate release, e.g. Co, Cu, Ni, Se, Zn (Se and Zn are shown in Figure 3). Such correlations suggest that the elements are either (i) present in the matrix of the reacting sulfide minerals, or (ii) sourced from minerals (e.g. carbonates, silicates) reacting in response to the acidic conditions produced by sulfide oxidation.
- Some elemental releases are controlled by pH dependent mineral solubility, such as Al and Fe as shown in Figure 3 (consistent with solubility of hydroxysulfates or hydroxides).

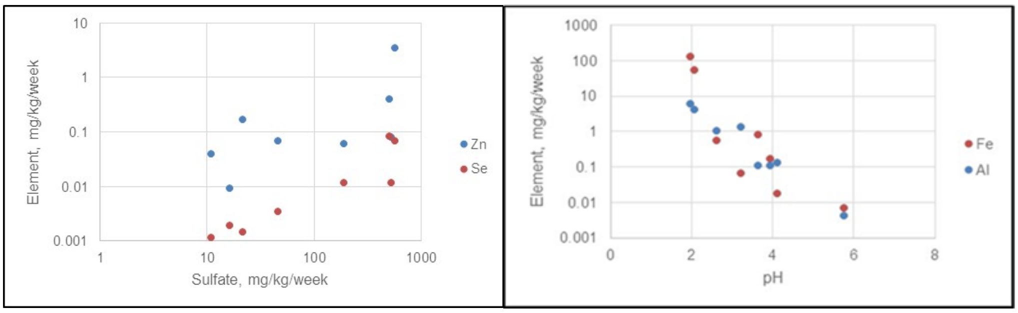


Figure 3 Minor and trace element release as a function of sulfate release (left) and pH (right)

3.3 Scaling for Application to Pits and Dumps

At field scale, conditions differ from the controlled conditions applied during laboratory testing. Amongst other factors, sulfide oxidation rates are a function of the composition of the oxidising material, transport of reactants such as oxygen and water, and temperature. Within a full scale waste rock dump, oxidation rates will be spatially and temporally variable. To utilise the laboratory-derived solute production rates to estimate long-term weathering rates, a series of 'scaling factors' and other approximations were adopted (see Table 1). Values for the scaling factors are assigned based on a combination of theoretical considerations (e.g. surface area as a function of particle size, expected gas transport mechanism) and professional experience.

Laboratory-derived rates were combined with the scaling factors presented in Table 1 to generate a set of field-scale solute production rates (per m^2) that were applicable to NAF and PAF portions of the pit walls and dumps, see Table 2. NAF production rates were estimated on the basis of NAF-classed material. PAF field-scale production rates were estimated using the average of column data for samples with sulfur content greater than 0.3%.

Table 1 Summary of base case scaling factors and approximations

Description	Units	Talus		Exposed wall rock		Dump/ backfill run-off		Dump/ backfill seepage	
		NAF	PAF	NAF	PAF	NAF	PAF	NAF	PAF
Surface area correction	-	0.2	0.2	0.01	0.01	0.2	0.2	0.2	0.2
Fraction flushed by rainfall/infiltration	-	0.4	0.4	0.1	0.1	0.5	0.5	0.3	0.3
Assumed thickness oxidising[1]	M	1	0.5	1	0.3	1	0.5	10	3

[1] In the full-scale landform, oxygen may not be readily available in volumes where oxygen consumption rates exceed rates of oxygen supply – e.g. interior of large waste dumps, and intact rock volumes located behind pit walls. There is insufficient data to fully define gas transport processes in the context of the site landforms. For the current assessment, oxygen availability has been approximated using an assumed thickness for the actively oxidising zone. Zones are thinnest for reactive PAF materials and for intact pit walls (where low porosity and permeability would be expected to result in slow gas transport).

[2] No overt evidence of high temperatures was observed in the field (e.g. steam emanating from dump surfaces). It is considered likely that dump construction practices (i.e. PAF encapsulation) may be limiting oxidation rates and heat generation within the dumps. The illustrative calculations therefore did not include a temperature correction.

Table 2 Field-scale production rates for selected solutes, mg/m^2/month

Parameter	Pit walls (talus and exposed wall rock combined)		Dump run-off		Dump seepage	
	NAF	PAF	NAF	PAF	NAF	PAF
Al	0.89	170	2.7	520	16	1900
Ca	400	150	1200	460	7300	1700
Cd	0.76	3.4	2.3	10	14	37
Cu	17	12000	53	37000	320	130000
Fe	1.5	2800	4.4	8500	27	31000
Mg	330	73	990	220	5900	800
Mn	47	6.6	140	20	860	73
Ni	0.88	5	2.7	15	16	56
Pb	0.024	0.02	0.074	0.061	0.44	0.22
Sb	0.024	0.044	0.074	0.14	0.44	0.49
Se	0.24	2.7	0.74	8.2	4.4	30
SO_4	2300	28000	7100	86000	42000	310000
Zn	8.2	64	25	200	150	700

4 Water Quality Estimates

4.1 Dump and Backfill Run-Off and Seepage (During Operations and Active Closure)

Water flows for the site, including dump/backfill run-off and seepage, were calculated using the Closure Water Balance Model (CWBM) described in a companion paper (Luinstra et al. 2018). Due to the highly seasonal nature of rainfall in the area, calculated flows were very variable; rapid flows in the wet season, and limited or no flow during the dry season. The solute production rates described earlier were combined with the calculated flow rates to generate chemistries for dump and backfill run-off, and for basal and toe seepage.

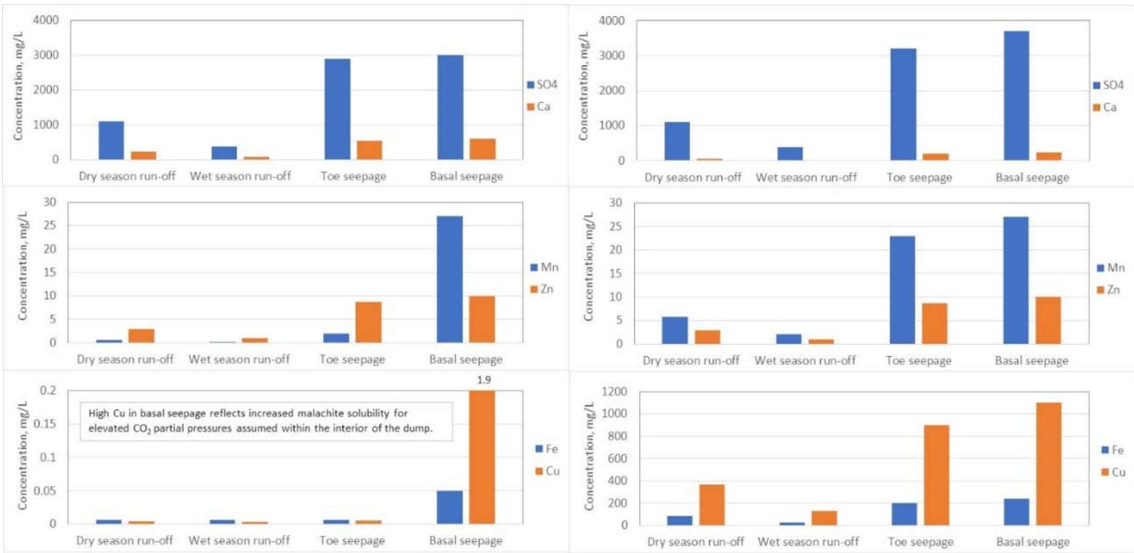
For run-off, solute concentrations during dry season conditions are appreciably higher than during the wet season. In the case of basal and toe seepage, seasonal variability in surface recharge would not necessarily be observed (for example, due to water storage within the dump). For the purposes of the water quality calculations, average annual seepage quantities were generated, which were used to calculate constant monthly seepage flows.

Table 3 Comparisons of calculated chemistry with seep survey results – selected parameters

Parameter	Calculated ranges		Seep survey
	Run-off (Wet Season)	**Toe Seepage**	**Min – Max**
pH	3 (ANC depleted), ~8 (neutralised)	2-5-3 (ANC depleted), ~8 (neutralised)	3 – 9.4[1]
SO_4	170-380	1,800-3,200	5 – 2,440
Ca	<20 (acid), 40-80 (neutral)	200-230 (acid), 300-550 (neutral)	3.1 – 352
Cu	30-370 (acid), ~0.004 (neutral)	200-1,000 (acid), <0.01 (neutral)	0.02 – 160
Mn	~2-7 (acid), 0.05-1 (neutral)	20-30 (acid), 1-2 (neutral)	0.012 – 28
Zn	<1-3	5-10	0.01 – 2.57

Units – mg/L, except pH

[1] The maximum pH value (9.4) corresponded to a sample from a diversion trench which may also receive flow from an agricultural area, possibly explaining the unusually alkaline pH.



(a)Neutral conditions (b) Acidic conditions

Mineral controls:	Dolomite gypsum, iron hydroxide, gibbsite, manganite, malachite/tenorite	Jarosite (basal seepage only)

Figure 4 Calculated dissolved concentrations for selected elements in run-off and seepage from the Phabing dump (during operations and active closure phases)

Water quality was estimated for percolate contact with (and without) ANC; ANC was represented in the calculations by equilibration with dolomite. It is reasonable to expect that freshly placed material may contain ANC, and that initial run-off and seepage may be pH neutral. However, ANC may not always be present, and, for PAF materials, would deplete in time. Where no ANC is available, contact water chemistry from PAF materials would be acidic. Mineral-equilibrated solute concentrations were calculated using PHREEQC (Parkhurst and Appelo, 2013). In dolomite-equilibrated, pH neutral solutions, dissolved concentrations of Fe, Al, Mn and Cu were calculated to be controlled by the solubility of iron hydroxide, gibbsite, manganite and malachite/tenorite, respectively. In the most saline solution chemistries – gypsum solubility placed upper bounds on dissolved SO_4 and Ca concentrations.

Figure 4 shows calculated dissolved concentrations for selected elements in the case of the Phabing dump, one of the largest PAF dumps at the site. The higher concentrations calculated for basal and toe seepage, compared to run-off, relate to more advanced AMD from PAF materials, combined with lower volumes of contact water. Table 3 compares the ranges of calculated chemistries (for all dumps considered to represent AMD sources) with results from a seep survey conducted during 2017 (during a period of unusually high rainfall). Observed and calculated ranges compare relatively well, giving a degree of confidence that representation of solute production within the dumps is appropriate. It must however be acknowledged that both observed and calculated ranges are wide; greater confidence could be achieved with a more extensive set of observational data – for example covering wet and dry season conditions (and in particular more typical conditions than those experienced during the seep survey event).

4.2 Dump and Backfill Run-Off and Seepage (Post-Closure)

Following closure, once closure mitigation measures (e.g. soil covers) are in place and dump surfaces have been revegetated, run-off water quality is expected to resemble natural catchment run-off. Recharge to dump surfaces is expected to be reduced and other conditions may change, including:

- Infiltration rates would decrease and the fraction of material contacted by infiltrating water would be lower.
- Zones of oxidising material would be thinner, reflecting reduced oxygen supply through the cover.

Revised water balance calculations were performed to represent these changed conditions by adjusting the scaling factors to reflect field-scale conditions as shown on Table 4.

Table 4 Comparison of base case and post-closure scaling factors and approximations (dump seepage)

Description	Units	Base Case (see Table 1)		Post-Closure	
		NAF	PAF	NAF	PAF
Surface area correction	-	0.2	0.2	unchanged	
Fraction flushed by rainfall/infiltration	-	0.3	0.3	0.05	0.05
Assumed thickness oxidising	m	10	3	5	0.5

The modelling indicated that placing covers on the dumps, to reduce both infiltration and supply of oxygen, would result in significant beneficial outcomes. Although the potential for acidic drainage (pH 3-4) remains, overall solute loadings were significantly reduced.

4.3 Pit Lakes (Post-Closure)

Based on the net positive water balance for the site (Luinstra et al. 2018), lakes are expected to develop in the pits. To simplify the overall assessment the transient evolution of pit lake water quality during rebound has not been assessed; rather the longer term steady state conditions were estimated. The site water balance indicated that the pits will form lakes that will overflow during the wet season. Pit outflow chemistry is expected to be dominated by solute loadings from PAF material exposed on pit walls above the lake elevation.

Calculated outflow chemistry varied seasonally due to the variations in flows. During the wet season solute concentrations are diluted and lower than is the case during the dry season. Table 5 presents comparisons of calculated chemistries with routine pit lake water quality monitoring (noting that some of the pit lakes are subject to active treatment) and incidental samples obtained during the seep survey. While the concentration ranges that are calculated for wet season conditions were lower than some of the monitoring results, the calculations assume completely mixed conditions; this may not have been the case when the incidental samples were obtained as they represent shallow surface water grab samples.

Nevertheless, the calculated pit outflow chemistries lie within the (large) ranges observed in routine pit lake monitoring. As already mentioned, the routine monitoring dataset is influenced by active treatment measures in place for some of the pit lakes. Treatment increases the pH to alkaline maximum values, with a coincident reduction in dissolved concentrations of many metals.

Table 5 Comparisons of calculated chemistry with seep survey results – selected parameters (pit lakes)

Parameter	Calculated ranges (base case conditions; ANC depleted)		Pit Lake samples obtained during seep survey (wet season)	Water quality monitoring[1]
	Jan (Dry Season)	July (Wet Season)	Min – Max	Min – Max (25^{th} – 75^{th} percentile)
pH	2 – 3	4 – 5	3 – 7.8	2.1 – 12.09 (6.4 – 8.3)
SO_4	1,200 – 4,500	10 – 50	9 – 1,780	2 – 10,200 (52 – 600)
Ca	60 - 110	18 – 25	2.9 – 236	0.01 – 991 (38 – 205)
Cu	300 – 1,800	0.01 – 22	0.02 – 85	0.001 – 1,569 (0.033 – 0.85)
Mn	6 – 10	0.08 – 0.13	0.03 – 18.8	0 – 82 (0.16 – 1.81)
Zn	3 – 10	0.06 – 0.14	0.01 – 2.87	0.001 – 105 (0.02 – 0.65)

Units – mg/L, except pH

[1] Excerpts from site water quality monitoring dataset. Some of the pit lakes are treated with lime; the observed very alkaline maximum pH, and low minimum solute contents reflect treated waters.

5 Conclusions

Laboratory-derived data have been used as a basis to estimate solute production rates under field conditions. Whilst many assumptions and simplifications were necessary – it was possible to generate solute loadings for multiple AMD sources (pits and dumps) around the site that resembled current observations. The calculated ranges of chemistries for AMD-impacted waters during operational, active closure conditions were found to lie within the range of chemistries observed, giving confidence that the estimates can be used to inform closure planning. Incorporation of derived solute loadings in an overall site-wide water and load balance was used to assess closure requirements and is described in a companion paper (Chapman et al. 2018).

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Radiological Aspects of Mine Closure and Site Remediation at the Wismut Site of Schlema-Alberoda

P Schmidt *Wismut GmbH, Germany*

J Regner Wismut GmbH, Germany

C Schramm Wismut GmbH, Germany

Abstract

Uranium mining in Schlema-Alberoda took place from 1946 to 1991. With its extension to a depth of about 1,800 m from surface, the Schlema mine was at that time the deepest mine in Europe. Deep mining and the development of underground mine openings, tunnels and galleries with a total length of 4,200 km was accompanied by piling up of 47 million cubic metres of low-grade ore and radioactive waste rock material. When Wismut GmbH commenced in 1991 with mine flooding, remediation of waste rock piles, decommissioning of buildings and structures, and with clean-up of radioactively contaminated industrial areas, a number of radiological problems had to be managed in Schlema-Alberoda. Improvement of the radon situation, treatment of contaminated mine and seepage waters, and safe disposal of radioactive wastes and residues were the key remedial tasks from a radiation protection perspective. The present paper describes the radiological situation immediately after termination of uranium mining in Schlema-Alberoda, gives an overview on the main remedial activities and evaluates the achieved state of remediation. The paper serves also as introductory lecture for the Schlema-Alberoda field trip as part of the program of the present mine closure conference.

Keywords: *mine closure, legacies, remediation, radiation exposure, radon*

1 Introduction

Since 1991 the national corporation Wismut GmbH has been conducting the remediation of the uranium production legacies in Germany's federal states Saxony and Thuringia.

Schlema-Alberoda is one of the seven remediation sites under responsibility of Wismut GmbH, but in some ways it is a special Wismut site. First of all, there is the history of the place. Before world war two, Schlema was an internationally well reputed spa where every year thousands of patients and recreation seekers were treated by use of radon containing water from the then strongest radon water source worldwide. After the war, Schlema-Alberoda became the hub of intensive uranium ore mining. More than 80,000 t of uranium were brought to surface. Radioactive waste rock material with a volume of 47 million m³ was piled up in altogether 20 piles, often erected adjacent to residential areas. This all caused serious impacts on the environment and public health, and a dramatic devastation of the landscape. Compared to other Wismut sites, the highest radon concentrations were found in Schlema-Alberoda. Thereby, not only radon emanating from waste rock material but also radon from near-surface mine galleries contributed to the exposure of members of the public. Radiological exposure along the water pathway was however of minor relevance.

And special is also "the now"! After more than 25 years of successful remediation, Schlema-Alberoda is today considered a unique example of the transformation of a severely damaged mining site into a place with high attractiveness for housing, leisure activities and recreation. In 2005, the municipality regained its former name Bad Schlema. With this name the rebirth of the spa became officially recognized by the Saxony government.

2 Legacies at the site, impacts and radiological characteristics

Radioactively contaminated mining sites, as uranium mining sites, are characterised on the one hand by low levels of radioactivity in the residues and environmental media (LLW - Low Level Waste), and on the other hand by big amounts of contaminated material as well as by large areas of contaminated land. The release of radioactivity from the solids results in radioactively polluted water (mine water, seepage water → groundwater, → surface water) and elevated radioactivity in air (in the mine air, indoors and in the free atmosphere). The radioactive noble gas radon (Rn-222) may also emanate from mine and seepage water.

Table 1 gives an overview of the scale of the legacies and of affected environmental media, and provides data for the radiological key parameters in mining materials and media for the Schlema-Alberoda site.

Table 1 Legacies in Schlema-Alberoda, impacted environmental media and radiological key parameters in 1991

Legacies/ environmental media		**Scale**	**Environmental impacts/ impacted by**	**Radiological key parameters (typical levels)**
Industrial areas*		5.7 km²	Ground contamination	Ra-226: 0.2-locally 10 Bq/g
Waste rock piles*	Number	20	Ground contamination	Ra-226: 0.3-1 Bq/g
	Area	3.7 km²	Radon exhalation	Rn-222: 1-10 Bq/(m² s)
	Volume	47 Mm³	Seepage water emission	1-5 mg/l U-nat in seepage water
Tailings pond	Number	1	Ground contamination	Ra-226: 1-5 Bq/g; U-nat: 200 g/t
	Area	0.035 km²	Radon exhalation	no (water covered)
	Volume	0.25 Mm³	Seepage water emission	1-5 mg/l U-nat in seepage water
Mine	Volume	39 Mm³ space 54 shafts 62 levels	Mine water contamination	4-6 mg/l U-nat in mine water
			Radon mitigation	Rn-222: hundreds of kBq/m³
			Geotechnical instabilities	Not applicable
Mine water		<39 Mm³	Mine, ground contaminat.	4-6 mg/l U-nat; 2-5 Bq/l Ra-226
Seepage water		Unknown	All legacies	1-5 mg/l U-nat
Surface water (r. Mulde)		3-20 m³/s	Seepage, treated mine w.	<10 µg/l U-nat (river Mulde)
Mine air (ventil. 2017)		1,280 Mm³	Mine	Rn-222: up to 1 MBq/m³
Outdoor air		Not applicable	Waste rock piles, mine	Rn-222: 30-1,000 Bq/m³ Rn-222
Indoor air		Not applicable	Mine (no ventilation)	Rn-222: > 10,000 Bq/³

*included are the small areas and piles of the Pöhla site close to Schlema-Alberoda

Rehabilitation of areas, demolition of structures and handling of LLW under the Wismut Project required and is still requiring the resolution of specific issues in terms of radioecology and translating radioprotection into practice. In essence, this applies to the implementation of basic ICRP radiation protection principles (ICRP 1990; ICRP 2007), namely the principles of justification, limitation and optimisation. Their implementation includes the successful handling of the following subtasks:

- Development of assessment criteria for the justification of rehabilitation activities
- Development of a radiological monitoring system including measures to survey occupationally exposed persons
- Inventory of the initial radiological situation, assessment of baseline conditions, and object-related rationale for the justification of rehabilitation activities
- Object- and site-specific optimisation of rehabilitation measures
- Development of appropriate measuring procedures for contamination determination as well as of release measurement procedures including the establishment of a quality assurance system
- Management of radioactive wastes and residues; e. g. residues arising from water treatment
- Implementation of effective measures to ensure practical radiation protection for employees and to minimise impacts to the general public from rehabilitation operations
- Training and retraining of involved employees in radiation protection matter
- Public relations including the participation of persons concerned by the rehabilitation, of population groups, organisations, and public authorities, etc. (stakeholder involvement)
- Management of the approval and licensing process, and
- Development of procedures to demonstrate the success of the restoration effort.

The "1 mSv/a" criterion has been established as a primary recommended guidance level to assess the need for remediation of uranium legacies in Eastern Germany (SSK, 1992). This guidance level is geared by the variation width of the natural radiation exposure and comprises all potential exposure pathways. The need to rehabilitate was (and still is) derived from the results of an object and/or site specific exposure pathway analysis and by comparing the established effective dose to the guidance value of 1 mSv/a.

3 Radiological exposure at the Schlema-Alberoda site

Exposure of members of the public through to human consumption of contaminated water und the use of contaminated water for irrigation purposes and livestock watering is not critical. Usable ground water aquifers are not developed at the site. Seepage waters are diffusely dispersing into the ground towards the mine. Flooding of the mine is controlled by mine water drainage and water treatment. For this purpose, in 1999 a powerful water treatment plant was brought to operation. Seepage water emerging at the surface, for instance at the toe of waste rock piles, is collected and either discharged into the mine or directly drained into the large receiving river Zwickauer Mulde. Clean water for human consumption, irrigation and watering is sufficiently available at the site.

It is primarily the noble gas radon which causes or may cause significant effective doses at the Schlema site, and there are two reasons for this:

3.1 Radon exhalation from waste rock piles

Waste rock and low-grade ore generated by uranium mining in the order of 47 million m³ was dumped on slopes around and within the local community of Schlema-Alberoda in such a way that dwellings were only a couple of metres away from the rim of the mine dump. Thermally driven convective air flows similar to natural mine ventilation occur within the waste rock dumps. In summer conditions when atmospheric temperatures are above the relatively stable air temperature within the body of the mine dump, the air flows from the upper part of the dump down to the toe where it exits. Radon release from the toe is funnelled to a small surface area which in the majority of cases is in close vicinity to the residential areas.

In the following, a typical exposure situation for people living at the toe of a waste rock dump is presented. By exposure pathway analysis in accordance with (BfS, 2010) the effective doses for an infant in the age group of 2-7 years and an adult reference person, both living permanently in the immediate neighbourhood of a large uncovered mine dump and using seepage water to irrigate their garden, were estimated. The analysis was based on the following mining-induced radiological data (i.e. without background radiation):

- Mean specific activity of U-238 in waste rock material = 1 Bq/g, in radioactive equilibrium with daughter nuclides
- Rn-222 concentration on top of and alongside the mine dump: 150 Bq/m^3
- Ambient dose rate on top of and alongside the mine dump: 530 nSv/h
- Concentration of long-lived alpha emitters on top of and alongside the dump: 1 mBq/m^3
- Seepage water concentrations: 1 mg/l U_{nat}; 0,5 Bq/l Ra-226 and Th-230; 0,1 Bq/l Po-210 and Pb-210; 0,01 Bq/l Pa-231 and Ac-227.

Relevant exposure pathways in the case under consideration include exposure by:

- Ingestion of locally grown garden products (GP; 25% of total consumption rate)
- Ground gamma radiation (Ext)
- Inhalation radon and its short-lived decay products (Rn/DPr)
- Inhalation of dust-borne long-lived alpha emitters (LLA)
- Direct ingestion of waste rock material (Dir-Ing).

An annual dwelling period of 7,000 hours near the mine dump and a total annual sojourn on the dump surface of 250 hours (child) and 100 hours (adult), respectively, were assumed. Figure 1 depicts the findings of the exposure analysis. The example illustrates the predominance of the exposure pathway "Inhalation of radon and its short-lived decay products".

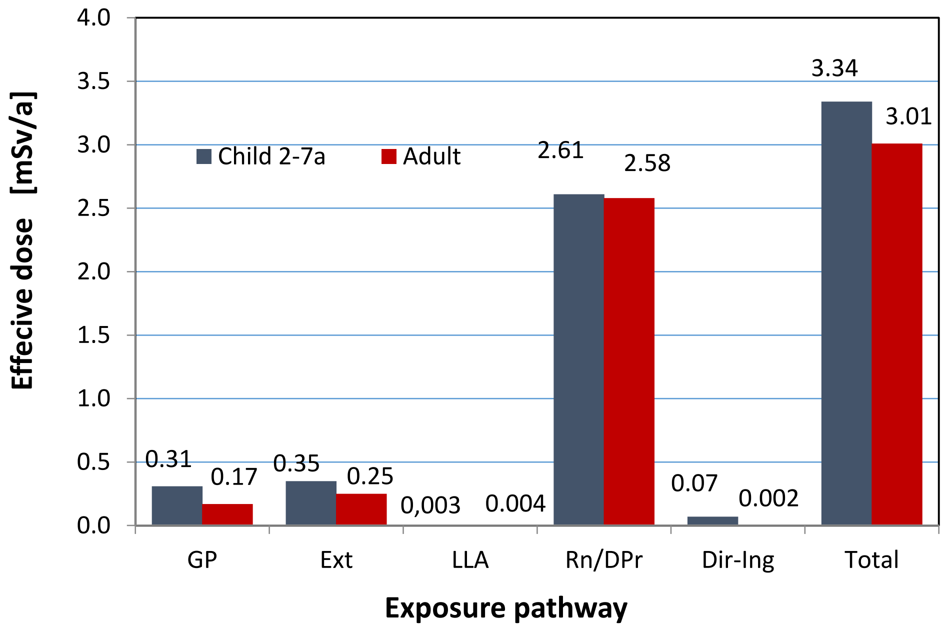

Figure 1 Typical exposure situation at an un-remediated waste rock pile in Schlema-Alberoda

3.2 Radon migration from near-surface mine galleries

Even at the end of the flooding process of the Schlema-Alberoda mine to be accomplished in a few years, the water level will not exceed the elevation of the Markus-Semmler adit. As a consequence, mine voids located at the higher elevations will remain permanently non-flooded and constitute a potential radon source, in particular for homes sitting above. Many years of complex investigations into the impact of near surface mine workings on the radon situation in Schlema provided evidence that in the presence of natural buoyancy conditions convective gas transport processes may carry radon from the mine into houses through bedrock disturbed by mining even over extended distances. Under natural ventilation conditions, radon concentrations within the mine workings may rise up to levels of several hundred kBq/m³, in extreme cases of up to 1 MBq/m³. In this way, convective gas transport processes would in particular cases provoke indoor radon concentration levels significantly above 10,000 Bq/m³ which would result in an inacceptable radiation exposure of the residents.

At the moment, the indoor radon situation in Schlema is effectively controlled by ventilation of the mine. Through a sucking ventilation system, a negative air pressure condition in the order of ca. 100 Pa is generated. The air pressure in the mine is maintained lower than the atmospheric air pressure.

The dependence of the radon concentration from the mine ventilation conditions has been studied by Wismut in a number of homes. Use of tracer gas (SF6) in combination with real-time radon concentration measurements was successful in providing experimental evidence of the radon transport from the mine into homes and quantifying that phenomenon in individual cases. Figure 2 illustrates by way of example the impact of mine ventilation on radon concentration levels in a basement.

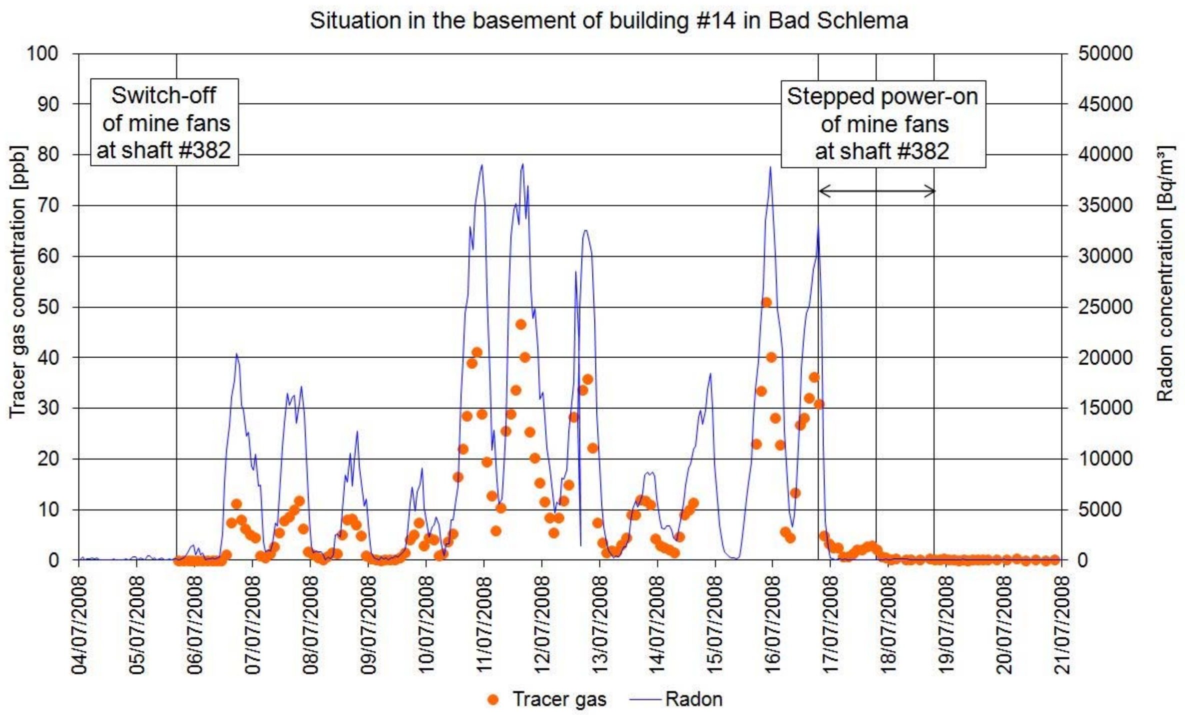

Figure 2 Impact of mine ventilation on radon concentration levels in a basement of a dwelling house in Schlema-Alberoda

4 Major remediation activities

The major remedial measures and related activities for the different types of legacies at the Schlema-Alberoda site are listed in Table 2.

Table 2 Remedial measures and activities

Legacies	Major measures	Related activities
Industrial areas	Demolition of buildings and structures	Sorting of debris and scrap, disposal of contaminated material at waste dump #371, re-use of not/lowly contaminated scrap
	Site clean-up	Excavation and disposal of contaminated soil (completely or partly depending on re-use option), refilling, coverage
Waste rock dumps	Relocation (only dump #250)	Refilling of the footprint area, coverage of the waste material at the site of relocation ("deformation area")
	In-situ remediation (all other dumps)	Dump body regrading to ensure slope stability, relocation of excess material to the Borbach valley (see tailings pond remediation), covering, surface vegetating
Tailings pond Borbach valley	Dry in-situ remediation	Dam stabilisation, removal of supernatant and pore water (tailings stabilisation), construction of an interim cover with waste rock material, final coverage, surface vegetating
Mine	Controlled flooding	Removal of structures, pumping (water level control) and treatment of mine water; disposal of water treatment residues at a special disposal facility on waste dump #371
	Stabilisation of near surface galleries	Partly refilling, mainly mining works / gallery strengthening, establishment of water derivation systems, mine ventilation

In chapter 3.1, radon inhalation was reported as the dominating exposure pathway in Schlema-Alberoda, with waste rock piles close to residential areas as source of radon. Since relocation of the huge amount of waste rock material was not possible (lack of a disposal site remote from Schlema-Alberoda, costs for back-filling into the mine), the focus was put on the development of a cover on the dumps with sufficient ability for mitigation of the release of radon. A 1 m thick standard cover consisting of a radon barrier (0.8 m thick) and an above-laying 20 cm thick re-cultivation layer was developed to manage the local radon situation. Figure 3 illustrates the standard cover design. The positive remedial effect is exemplified in Figure 4.

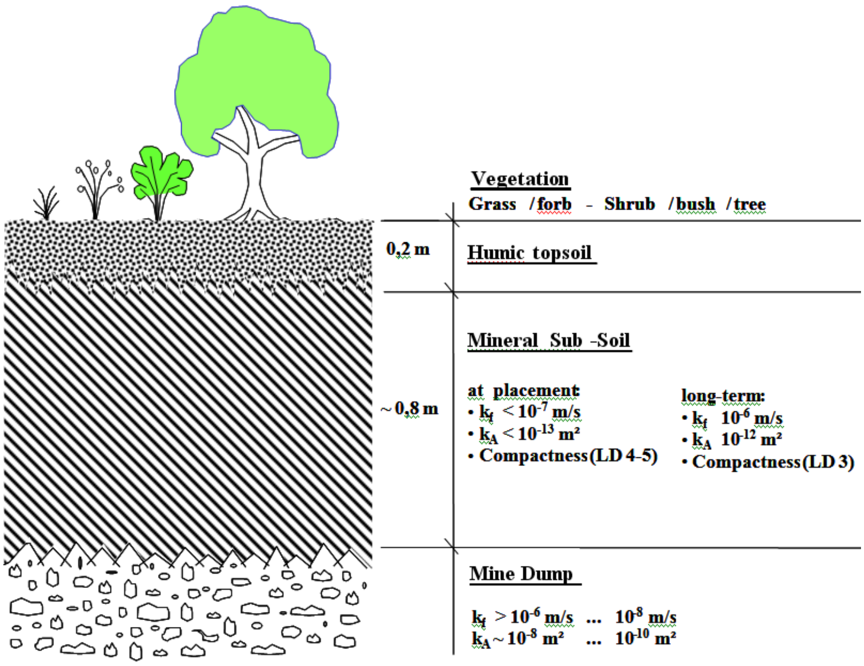

Figure 3 Cover design to control convective radon release from steep mine dumps.

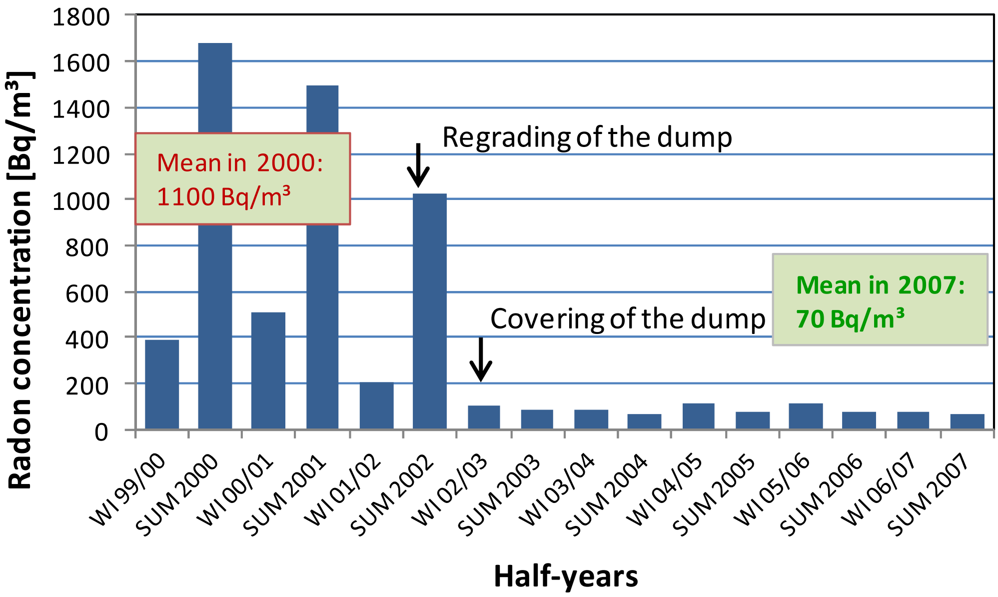

Figure 4 Evolution of outdoor radon concentration at the toe of a mine dump prior to rehabilitation, during intermediate regrading, and in post-remedial condition.

5 Present state, still existing radiological problems and outlook

5.1 Industrial areas

More than 90% of the areas are cleaned up. Some demolition and site remediation work is still to be done at the former shaft site #371, were the local Wismut branch is actually head-quartered. This local site is under preparation for hosting offices and technical structures for the implementation of long-term monitoring and surveillance activities at the Schlema-Alberoda site.

5.2 Waste rock piles

All the heaps in close vicinity to residential areas are covered and re-vegetated. At two smaller dumps (#309, #310) remote from places of residence covering and construction of the surface water drainage system have to be completed. At the almost completely covered surface of the big waste rock dump #371, the disposal facility for residues from water treatment will be operated for a longer time. Dump #371 is also far from living houses.

The remediation of the waste rock piles resulted in a significant reduction of the radon releases, and subsequently in lower effective doses for the public. Observations however show that a couple of years after completion of the cover its radon attenuation effect tends to decline locally. The probable cause is deep-rooting plants and burrowing animals (so-called bio-intrusion). Hence, at the toe of large recovered dumps (#38neu. #Hammerberg), the 1 mSv/a criterion is locally not yet met. Wismut GmbH currently investigates various solution approaches to control mine-related radon.

5.3 Tailings pond Borbach valley

Remediation of this small tailings management facility was terminated already in 1998.

5.4 Schlema-Alberoda Mine

Flooding of the mine is in a very advanced state. Ca. 36 Mm^3 of the formerly open mine space of 39 Mm^3 are water-filled. By pumping of water in an order of 1,000 m^3/h, the water level is kept at 30 m below the natural flooding level (Markus Semmler adit level). The conveyed contaminated mine water is treated. Resulting radioactive residues are disposed of at the waste rock dump #371. While uranium has been slowly, but steadily declining in the mine water over the past two decades, no trend has been observed for Ra-226. Wismut GmbH therefore considers the need for water treatment to be necessary for a longer period of time. Current plans for water treatment are focusing on the level of the year 2045 and later.

The mining works for stabilisation of those voids above the Markus Semmler adit, which will be permanently not-flooded and which will serve for water drainage will be completed around 2025. After that, surveillance of geo-stability of the mine openings and control of the functionality of the water diverting system will be the focus of the long-term activities.

With respect to mine ventilation as a measure to control the convective radon transport from mine voids through the disturbed bedrock, and to control indoor radon, experiments and model calculations have been performed to arrive at an optimised ventilation system. The sucking ventilation system developed by Wismut GmbH will require in the long run a relatively low fan power of < 10 kW. Centralized generation of negative-pressure conditions has the key advantage of large-scale action which, as a rule, dispenses with the need for specific mitigation to be performed at individual homes. The responsible radiation protection authorities in Saxony are however still reluctant to accept the permanent ventilation as the optimised measure for the long-term control of indoor radon.

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Safe Management and Remediation of Abandoned Uranium Mining Sites in Central Asia – A Review of Numerous Feasibility Studies

T Metschies *Wismut GmbH, Germany*

P Schmidt *Wismut GmbH, Germany*

U Barnekow *Wismut GmbH, Germany*

M Paul *Wismut GmbH, Germany*

Abstract

The uranium mining legacies in the Central Asian states of Kyrgyzstan, Uzbekistan and Tajikistan were recognised by IAEA and international donor organisations as posing tremendous risks to the health of local population and the environment. A Strategic Master Plan was set up to address these risks and to provide technical and financial support to the respective countries. As basis for the necessary remediation steps various feasibility studies were financed by the European Commission to identify the existing risks and prepare a risked based prioritisation of remediation measures. In consortia with or contracted by other companies such as WISUTEC Umwelttechnik GmbH, G.E.O.S. Ingenieurgesellschaft mbH, Facilia AB, SCK•CEN as well as local subcontractors experts of Wismut GmbH were involved in a number of these projects preparing environmental impact and risk assessments as a basis for feasibility studies and for remediation planning. This paper presents a review of the works made as part of the feasibility studies, the experiences gained and summarises the main findings of the respective site characterisations and risk analysis at reference sites in the three countries. General conclusions are presented and recommendations for the remediation works and the monitoring of the impacts are given.

Keywords: *uranium mining legacy, remediation, Central Asia*

1 Introduction

Uranium mining and milling started in Central Asia in the mid 1940s. During the 1970s and 1980s, more than 30% of the uranium production of the former Soviet Union (USSR) originated from this region (Jakubick et al. 2008). The subsequent decline of many of the former Soviet production centres left behind a series of legacy sites in the Kyrgyz Republic, Tajikistan and Uzbekistan, which are situated along several tributaries to the Syr Darya River. The Syr Darya is running through the Fergana Valley, which is shared by the three Central Asian countries and is known to be the densely populated agricultural centre of the region. All sites have been abandoned without appropriate remediation, monitoring and maintenance. Therefore, many of the former production facilities and waste objects pose a relevant impact on environment, human health and local communities.

The International Atomic Energy Agency (IAEA) together with the countries concerned and representatives of international organisations such as the European Union (EU) developed a Strategic Master Plan referencing relevant sites and remediation priorities. This plan defines hotspots and priority objects based on environmental impact assessments and feasibility studies funded by the EU and studies prepared by Rosatom. The EU has allocated a total funding of EUR 14.7 million to implement work at seven priority uranium legacy sites in Kyrgyzstan, Tajikistan and Uzbekistan to improve the safety at former uranium mining and milling legacy sites.

In consortia with or contracted by other companies such as WISUTEC Umwelttechnik GmbH, G.E.O.S. Ingenieurgesellschaft mbH, Facilia AB, SCK•CEN as well as local subcontractors experts of Wismut GmbH were involved in a number of these projects preparing environmental impact and risk assessments as a basis for feasibility studies and for remediation planning. Wismut's experts provided particularly radiological, hydrogeological, geochemical and geotechnical engineering expertise. The abandoned uranium mining and milling sites include Mailuu-Suu, Min-Kush and Shekaftar in Kyrgyzstan, Charkesar and Yangiabad in Uzbekistan as well as Istiklol (formerly known as Taboshar) and Degmay in Tajikistan (Figure 1). The work performed by Wismut's experts mainly focused on aspects of site characterisation, environmental impact and risk assessment, and environmental monitoring including the identification of remedial needs, the priorization of objects to be remediated. For some of the objects the mandate did also include the conceptual planning including the evaluation of the preferred remediation option and the design and construction planning. Based on the experiences gathered from those projects this paper intends to outline general findings and to characterize the present status at the sites concerned including an outlook on appropriate actions to be considered.

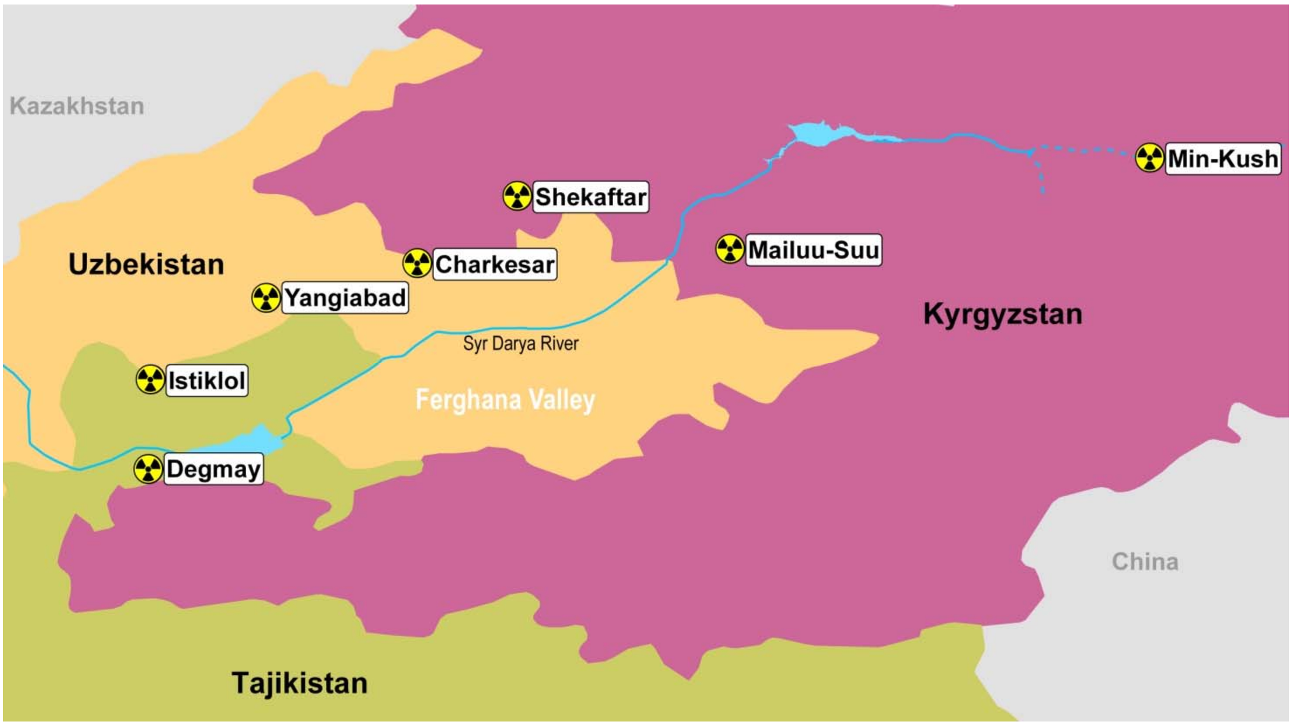

Figure 1 Investigated former uranium mining and processing sites in the Central Asian countries Kyrgyzstan, Tajikistan and Uzbekistan

2 Review

At several of the examined sites both mining and processing took place resulting in the respective legacies of mines, waste rock piles, dumped processing residues and tailings ponds. At some of the sites closure of mines and processing sites was carried out before the 1970s with former mining installations decommissioned according to the standards of the Soviet Union (Kunze et al. 2007). Others were run till the mid of 1990s.

Characteristic for all the legacy sites are elevated concentrations of radioactive as well as chemo-toxic substances in solids and waters. This causes radiological risks for the local public and risks due to the potential intake of chemo-toxic substances. In addition geotechnical risks may be of major importance for public safety. In water uranium is the most important polluter for the health impact on members of the local public, whereby primarily the chemo-toxicity of uranium is of relevance. In soil and air, elevated concentrations of the decay nuclides of U-238, as Ra-226, Po-210 and Pb-210, may cause radiation exposure. In addition, the radioactive noble gas radon may locally be important from a radiation protection perspective.

Because of limited access to former mine surveying documents, usually only scarce information concerning the location and extent of underground mine workings at the site are available. Information on the present status of the mine workings as well as flooding levels or water balances of any operational status are usually not accessible. Therefore, baseline information on relevant mining structures must mainly be collected from site visits gathering information based on surface structures and other visible mine related impacts. The decommissioning of the underground mines often just consisted of the closure of surface openings by either material dumping in front of or even blasting of mine entrances. Surface structures of shafts were mostly removed and the shaft opening covered by a concrete slab. However, building debris or even complete structures mostly remained at the sites with no clean-up of the adjacent working areas. Especially in remote areas an appropriate closure was not conducted and adits or shafts are still open. In some cases locals have removed the sealing material to gain access to the mine for secondary mining or to use mine water as water resource. Building structures were often just without any defined after-use or blasted with debris remaining.

In case water is decanting at the surface usually no controlled water discharge from the mines has been implemented. Water emerging from adits flows out freely and is mostly easily accessible irrespective of its chemical composition. Especially in remote areas this water may be used for irrigation, animal feeding or even as drinking water. Uranium concentrations in these decanting mine waters could even reach up to 1.5 mg U/L (adit 6 at Istiklol/Tajikistan). Most decanting mine waters exceed the WHO guideline value for uranium in drinking water (30 µg/L) or even respective values in the national legislations by orders of magnitude. Locally this mine water outflow could even be the only water source feeding small brooks during dry season. This results in a relatively wide spreading of the contaminants along the streambed. If the water in the brooks is utilised for irrigation contaminants are spread even on wider areas with horticultural use.

Due to mountainous morphology at the various sites mine wastes and processing residues were mostly dumped at a multitude of plots. This led to a relatively high number of dumps hosting only small material volumes. Nevertheless, these dumps pose various hazards due to their geotechnical properties and subsoil conditions, the risk of material displacement due to landslides or flood events as well as the release of contaminants by seepage waters from the dumped material itself. E.g. at Mailuu-Suu in Kyrgyzstan 23 tailings ponds and 13 waste rock piles remained at the territory of the former enterprise from a total production of 10,000 t of U_3O_8. As at other sites some of the piles containing the residues of mining and milling are situated close to or even within settlements. In most cases the piles were contoured during decommissioning and at least pre-emptively covered, the surface water discharge was resolved by constructing discharge channels at the boundary of the objects. However, the cover thickness is insufficient by present-day standard and does not reduce the infiltration to a significant extent. Often the covers are damaged by burrowing animals resulting in waste rock or tailings materials being exposed.

The sites are often located in areas characterised by strong erosion due to high seasonal surface water discharges, steep and instable hillsides with high landslide potential and high probability of strong earthquakes. Partly, the dumps are close to river banks being prone to erosion in the long-term. Thus the geotechnical stability and structural integrity of these objects is endangered to the long term. Supported by Wismut's experts stabilisation measures were already planned and implemented during the past years by constructing reinforcements of riverbeds and their side slopes e.g. with gabion walls or even relocating tailings material as performed at the former tailings pond No. 3 at Mailuu-Suu, Kyrgyzstan. Here tailings pond no. 3 was endangered by large landslide body located uphill. Resulting from the feasibility study relocation was identified as the preferred remediation option for this site. Supported by Wismut experts here the tailings remediation was planned by 2008 as relocation to another newly constructed safe disposal cell. These works were later successfully implemented supported with Wismut's radiological expertise and completed by 2011. In addition Wismut's experts planned in Mailuu-Suu the remediation of certain waste dumps which was implemented as well. Seven years later,during our current project in Mailuu-Suu we could find these remediated objects to be in full functionality and properly maintained.

Due to limited care and maintenance the water collection systems may deteriorate over time and surface waters may affect the objects leading to material erosion. Another risk arises from landslides which may block surface water courses and, as a consequence, flood the dumped material which may then be released as a mudflow. In addition the Tuyuk-Suu tailings pond is located in a steep and narrow valley with a creek flowing in a channel located on and along the tailings pond. The upstream catchment area of this river covers approximately 90 km^2 and is located in mountainous region thus causing a significant risk for the town due to potential flood events Such scenarios have to be considered for the Tuyuk-Suu tailings pond located upstream of the town of Min-Kush in Kyrgyzstan. Wismut's experts were involved in the preparation of the feasibility study for this object. In 2016 this work resulted in a decision for relocation of this tailings pond to another site.

From 2015 till 2017 Wismut's experts were also involved in the preparation of the feasibility study for the Degmay site nearby the city of Khudjand in Tadjikistan. The air-exposed radioactive tailings surfaces led to radioactive dusting. Erosional stability was insufficient for both the tailings surfaces and the dam slopes. Here Wismut's experts were involved in the design and construction planning for the in-situ remediation of the Degmay tailings pond. The remediation design included the diversion of runoff from the upstream catchment area around the tailings pond and re-contouring and covering of the tailings pond with an erosion protection cover. The surface cover grants erosional stability and structural integrity of the tailings pond to the long term while excluding the unacceptable after-use scenario (cattle pasture with shepherds staying on the site) with respect to dose exposure via the air pathway.

At Min-Kush in Kyrgyzstan seepage waters emerging at or in the close vicinity occur at several waste rock dumps and tailings piles. At tailings piles these waters mainly have elevated salt and metal concentrations. Uranium may reach up to 50 mg/L in such kind of waters. But concentration between 1 and 10 mg/L usually occur. Even with discharges limited to or less than 1 m^3/h uranium loads between 10 and 100 kg may be released annually at these sources.

Especially during the dry season and in remote areas in Central Asia accessible water resources are limited resulting in the use of influenced surface and ground waters. Very often former mining and milling sites serve as grazing grounds and animals are getting in contact with the contaminated mine and seepage waters. On the other hand especially in larger settlements authorities paid attention to provide drinking water supply from sources upstream of the mining site without mining impact (Istiklol, Min Kush, Mailuu-Suu). However, the water supply systems are usually outdated and in poor conditions resulting in frequent close downs. As a consequence the local population relies on other sources which might be impacted by the uranium mining and processing legacies. Furthermore, not all parts of such settlements are connected to a central water supply, so that people are forced to use potentially polluted water sources.

Regardless of the high contaminant concentrations in single streams the uranium concentrations in rivers draining the mining area do not exceed 15 µg/L. Concentrations are mostly even below 10 µg/L but are increased compared to the respective background values at the sites. As a result of dilution with uncontaminated surface water from the wider catchment area there is only little concern regarding the human health impact in the regions downstream. However, due to the relatively high discharge rates considerable uranium loads are released from the sites. Comparing these releases with the situation measured and reported in the Syr-Darya it becomes clear that apart from the mining sites there are additional uranium sources influencing the uranium concentration in the surface waters of the entire Central Asian region. Skipperud (Skipperud et al. 2013) reported measured uranium concentrations of 36 and 45 µg/l in the Syr Darya river at Khujand downstream the Kyrgyz and Tadjik mining and processing sites. This order of magnitude could be verified by own measurements (17.4 µg U/L).

Monitoring and supervision activities are conducted sporadically at the former legacy sites (Jakubick 2008, Djenbaev 2015). Neither mine surveying data nor consistent environmental monitoring data are easily available apart from published study results or studies funded by international institutions. Missing overall monitoring programs, maintenance plans as well as environmental and object data management impedes to draw a consistent picture of the environmental impacts. Processes resulting in temporal changes of conditions are difficult to determine. Just these processes could either improve the situation by natural attenuation or increase adverse effects by increasing the contaminant release in the long-term. Therefore, the preparation of the feasibility studies required the generation of a consistent data set describing the present structural conditions of the mining and milling objects on the one and the environmental impacts on the other side. The findings were mainly verified by published data from numerous former international projects dealing with individual aspects of the environmental impact.

As a rule, amongst the local population awareness to the hazards emerging from the former mining objects is nevertheless existent. However, the need for resources such as water especially for irrigation is driving the use of water of pure quality in the mining areas. Usually the former mining objects are marked by signposts or have been even fenced in the course of remediation projects.

3 Main findings

Uranium mining conducted on the territory of today's Central Asian countries Kyrgyzstan, Tajikistan and Uzbekistan left a tremendous legacy. The environmental impacts are considerable because the decommissioning of the activities did not include an appropriate remediation of the sites. Apart from slack or even inexistent environmental standards the morphological site conditions influenced not only the way how residues were disposed but also add to the various risks emanating from the uranium mining legacy. Usually a vast number of decentralised objects exist per site which are difficult to be managed in terms of a long-term maintenance. Concurrently a remediation of all these objects is difficult to achieve. With respect to financial restrictions or need for funding this requires an identification of priority measures based on a robust set of decision and well justified weighting criteria reflecting the general main hazards. This risk based ranking of necessary measures has to take into account the legal requirements in the respective countries but also the local conditions, habits and needs of the population. Robust solutions without the need for long-term care and maintenance and a minimum of institutional control requirements are necessary to be implemented.

Among others decommissioning of mines comprised the closure of mine openings and the removal of main structures while in more remote areas some of the mine openings remained open. At the shaft sites still ruins of the building structures remained and essentially no remediation of the working areas was conducted. Mine water outflows occur from a number of mine openings. There are no water collection and discharge structures so that a free access to the decant mine water is possible irrespective of the level of contamination. This water is mainly used for animal feeding and irrigation.

Awareness of the general public to the radiological and environmental impacts was raised by various projects in the past. Critical objects are mostly signposted or even fenced. Due to the lack of resources, however, a number of people utilise impacted waters or land plots.

4 Summarized conclusions

The need for additional effort to remediate the former uranium mining legacy sites was recognised by international institutions such as IAEA, EU or Rosatom combined with the willingness to provide the necessary funding. Due to the extent of the impacts necessary activities need prioritisation based on feasibility studies. These studies follow an overall site approach determining the most important measures with a maximum reduction of impacts at reasonable costs. Any planned remediation solution must be practical and robust to the long term. This implies that the main hazards will be addressed. While taking into account the economic strength of the Central Asian countries and the available level of institutional control individual long-term stable remediation measures have to be identified resulting in conditions which remain stable even in case of missing regular maintenance. Technical assistance to local experts and strengthening of the necessary knowledge to manage and conduct monitoring and maintenance activities over the horizon of the present projects is essential. Therefore, apart from stakeholder involvement knowledge transfer is understood as an integral part of the process preparation of the feasibility studies.

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The Wismut information management in context of legacy management tasks

A Hiller *Wismut GmbH, Germany*

E Kreyssig *Wismut GmbH, Germany*

Abstract

The Wismut environment project undergoes transformation from ongoing remediation activities to the stage of long-term tasks and legacy management. This transformation calls for a new information supply und knowledge management. The present electronic compound system AL.VIS/W has to be developed as a universal map-based information system about all terms of remediation objects. Existing documents have to be collected from scattered storage places, partly digitalized and implemented into the information network in a long-term valid form. These modifications will help to provide information even to people, who will be not familiar with the remediation objects and technology in the future. The improvements started quite late and will require major efforts for their realization.

Keywords: *electronic compound system, information management, record management, remediation documentation*

1 Introduction

An outstanding project of uranium mining was started right after World War II in East Germany. The Soviet-German Wismut Company recovered about 231,000 t of uranium from numerous deposits in Saxony und Thuringia within 45 years. Mining and milling operations were terminated for economic reasons in 1990, shortly after the re-unification of Germany. However, it caused serious impacts to nature, infrastructure and public health. The responsibility for the required remediation activities was given to the newly founded state-owned Wismut GmbH.

The Wismut remediation project started in 1991 and has continued for more than 27 years. Almost 2,000 singular objects, included in the working program, are already cleaned up successfully and completed. A large number of remediated parcels has been prepared for reuse and was sold to new owners. Nevertheless, a certain part of it has special characteristics regarding reuse restrictions caused by covered remaining contaminations in the underground. These objects have to be included into a long-term legacy-management, supported by preserving their property information.

2 Initial situation

During remediation operations, Wismut has designed the electronic compound information system AL.VIS/W to supply information for ongoing tasks of documentation and reporting. This complex information network supports daily operations, ranging from the collection of environmental data up to the generation of all kind of object records. The connected databases provide information about the remediation objects, all kind of monitoring data, parcels, permits, remediation areas, engineering reports and pictures. The system enables geographic, site-based, object-based and semantic access to data. The search is supported by several assistant tools. Consequently, AL.VIS/W represents a useful tool for the current work.

Concerning the included documents, there is a well sorted stock of permits and engineering reports. Beside them, numerous insufficient structured collections of remediation documents exist in several archives, in professional departments, and in the remediation units in paper-based form.

3 Challenge and decision

Remediation activities generate extremely dense information about the objects. Data are permanently collected during exploration of contaminations and by monitoring during and after remediation activities. These data are stored and used by Wismut experts and extern engineering contractors to compile documents (studies, projects, planning documents and other records). Further quantities of documents are created during permitting procedures and in the stage of aftercare. All the collected information is high valuable for the phase of long-term activities at the remediated sites and has to be preserved. A second aspect of knowledge aggregation is connected to the preservation of the know-how about the particular sites and objects, about their history and technology of remediation implemented.

The future task consists not only in preserving the gained data, information and knowledge. The main challenge is to transfer the existing information management into the time frame of long-term tasks. Future users will demand fast and reliable access to data, information, and documents of remediation without knowledge about object and remediation history. Consequently the map-based access has to be improved. Paper-based documents have to be collected and clustered into object related remediation documentations. These documentations are to be transferred into digital documents to include them into the existing information network.

Nowadays it is not sure if Wismut will keep the responsibility for the legacy management in the distant future. However, the Wismut management decided to develop the knowledge transfer to upcoming generations despite the expected costs and efforts.

4 Method and steps of implementation

Wismut started the process about 10 years ago. Conducted studies have lead to several recommendations how to preserve the existing knowledge for future tasks. But due to limited capacities, these recommendations could not be realized.

Subsequently, in 2012 a so called Document and Information Centre (DIC) was formed to improve the documentation work of the enterprise. It was established as a matrix structure, which means that all colleagues remain in their units and work for the general aim. The DIC activities were aimed to identify the goals of the intended development. The current situation in Wismut was analyzed in detail and carefully. Involved experts visited comparable projects in North America, searching for experience in this working field. The practical work of DIC proceeded in following directions:

- Identification of remediation objects with complex structure and long-term requirements,
- Development of the strategy for remediation documentation with a standardized structure according to a paper-based document collection,
- Preparation of a database-supported solution for a digital documentation, which can be included into the existing information network,
- Further development of the AL.VIS/W information network by extension of functionalities and integration of additional sources of information,
- Identification, conservation und utilization of the available paper-based documents,
- General intensification of all documentation activities by the involved units of the enterprise.

Regarding the remediation documentation, DIC defined a set of basic rules. Some 400 complex objects (particular with long-term character) were identified as a matter of remediation documents. A standardized folder structure was established representing the remediation process. The storage places for several kind of documents have been established. The compilation of short overview information (so called ‘vitas’) for every singular remediation object was launched.

Despite the great work of DIC within 5 years, the progress in development of the remediation documentation and the design of the digital documentation did not meet the time line expectations.

As a result, the Wismut management decided to reorganize the kind of organization structure. With the beginning of 2018 a self-reliant department of information management (DIM) was founded. The department merges specialists for data management, colleagues with experience in archiving and co-workers from all branches. The provided capacities ensured a more concentrated work already during the first months. Using the results of the previous work DIM started current activities in collection of paper-based documents and connected file information.

The general goals of the team are similar to these of DIC. The documentation process is to establish as a part of the information management due to the following scheme.

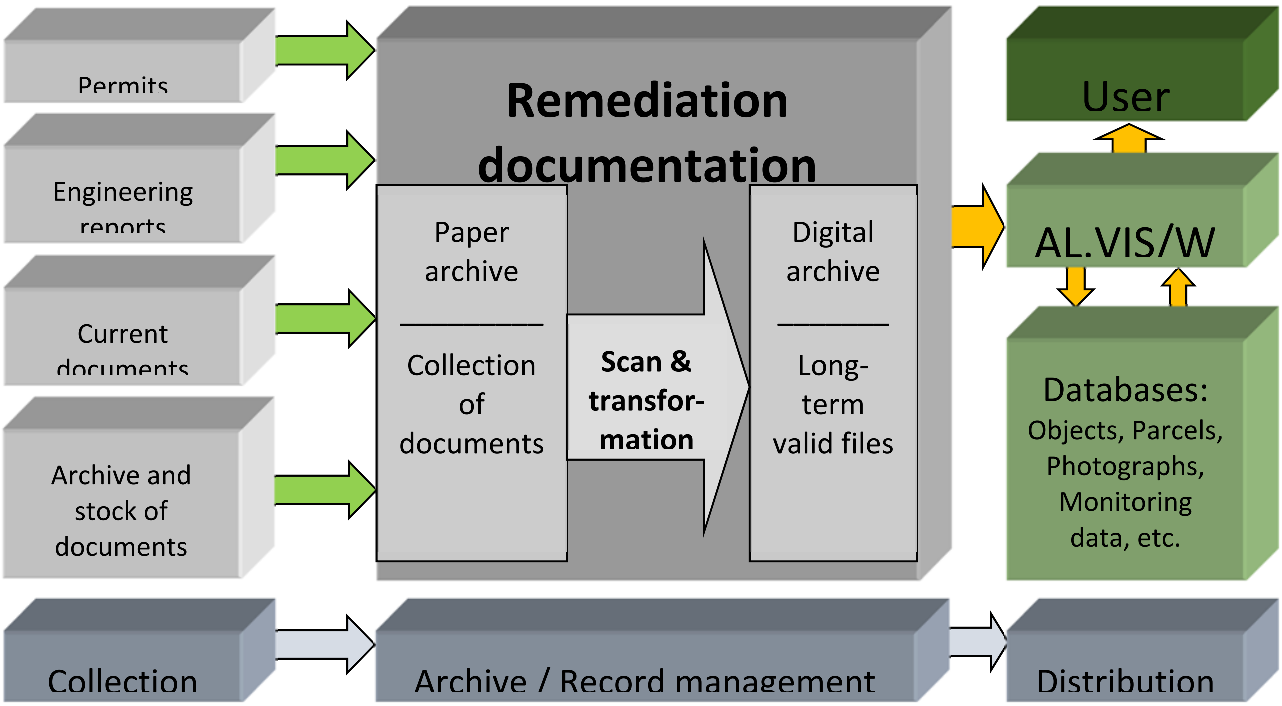

Figure 1 Integration of the remediation documentation into the Wismut system of information management

The current conceptual activities are focused on creating a digital archive:

- Identification of a storage technology for long-term valid digital records,
- Development of the workflow for creating digital records required for the digital version of the remediation documentation, especially for the digitization of paper-based documents,
- Adapting an already existing commercial document management system (DMS) to the specific conditions regarding the document structure,
- Refinement to the inquiry and edition operations to perform the data supply with regard to the existing branch distribution,
- Development of regulations including thesaurus, keyword lists, etc. for a consistent approach to documentation tasks at every branch.

The team of DIM has already achieved first results:

- The collection of all current records is completely organized. At the same time, digital files are saved in certain storage places.
- PDF/A format has been determined as the long-term valid format for the digital archive.

In a next step the workflow for the transformation technology from paper-based documents to digital files has to be completed. The routine operations for scanning and data transformation will start in autumn 2018. The time frame for the generation and digitalization of all remediation documentations is estimated up to 10 years.

5 Lessons learned

The existing experience with information management in Wismut leads to the following conclusions:

- Wismut started the activities quite late, may be too late.
- It’s not a trivial task to generate long term valid documents for a sustainable knowledge management. The workflow has to be designed s very carefully.
- The acting workers and the management should be aware of required cost, long time frame and personal capacities.

However, Wismut estimates the preserving of data, information, and knowledge as a necessary element of the remediation process. Consequently, the challenge of knowledge transfer has to be accepted.

The Wismut uranium tailings remediation project – Progress achieved with respect to diversifying legal requirements

U Barnekow *Wismut GmbH, Germany*

G Merkel Wismut GmbH, Germany

Abstract:

Uranium mining in the Eastern part of Germany lasted from 1945 until 1990. As a part of its mine closure program Wismut GmbH is decommissioning the large uranium mill tailings ponds Culmitzsch, Trünzig, Helmsdorf and Dänkritz 1 (total area 580 ha; vol.: 160 million m^3 of uranium tailings). Based on a federal act the state-owned Wismut GmbH was established in 1991 and made responsible for decommissioning and remediation of the uranium mining sites. Dry in-situ decommissioning is the preferred remediation option for all of Wismut's tailings ponds. This paper presents the follow-up of the main remediation steps including installation of a water collection and water treatment system, interim covering of tailings, dam reshaping, re-contouring of pond areas, final covering and vegetation, hydraulics constructions for diversion of runoff and connection to the receiving streams. Particular attention will be drawn to the challenges on nature conservation restrictions.

Keywords: *mine closure, remediation, decommissioning, tailings, tailings pond, cover, law*

1 Introduction

In Eastern Germany uranium mining lasted from 1945 until 1990 leaving enormous environmental impacts. The former Soviet-German Wismut company produced a total of about 216,000 t of uranium, mainly in two large mills located near Seelingstädt (Thuringia) and Crossen (Saxony). Nearby the former Seelingstädt mill, tailings dams were erected in mined-out open pits for separate disposal of uranium mill tailings from soda-alkaline and from acid leaching processing schemes. Nearby the Crossen mill only tailings from soda-alkaline leaching were discharged into tailings ponds erected in ancient gravel quarries and valleys. The tailings ponds Culmitzsch A and B, Trünzig A and B near Seelingstädt and the tailings ponds Helmsdorf and Dänkritz 1 near Crossen cover a total area of about 580 ha and contain more than 160 million m^3 of uranium mill tailings. Based on a federal act the state-owned Wismut GmbH was established in 1991 and made responsible for decommissioning and remediation of the uranium mining sites.

Dry in-situ decommissioning is the preferred remediation option for all of Wismut's tailings ponds. The field trip will familiarize the participants with the remediation approach, the main remediation steps and the progress achieved to date. This paper will present the follow-up of the main remediation steps including for example the installation of a water collection and water treatment system, interim covering of tailings beaches and of soft fine tailings, dam reshaping, re-contouring of pond areas, final covering and vegetation of the tailings sites, construction of access and maintenance roads and hydraulics constructions for diversion of runoff and connection to the receiving streams. Particular attention will be drawn to the challenges of remediation regarding the tailings stabilization, water treatment and management as well as nature conservation restrictions, which determined the project progess of the planned remediation of the Dänkritz 2 tailings pond and its created replacement waters for birds. To date completion of the tailings remediation project is planned to be completed by 2028.

2 Remediation aims

Remediation of the uranium mill tailings ponds has to meet the following most relevant remediation aims:

a. The radioactive dose to the population caused by the uranium mining sites and by decommissioning works is to be limited to not more than 1 mSv/year. This radioactive dose includes doses to people by inhalation and by ingestion of radioactive nuclides and by direct radiation;

b. Water released from the sites into the hydrographic net must comply with regulatory discharge standards for contaminants;

c. Remediation objectives have to be sustained in the long term. This means that sufficient stability and functionality of all relevant constructions, like i.e. soil covers or reshaped dams, shall be ensured for periods of 200 years up to 1,000 years with minimum maintenance and care required in the long term. For example geotechnical stability of large dams is to be proven with respect to the maximum credible earthquake. Nevertheless various environmental monitoring, inspections and maintenance works will be needed at all Wismut tailings sites in the long term.

3 Site characterization

Most of the uranium mill tailings ponds were established in worked-out open pits surrounded by either autostable tailings dams or by waste rock dams. Only the Helmsdorf tailings pond is located in a natural valley. Uranium ore was processed by soda-alkaline leaching or by acid leaching followed by neutralization before tailings disposal. The tailings slurry was usually discharged from the perimeter into the centre of the tailings ponds. Due to the historic discharge regimes, coarse-grained tailings settled out close to the discharge spots creating thick sandy tailings beaches. Fine-grained tailings travelled further and settled toward the pond centre below the water table where they formed up to several 10 m thick fine tailings layers. The transition zones in between the tailings beaches and the fine tailings zones consist of an interlayering of fine-grained and sandy tailings layers. The fine tailings can be characterized as very compressible fine-grained soils of medium or high plasticity. The water content of the fine tailings is typically above the liquid limit (acc. to Atterberg limits). The fine tailings are typically of a pulpy or weak consistency, their permeability is very low. The sandy tailings usually consist of silty fine sand with a certain portion being medium sand. When saturated, such soils may be prone to liquefaction due to dynamic loading by seismic events or by earthwork equipment. The tailings pond are hydraulically connected to the surrounding geological underground layers. Therefore contaminant seepage can enter the groundwater flow. Site specific water catchment and collection systems were erected. At each site the contaminated water is pumped to a treatment plant and treated before beind discharged into the receiving stream.

Figure 1 shows the tailings ponds Helmsdorf and Dänkritz 1 near Crossen (Saxony) in 2000 during an early stage of remediation. At the upper rim of this photo one can also see a part of the Dänkritz 2 tailings pond which is not included in the Wismut tailings remediation project.

Figure 2 shows the tailings ponds Trünzig in 1992 before remediation started. Figure 3 presents tailings pond Culmitzsch in 1993 before remediation.

Basic structural data of the tailings ponds and some descriptive radiological and chemical data of the tailings are listed in Table 1 and Table 2 below.

Figure 1 Tailings ponds Helmsdorf and Dänkritz 1 (background) in 2000 (WISMUT air photo L972/10)

Figure 2 Tailings Ponds Trünzig in 1992 (WISMUT air photo L113/55)

Figure 3 Tailings pond Culmitzsch in 1993 (WISMUT air photo: L 179/12)

Table 1 Basic technical data of uranium mill tailings ponds

Mill tailings pond	Tailing vol. (106 m^3)	Area (ha)	Max. tailings thickness (m)	Tailings pond type	Processing
Helmsdorf	45	200	50	valley type	soda-alkaline leaching + neutralization
Dänkritz 1	4.6	21	23	ring dam type	soda-alkaline leaching + neutralization
Culmitzsch A	61.3	158	72	filled open pit	acid leaching
Culmitzsch B	23.6	85	63	encl. by dams	soda-alkaline leaching + neutralization
Trünzig A	13	67	30	filled open pit	acid leaching
Trünzig B	6	50	23	encl. by dams	soda-alkaline leaching + neutralization
total	**153.5**	**582**			

4 Defence measures against acute risks

The required defence measures were designed at short notice and implemented without delay. Defence measures against acute risks involved the following activities:

- Installation of fences surrounding the sites to prevent human or animal access.
- Interim covering of all subaerially exposed (trafficable) sandy tailings beaches to reduce radon exhalation, direct radiation and radioactively contaminated dusting.
- Refurbishing or construction of new catchment systems to collect the entire seepage and runoff from the tailings ponds.
- Geotechnical investigation of dam stability with regard to short term dam stability.
- Construction of water treatment plants to treat the seepage and runoff as well as removed supernatant and pore water with regard to uranium, radium, and arsenic, if need be.
- Installation of monitoring systems on and around the sites to monitor the impacts of the tailings ponds on the surroundings before and during decommissioning activities.

5 Remediation Design and Progress achieved

By the mid 1990's Wismut identified the dry decommissioning in situ to be the preferred remediation option for all of its uranium mill tailings ponds. Dry remediation option is costly but the risks are significantly lower compared to wet remediation options. According to the principal follow-up of the major remedial work steps the dry decommissioning in situ is presented below.

5.1 Water catchment, treatment and discharge

The water catchment system includes gravel-filled drainage walls, pumping wells, drainage ditches, collection/retention ponds and the pumping system. Water catchment includes the removal of pond water, the collection of seepage water and runoff from the tailings pond, pumping of tailings pore water from wells located either in the tailings or downstream of the tailings pond. All collected water is treated with respect to the respective discharge limits before being discharged into the receiving streams. Currently the water is treated with regard to meeting discharge criteria for uranium, radium and, if needed also other metals. For example in the past, up to 72 m of thick tailings beaches of Culmitzsch tailings pond A and B were dewatered by pumping from deep wells located in the tailings beaches. Shallow and deep wick drains were and are currently stitched in fine tailings before and locally also after interim covering in order to speed up the fine tailings consolidation during ongoing interim covering and re-contouring of the compressible fine tailings areas. The expelled pore water is to be pumped to the water treatment plant and treated before being discharged to the respective receiving stream.

5.2 Interim covering

Interim covering of exposed sandy tailings beaches suppresses dusting and creates a trafficable surface for any further decommissioning works. Removal of the pond water allows subaerial tailings surfaces to dry out, thus consolidating the upper near surface tailings layers with a view to increasing their trafficability. After a while, geotextiles and geogrids are being placed. Then drain mats or a first thin permeable interim cover layer is placed on top of the geogrids to provide lateral drainage of tailings pore water which is squeezed from fine tailings layers in response to further surcharge loading. The upper interim cover layers may consist of waste dump material. Speed and progress of placing interim covers on fine tailings zones are a function of the time-dependent consolidation and dewatering of fine soft tailings whereby their shear strength is improving. The placement of the first interim cover layer on the fine tailings surface is of critical importance for the over-all decommissioning progress. To speed up the emergence of a trafficable tailings surface, vertical wick drains are stitched into the fine tailings down to a depth of approximately 5 – 6 m. In certain areas of the thick pulpy fine tailings layers, a first interim cover layer was subaqueously placed from floating barges. Initial cover layers of that type were placed on sections of the fine tailings zone of tailings ponds Culmitzsch A and Helmsdorf. Within the Wismut tailings remediation project the last interim covering was completed on Culmitzsch A tailings pond by 2017. Within the joint funding for abandoned uranium mining legacies Wismut is planning to place the same interim cover on the Dänkritz 2 tailings pond in the next years after having the planning approval in force.

5.3 Dam reshaping and re-contouring of pond areas

Tailings dams at all Wismut sites are reshaped with respect to long term seismic stability, taking the maximum credible earthquake into account. Reshaped tailings surfaces of autostable tailings dams were covered. The upper 0.5 m or 1.0 m respectively thick layer of reshaped surfaces of waste rock dams and of dam buttresses consists of waste rock ensuring a specific activity of Ra-226 < 0.2 Bq/g. Dam reshaping has been completed for all of Wsimut's tailings dams except the south/southeastern dam of Culmitzsch A tailings pond which is currently under reshaping. The tailings dams and rock-fill dams were either reshaped by dam buttressing and flattening of the upper dam slope inside the pond area or by only flattening the dam slope inside. Reshaping of the last dam, the south/southeastern dam of Culmitzsch tailings pond, will be completed by 2021. Here the fine tailings in front of the dam crest were stabilized by placement of a large embankment fill together with deep vertical wick drains in the fine tailings layer. This embankment which is currently removed again.

Re-contouring of the pond areas creates a new landscape and shall provide the functionality of the overlying final cover including a stable surface runoff from the pond areas in the long term. Design of this new landscape has to take into account time-dependent settlements and deformations of the underlying tailings during and after decommissioning phases. The newly constructed landscape should blend into the surrounding landscape. Based on the results of hydrological and hydraulic modelling of the precipitation runoff from the tailings pond and from the regional catchment area, a system ensuring safe diversion of runoff and consisting of ditches and, if needed, runoff retention ponds has been designed for all of Wismut's tailings ponds.

On certain areas of thick fine tailings layers embankments were placed in the past to speed up consolidation of fine tailings along the main ditches for diversion of runoff. For instance up to 27 m deep vertical wick drains were stitched into weak fine tailings on tailings pond Trünzig A. Consolidation was enhanced by placing an up to 11 m thick and 1100 m long embankment fill along the planned main runoff diversion ditch. The same technology with a 1600 m long embankment fill was applied for the Trünzig B tailings pond. Both embankment fills partly removed later and blend in the recontoured surface.

On a part of the thick fine tailings zone of tailings ponds Helmsdorf and Culmitzsch vertical wick drains were (Helmsdorf, Culmitzsch B) and are currently being stitched (Culmitzsch A) into the fine tailings down to a maximum depth of ca. 25 m below tailings surface in order to speed up the fine tailings consolidation during ongoing re-contouring works.

5.4 Final covering and vegetation

The final cover is the last important earthwork construction step of dry in-situ remediation. Among other functions it shall primarily prevent any direct human or animal contact with tailings in the long term, provide conditions for stable vegetation and allow storage and evapotranspiration of water from precipitation and shall control percolation through the final cover into the tailings. The functional requirements to be met by the final cover have been defined in the light of the findings gained from a site model of contaminant transport from the tailings ponds to the receiving streams. The site model implements the three dimensional internal structure of the tailings ponds and the results of numerical geochemical transport models and numerical hydraulic models applied. In addition, Wismut evaluated for many years the performance of different final cover types in a number of test fields including store-and-release cover, capillary barrier cover and different cover types including a sealing layer. The regional climate is characterized by a dry summer/autumn season and by a wet winter/spring season.

A 1.5 m thick store-and release cover has been constructed on Dänkritz 1 tailings pond and another one is currently being constructed on Helmsdorf tailings pond. Here final covering shall be completed by 2020.

The final cover design for the Trünzig tailings pond was completely permitted by 2006. The final cover design depended on the underlying tailings types. On sandy tailings beach zones, the final cover consists of a 2 m thick storage layer including a compacted bottom lift (0.5 m) above a compacted 1 m thick interim cover. Immediately before final cover placement, the upper layer of the interim cover was compacted, granting a hydraulic conductivity of $k_f \leq 5 \times 10^{9}$ m/s. In addition, the lowest 0.5 m thick layer of the final cover was compacted to at least 95% of Proctor density. The final cover material on the Trünzig tailings pond consists of waste rock dump material (mixed-grained soil) from the Lokhalde WRD located in the vicinity of the Culmitzsch tailings pond. On fine tailings zones, the functionality of the final cover shall be granted by a minimum 2.5 m thick layer consisting of mixed-grained waste rock dump material compacted to 95% of the Proctor density. The waste rock dump material of the Lokhalde WRD is characterised by an average specific activity of 250 – 300 Bq/kg Ra-226. Depending on the geological origin, certain volumes of the Lokhalde WRD can be characterised as clean soil, having a specific activity of Ra-226 ≤ 200 Bq/kg. Those mixed-grained soil materials have to be used to construct the uppermost 0.5 m layer on the fine tailings and the entire 2 m thick final cover on the tailings beaches.

Wismut received the planning approval for final covering of the entire Culmitzsch tailings pond in December 2012. The final cover design was prepared with respect to the results of the conceptual site modelling on contaminant transport from the sources (tailings) to the receiving streams. On the fine tailings zone the desing is equal to the design realized on the Trünzig tailings pond. On the tailings beaches the subsurface of the final cover was recontoured in a shallow valley and the hills were structured with a slope fall of at least v:h 1:15 to 1:10 and a slope length below 100 m. On the tailings beaches and transition zones, covering approximately 100 ha, the designed final cover consists of a 2.0 m storage layer above a 0.3 – 0.5 m drainage layer with a hydraulic conductivity of $k_f \geq 1 \times 10^{4}$ m/s. The reason for this design was the given suffosion stability of such a drainage material with respect to the overlying soil in the long term. Below the drainage layer, an 0.3 m thick sealing layer ($k_f \leq 1 \times 10^{9}$ m/s) made of clean clayey soil is placed underlain by 0.7 m thick sealing layer made of mixed-grained soil from waste rock dumps ($k_f \leq 5 \times 10^{9}$ m/s). After initial establishment of grass for erosion protection, grassland will be established and maintained in the long term.

Figures 4 to 6 demonstrate the current status of remediation progress at Wismut's uranium mill tailings ponds.

Figure 4 Aerial view of the remediated Trünzig TMF (May 2018)

Figure 5 Aerial view of Culmitzsch TMF (view from SE to NW), Oct. 2017

Figure 6 Aerial view of Helmsdorf/Dänkritz 1 TMF including replacement waters for avifauna (view from S to N, Oct. 2017)

5.5 Diversion of runoff to the receiving streams

For Helmsdorf and Dänkritz 1 tailings pond the diversion of runoff from the remediated surfaces was applied for all surfaces. To date only the last southern part of the site area has not yet been permitted. The respective planning approval procedure is currently ongoing.

The runoff from Trünzig A tailings pond is already connected to the receiving streams. The ditch for runoff diversion from pond B shall divert the runoff from Thuringia across the border to Saxony. In Saxony we have to erect a runoff retention pond that protects the downstream part of the valley in Thuringia. Unfortunately this required two separate planning approval procedures in the two different countries with interdependencies. Therefore is still going on for quite a long time. We expect to receive the final planning approval for erection of the new runoff retention pond in Saxony in autumn 2018. Then this runoff retention pond shall be constructed. After that we shall receive the final planning approval from the Thuringian upper water authority and the main ditch for runoff diversion from pond B can be constructed. To date these works are planned to be completed by 2020.

For the Culmitzsch tailings pond, the permitting authorities of Thuringia stipulated that the hydrological situation downstream in the receiving streams before remediation (1990) must be preserved for the future diversion of runoff with respect to flood water flow resulting from the 100-year precipitation event. The planned ditches shall divert the runoff into the Fuchsbach creek upstream of the Wolfersdorf village. Hydrological modelling was also carried out for the state before remediation (1990) and two states after remediation: an interim state with only grass vegetation on the remediated areas and a long-term state with grown-up trees established. The results show that the hydrological situation before remediation (1990) could not be preserved for the Fuchsbach creek without a runoff retention basin. Therefore, a runoff retention basin was planned for north of the Culmitzsch tailings pond. The location of the runoff retention basin was chosen to avoid the use of foreign land, to avoid contact with contaminated areas and to meet environmental criteria. This location also allowed costs to be reduced as much as possible. In June 2018 we received the planning approval for the diversion of the runoff from the Culmitzsch tailings pond to the receiving streams.

5.6 Site water management

Water management at all tailings ponds includes the collection and treatment of surface, ground and seepage waters at the tailings pond and in the surroundings. Various drainage systems and pumping wells were built to contain contaminated waters. However, in Seelingstädt there still is a small proportion of seepage water that still infiltrates the local receiving streams, influencing the chemical composition of the surface waters. Apart from the remediation objects managed under the Wismut remediation program, there are additional sources nearby upstream, which also influence the water quality of the receiving streams.

For the tailings ponds Culmitzsch and Trünzig nearby Seelingstädt standards for waste water discharge into the receiving streams were set by the regulatory authorities of Thuringia for metals, semi-metals and uranium. Limits for salt concentrations and water hardness are given for a sampling point in the receiving Culmitzsch creek and further downstream in major receiving stream the Weisse Elster river. At least temporarily, these limits restrict the discharge volume of treated waters and therefore curtail the water management operations at the Seelingstädt site.

To ensure that sufficient work progress is made, the water management at the site must do two things: (1) reduce the formation of contaminant water and (2) install a reasonable storage volume for the period up to the end of physical remediation works. Separately collecting uncontaminated surface waters from already remediated areas and directly discharging them into the receiving creeks implemented over the past years reduced the treatment volume significantly.

5.7 Landscape management and changing environmental requirements

Over more than 25 years of ongoing tailings remediation national legal requirements from environmental law, the law of protection of species, water law, legal requirements on environmental impact assessment, accompanying landscape management plans and others and European legislation and directives changed. Balancing the intervention measures with compensatory measures more detailed, different and stricter requirements developed. Often the antithetical requirements have to be met by the different laws or the respective permits. In particular requirements from radiation protection law and mining law (police law) may antithetical to nature conservation requirements.

I.e. the removal of the supernatant (toxic) pond water at Helmsdorf tailings pond was permitted without any request for replacement of such waters. The same applied for Trünzig tailings pond and Culmitzsch B tailings pond, but for Culmitzsch A tailings pond we were requested to replace the “lake” as existing in 2006. Based on a detailed ecological survey of the entire site, the landscape planning and vegetation of the Culmitzsch tailings pond and its surrounding dams and waste rock dumps was prepared with respect to balancing ecological intervention measures and compensatory measures with public interests. All ecological intervention measures are balanced by compensatory measures. Some of the needed compensatory measures including open grassland and lakes are to be realised about 15 km to the north, in the Ronneburg mining area. Supervision of the construction of all earthworks at the sites is accompanied by ecological construction monitoring, which prescribes in detail the preserving or compensatory measures to be taken during ongoing construction works. In 2011, we received planning approval for the landscape management plan for the entire site. It took several years to find appropriate sites for compensatory measures to fulfil the requirements fixed by the landscape management plan. In the meantime the landscape management plan has been further adapted to the permitted vegetation on the final cover. Requirements from the future planning approval for the connection of the runoff from the facility to the receiving streams may also have consequences for the landscape management plan.

The tailings remediation project for Dänkritz 2 tailings pond (Figure 7) is the most recent example for the ruling influence of the environmental law on the project progress and on the remediation design. In this regard, the changing requirements from the law of species protection required specific remediation measures. It is another object designated for remediation activities covered by supernatant water forming a “lake”. Over the last decades, a reed cover grown biotope and breeding habitat of strongly protected birds has evolved at that place (Figure 8). During the dry in-situ remediation of the Dänkritz 2 TMF this biotope shall be removed. As a precursory compensatory measure for the future tailings remediation, a replacement waters was constructed by 2012 on an area of 6 ha (Figure 8) in the west of the Helmsdorf tailings pond. The newly built replacement waters serves as passage and relaxation habitat for water-bound bird species occurring in that region. The project started in 2003. Currently we expect the planning approval for the entire project in this summer. Depending on the start of the works, the project implementation is currently foreseen to be completed by 2023 or 2024.

Figure 7 Dänkritz 2 tailings pond to be remediated: Biotope and breeding habitat of strongly protected birds

Figure 8 Replacement waters for avifauna located in the former western borrow area next to Helmsdorf tailings pond (Sept./Oct. 2017)

Organization and Legal Framework for the Remediation of Abandoned Lignite Mining Sites in East Germany

D Sonnen *Lausitzer und Mitteldeutsche Bergbauverwaltungsgesellschaft mbH (LMBV), Germany*

Abstract

After the German reunification the mining industry in former East Germany was profoundly restructured. Beside privatization of profitable parts of the former state owned combines the public sector took over responsibility for the mining operations to be shut down. Therefore LMBV cope with technical, ecological, and structural challenges. The rehabilitation and reclamation has to rededicate former mining areas to new use.

In the lignite mining districts there are around 100,000 ha of former mining area, a mining caused disturbance to the groundwater balance and to the system of surface water bodies of approx. 390,000 ha. The Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft (LMBV) is tasked with the responsibility to find and implement the solutions for the corresponding challenges.

The remediation of the former mining sites is technically and ecologically challenging owing to the scale of activities, the requirement to eliminate intensive disturbances of the environment, the rehabilitation of industrially contaminated sites and the concluding rededication to new use under condition of public safety. The results achieved over the past 28 years were made possible by a joint effort of the Federal Government and the German länder Brandenburg, Sachsen, Sachsen-Anhalt und Thüringen. The organization and the legal framework for these tasks will be presented, including financing, accompanied by examples of successful remediation.

Challenges and the Achieved Status in the Closure of Potash Mines in Eastern Germany

M Kuyumcu *TU Bergakademie Freiberg, Germany*

FC Benthaus *LMBV mbH, Germany*

T Pietsch *LMBV mbH, Germany*

ABSTRACT

With annual production of almost 3.5 million metric ton of K_2O, former East Germany (GDR) was the third-largest producer of potassium, ranking behind only the Soviet Union and Canada. More than 80 % of production was intended for export, to obtain urgently required hard currency. For this reason, beginning in the 1970s, East Germany also began mining of otherwise unprofitable hard-salt deposits and geomechanically problematic carnallitite fields. During increasing concentration of available mining resources on maximizing production, moreover, the backfilling of mined-out cavities, necessary over the long run, was more and more neglected. An additional development was the tendentially smaller dimensioning of the pillars used for supports in the mined fields, as well increasingly long spans between supports in the mined-out cavities. The purpose here was to further reduce the specific expense of mining. All these developments led to a critical increase in geomechanical risks in the underground workings. During restructuring from a centrally planned to a market economy, only two of the nine potash mines were classified after German reunification as economically viable and were privatized. All six potash mines in the South Harz Mining Region were closed between 1991 and 1993.

A geomechanical assessment of the potash mines in the South Harz Region, conducted as early as 1992, came to the result that several mining-field sections in mines at Sondershausen, Bleicherode, Sollstedt, and Bischofferode required securing measures in the form of backfilling of mining cavities. The purpose of these measures was to prevent danger to public objects on the ground such as communities, roads and streets, railway lines, and rivers. The current and predicted settlement at the surfaces above the mines reached a rate of up to 250 mm/a, and the increasingly strong and more frequent seismic results with Richter magnitudes up to 3 necessitated immediate action. Elaboration in the present study covers the locally specific necessity, as well as the type and extent of back-filling and securing measures. Because of the immediately and intensively conducted remedial measures taken, it was possible to prevent rock bursts and damage to public surface facilities. This documentation describes the safeguarding successes achieved to date, with appreciable reduction and stabilization of surface settlement and with reduction in the intensity of mining-induced seismic results. Also presented are concepts updated to the state of the engineering art for securing a large number of potash mining shafts for long-term effectiveness in separation of the workings from the watercourse levels in the cap rock.

During 100 years of potash mining in the South Harz Region, six mining dumps were operated, with a total volume of approximately 200 million m^3. They consisted of up to 95 % of water-soluble salts. Every year, precipitation dissolved up to 750,000 tons of these salts, which enter as highly concentrated solution into watercourses and ground water. Explanation follows of measures implemented for minimization of this environmental pollution by covering dumps and by controlled drainage of salt solutions from the dumps, also designated as dump leach. To the extent possible, the controlled leach solutions are used in production of self-binding backfill (hydraulic stowing) as well as in flooding of potash mines. Finally, presentation is made of the results of the successful work until now for new use of decommissioned mining sites by settlement of new businesses and industries for creation of additional jobs and for revitalization of the previously monostructured South Harz Potash Mining Region.

Keywords: *Eastern Germany, Mine decommissioning, Potash, Rock-mechanics, Modeling, Backfilling, Carnallitite, Rock salt, Mine-induced seismicity*

1 Introduction

Closure of mining operations, especially underground mines, is normally a long-term, forward-planning and execution process. This was not the case, however, after reunification of Germany, where between 1990 and 1994, a state-controlled economy was transformed with a speed previously unknown in world history, into a free-market economy. The mining industry was also subjected to this transformation process. In review of the initial situation in 1990 (Fig. 1), we shall initially treat the lignite industry, which covered 70 % of the primary-energy requirements of former East Germany. This extensive lignite mining occupied an area of approx. 140,000 hectares. Market-demand and operational cost-efficiency investigations after German reunification led to the findings that only eight of a total of 40 large open-cast lignite mines could profitably continue operations. These eight mines were privatized. The remaining mines, over an area of 100,000 hectares, were shut down – in some cases from one day to the next – and efforts to secure and revegetate this area followed. The pattern was similar in the potash and salt mines: only two potash mines and one salt mine were allowed to continue production and were privatized. The remaining six mines were closed. It was also necessary to close all twelve operational metal- and spar-ore mines, which had been unprofitable for decades. These included mines for tin, copper shales, fluorspar, barytes, and pyrites. Likewise, all operations producing uranium ore – all of which was required to be exported to the Soviet Union until 1990 – were also closed.

Figure 1 Mining regions in the German accession states in 1990

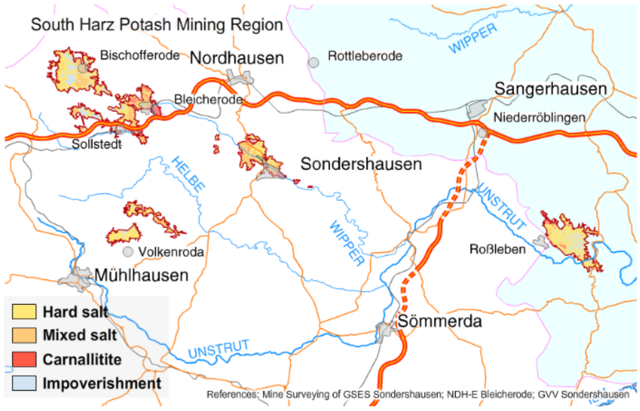

Figure 2 Closed mines of the South Harz Potash Mining Region, with salt facies

As a result, it became necessary: swift but orderly mine closure, assurance of public safety on mining sites and their rehabilitation, and the use of restored sites for economic revitalization of previously monostructured mining regions. These tasks were assigned to government-owned companies especially formed for this purpose:

- Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH (LMBV) for rehabilitation of lignite regions
- Gesellschaft zur Verwahrung und Verwertung von stillgelegten Bergwerksbetrieben (GVV), with headquarters in Sondershausen, Thuringia, for rehabilitation of potash, metal-ore, and spar-ore mining facilities (with merger since September of 2014 with LMBV)
- Wismut, for uranium-mining rehabilitation

The sheer number of mining operations destined for closure, most of which would have otherwise continued production for decades to come – as well as the great range of the engineering and ecological challenges to be mastered in the closure, securing, and rehabilitation of the mines and of the areas occupied by mining operations – represented an historically unique and extraordinarily demanding technical and ecological mission. In the course of meeting these challenges, the companies involved conducted application-oriented research projects to fill gaps in knowledge and insights, with the resulting gain in a great number and diversity of findings.

2 The point of departure in the south Harz potash mining region

Figure 2 shows the South Harz Potash Mining Region, whose six potash mines in Rossleben, Sonderhausen, Bleicherode, Sollstedt, Bischofferode, and Volkenroda were closed. During a period of about 100 years of potash mining there, approx. 559 million tons of crude salt had been extracted. The mines occupied a total underground area of 15,600 ha. After strata convergence and backfilling, the volume of mining excavations remaining open amounted to around 130 million m^3. The potash seams, extending to a depth of 400 to 1,000 m, were as a rule worked using room-and-pillar techniques. The rooms were mined 10 m wide and 6 m high. To ensure structural stability of the workings, pillars 10 to 20 m wide between the rooms were left unmined. The excavated yield lost by allowing these pillars to remain therefore depended on the dimensions of the pillars.

From the onset, potassium export was a significant source of foreign exchange for former East Germany. This importance resulted in continuous expansion of underground potassium mining. Production of fertilizer was 1.2 million tons of K_2O in 1950, which had doubled by 1970 and tripled by 1985. Over the same period, the export share rose from 60 to 83 %.

In the course of increasing concentration of available East German resources on production, beginning in the 1970s, the backfill of geomechanically critical mined-out cavities by hydraulic stowing was increasingly neglected – and was eventually discontinued in all mines except one (1). At the same time, it became necessary to extract lower-grade sections of potash seams to achieve output objectives. The selective extraction of pure hard salt (Figure 2) from sufficiently thick deposits was no longer sufficient. Beginning in the early 1970s, consequently, it became necessary in former East Germany to mine so-called mixed salt: i.e., a mixture of hard salt from thin seams, and of geomechanically critical carnallitite (Figure 2) – and beginning in the 1980s, even the mining of pure carnallitite fields was resorted to. The extraction of mixed salt and carnallitite led to significant economic disadvantages owing to the resulting reduction of K_2O content – already low enough in international comparison – in the crude salt extracted: from approximately 17 % to 11 %, as shown in Figure 3 for mining at Bleicherode (2).

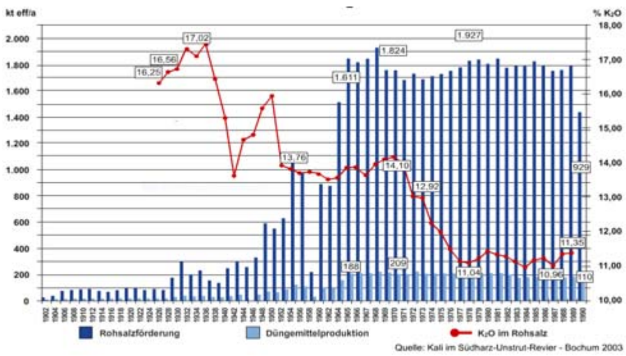

Figure 3 Crude salt mined at Bleicherode, with K_2O content

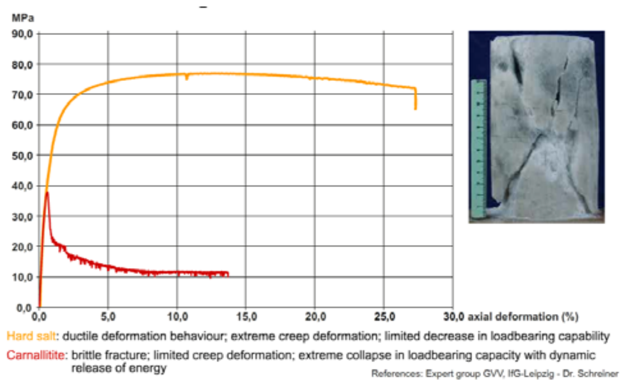

Figure 4 Stress-strain diagram for hard salt and carnallitite

The mining of carnallitite over such an extensive area resulted in predictable geomechanical problems. As shown in Figure 4, hard salt in a tri-axial compression test exhibits ductile (i.e., plastic) deformation and gradually fails due to creep, with a moderate drop in loadbearing capability. Carnallitite, on the other hand, tends to sudden brittle fracture, without creep-induced deformation, and with sudden reduction in loadbearing capability (3). This sudden collapse of the rock structure results in a dynamic release of energy.

Finally of mention: beginning in the 1980s, it became necessary to modify the dimensions of the pillars and the widths of the extraction rooms to the very limits of feasibility, to further reduce extraction losses.

2.1 Geomechanical assessment of the potash mines in South Harz, and development of the concept for safeguarding measures

Enormous surface subsidence and severe seismic events induced by mining, particularly in the urban area of Sondershausen, motivated GVV in 1992 to quickly establish an interdisciplinary team of experts from the fields of geotechnics, geophysics, and hydrology. Together with experts from GVV, this team was assigned to subject the potash mines in South Harz to a comprehensive geotechnical assessment, and to prepare the securing measures required over the short to medium term. On the basis of initial assessment results of the experts, the measures summarized in the following were decided:

It was necessary to secure the mines at Sondershausen, Bleicherode, Sollstedt, and Bischofferode with extensive backfill of the mining cavities associated with critical geomechanical danger. For a number of these workings, recommendation was made for immediate initiation of backfill measures, or intensification of such efforts that had already begun. For the mines at Rossleben and Volkenroda, the investigations disclosed no safety risks with special need for security measures. It was accordingly possible to limit the securing of these mines to assurance of compliance with the regular catalogue of measures for orderly decommissioning of such workings, to include long-term securing of the shafts in accordance with the current status of scientific and technical knowledge. The development of concepts for securing potash mines, and generally for salt mines, involves the following two focal points:

Securing mine workings: It is an essential and basic requirement – both during the operational phase and, most especially, during the post-operational phase – to prevent any and all entry of water or aqueous solutions into the workings. In cases in which it is possible, and after assurance of geotechnical safety on a long-term basis, the workings can also be filled with air: i.e., they can be secured on a so-called dry basis. In cases in which this is not possible, for example, in the presence of lower inflow that cannot be sealed off, the workings must be flooded with a suitable flooding medium. This solution is called hydraulic stowing. Securing of the surface shafts:

- Principally, the surface shafts must, by permanent means, be sealed watertight from the workings and the groundwater horizons.

For the individual workings, the following securing concepts were developed on the basis of the above-stated investigations:

- Sondershausen, Bleicherode, and Sollstedt: Securing by air-filling, with backfill of extensive geomechanically critical cavities
- Bischofferode: Hydraulic stowing owing to continuous ingress from lower inflow (fossil water from the time during which the deposits were created), but only after securing the workings by backfilling the geomechanically critical cavities. Owing to the circumstances dictated by the presence of various salt facies in the individual extraction rooms, flooding of these workings takes place with leach solutions, some containing $MgCl_2$ and some containing NaCl. Owing to the relatively steep and consistent slope of the workings toward the south, it is furthermore possible to flood the mine only partially, up to a certain level.
- Rossleben: Dry securing of closed mines by filling with air. Studies determined that the mine was not suitable for creation of a waste deposal facility. Within the context of the residual deposits of potash still remaining in the mine, and the possibility of their possible future extraction, the decision was reached not to put the leach solution, containing NaCl – which in any case was small in amount – resulting from the mining waste into the mine.
- Volkenroda - Pöthen: Hydraulic securing by flooding with leach solution from the Volkenroda mining waste dump. This mine was basically suited for dry securing by filling with air. Owing to the occurrence of large quantities of NaCl leach from the Menteroda mining dump, economic and

ecologic considerations prompted the use of mining cavities for disposal of dump leach, which would otherwise be routed for disposal into surface water. Since carnallitite facies had been hardly cut into in the Volkenroda mine, no geochemical or safety factors spoke against disposal of the dump leach there.

The following descriptions present selected examples from the many securing measures used to assure long-term structural stability of the exhausted underground mining cavities, for protection of communities, infrastructure, and facilities at the surface above:

2.2 Sondershausen East Field I mining area

Fig. 5 shows the town area of Sondershausen (shown in grey), the River Wipper, National Highways 4 and 249, as well as the carnallitite mining areas (shown in red), directly under built-up areas, including residential dwellings. In 1990 surface subsidence of 240 mm/y was registered, with forecast for a total subsidence of up to 3 m in the already damaged town area, as well as for inclination of building structures of up to 7 mm/m. Especially critical were frequent occurrences of seismic events, with magnitudes up to 2.5 on the Richter scale.

Figure 5 Sondershausen East Field I mining area, with overlying town area of Sondershausen (grey)

Figure 6 Massive floor strata uplift

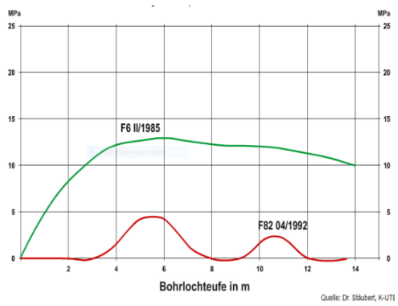

Figure 7 Plot of static fracking pressure

Because of the long periods since cessation of mining – up to eight years – massive floor strata, uplift movements in the mine underground increased from month to month (Fig. 6, (3)). Hydraulic fracking disclosed that certain individual pillars had completely lost their loadbearing capacity (Fig. 7, (3)). Collapse of the pillars, and of even completely mined areas, were altogether possible – resulting in mining-induced seismic events with magnitudes ≥ 3 and with serious surface damage affecting the community above. It was therefore decided to immediately and completely backfill the entire underground mined area. For the fill material in the critical mining cavities in the East Field, it was decided to use rock salt, a non-critical material from the rock-mechanics standpoint. It was possible there to extract the backfill from rock salt seams in the mining envelope by conventional drill and shoot methods, with loading and transport on non-rail vehicles or by conveyor belts. After crushing to size and dampening, it was transported to the old exhausted mine workings and tipped in layers. In the South Harz Mining Region, backfill material prepared in this way is called “backfill-mine rock salt”. A packing rammer was used on the uppermost backfill layer to achieve maximum degree of backfill: i.e., to ensure that the critical mined-out cavities were completely backfilled. This method ensured a high degree of traction grip between the backfill and the surrounding ground. This technique is also called in short “onsite backfill”, to differentiate it from material taken from outside the site (“offsite backfill”). Backfilling was conducted with great urgency: within five years, a total of 2.2 million metric tons of backfill was placed. The effectiveness of the backfill process was monitored by a complex geotechnical measurement system. Findings obtained from these measurements revealed that the actual results exceeded the expert-opinion specifications for backfilling of the exhausted mining cavities: degree of backfilling was 95 % (stipulated: 85 %) and the compressive strength of the backfill was 100 MN/m² (stipulated: 40 MN/m²). After only six years, the surface subsidence diminished rapidly: from originally 240 mm per year to less than 50 mm/a (Fig. 8).

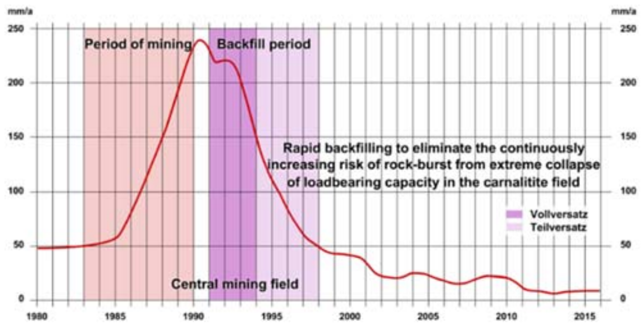

Figure 8 Subsidence rate at the ground surface over the Sondershausen East Field I mining area

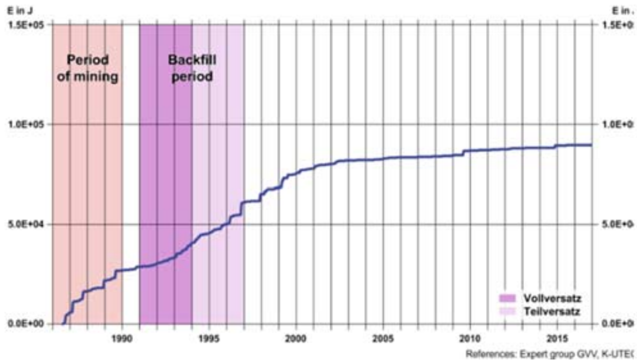

Figure 9 Cumulative energy release in the Sondershausen East Field I mining area, from 1986 to May 2012

The decline in severe seismic events was especially important. The initially very steep plot of the cumulative stress-release curve in the Beinioff diagram (Fig. 9) flattens out appreciably over time. This is because the loadbearing support provided by the backfill placed into the critical mine cavities caused a reduction in not only the number but also in the severity of the registered seismic events. Retroactive calculation performed on such geotechnical measured values enabled confirmation that the promptly executed backfilling successfully eliminated the danger of rock-burst with a magnitude of greater than 4, as well as any resulting, appreciable damage to the urban area of Sondershausen. The Director of the Team of Official Experts expressed his relief about the narrowly averted damage by making the statement, “We cheated the devil just by the skin of our teeth.”

2.3 Sollstedt mining area, Southeast Field

Although the mining of hard salt in the Southeast Field of the Sollstedt mining area did not create a critical geomechanical situation, the seams had been worked in several layers. Consequently, seams were able to be worked in two and even three stage levels (Fig. 10). In the course of years, the horizontal layers separating the vertical working levels had fractured (Fig. 11). The surface of the ground above the mine here had already begun to subside, and prediction was for an additional approx. 4 meters. Endangered objects, resources, built-up areas, and infrastructure included parts of the city of Sollstedt, public roads and streets, a railway line, and the River Wipper. Moreover, planning was to construct Motorway A38 above the mining area. It was accordingly necessary to employ backfilling for the relevant exhausted mining cavities to prevent the predicted consequences. Onsite backfill was also employed here. Prompt execution of the necessary measures arrested subsidence of the ground above the mines at a low level, and maintained it to an acceptable degree.

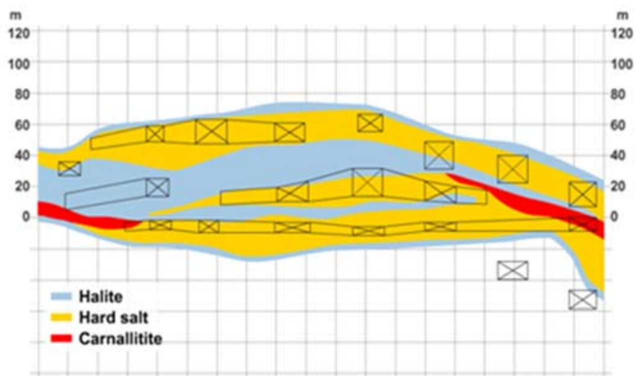

Figure 10 Schematic section through the SE-Field of the Sollstedt mine.

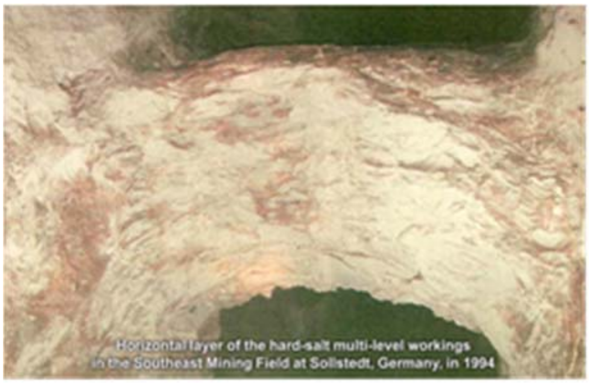

Figure 11 Horizontal layer of the hard-salt multi-level workings, SE-Mining Field at Sollstedt, 1994

In the course of extensively employed geotechnical monitoring for the closed potash mines in the South Harz Mining Region, and with practically oriented scientific procedures, it proved additionally successful to determine rock-mechanical parameters such as elasticity, creep, consolidation and deconsolidation, as well as dynamics of fracture. These efforts also resulted in appreciable enhancement of the integration of these parameters into engineering models for simulation of dynamic fracture processes and rock bursts. This achieved progress consequently enabled defensible decisions reached on the content and extent of the measures required to secure the closed mines. Concurrently, a complex geotechnical monitoring system was installed to detect changing conditions in the mine workings and in the surrounding strata, to assess the effectiveness of the executed restoration works, and for forecasts of their future development. A milestone in this context is the post-doctoral thesis by Dr. Wolfgang Minkley of the TU Bergakademie in Freiberg, Germany.

In 2000 a seismic event with a magnitude of 2.5 took place in the Northeast Field of the Sollstedt mining complex. This event required a closer examination of this old mining field, which had no longer been accessible in 2000 and which required new mining drives for the required measures. This investigation revealed a considerable number of so-called hourglass pillars (Fig. 12). After complex geomechanical assessment, a calculation model of the Northeast Field was prepared, which revealed (Fig. 13) that rock burst could not be ruled out in the workings. After several decades had passed following closure of this mine, a roof collapse in hard salt had spread to the overlying carnallitite. If a brittle fracture had taken place in the carnallitite, this would have triggered a chain reaction with collapse of workings and with immediate subsidence of up to several decimetres of land surface over the mine. Backfilling of the critical mined cavities prevented these dangerous occurrences.

Figure 12 Hourglass pillar, Sollstedt mine, Northeast Field

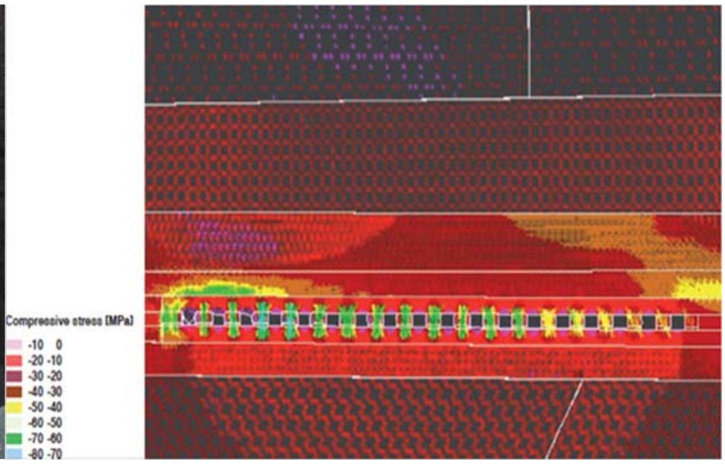

Figure 13 Plot from the calculation model for the Sollstedt mine, Northeast Field

2.4 The Bischofferode mine: securing the workings with onsite backfill and flooding

The standing salt solutions arising from the surrounding strata meant that the Bischofferode mine could not be dry-secured by filling with air: a situation that required at least partial flooding. It was concurrently necessary to assure that the neighbouring Bleicherode mine – which bordered on the shared mine boundary safety pillar – remained dry. This was required for two reasons: first, the Bleicherode mine featured large-area carnallitite exposure. It would have been possible to flood this mine with high-concentration $MgCl_2$ leach solution, but this solution would not have been unproblematic from aspects involving the kinematics of the solutions and rock mechanics. Second, the Bleicherode and Sollstedt workings were interconnected, with the consequence that flooding of Sollstedt would also have been necessary. To assure long-term securing at the workings at the Bleicherode and Sollstedt mines, it was necessary to guarantee that the hydraulic barrier effect of the mine boundary safety pillar between these two mines functioned flawlessly at all times (Fig. 13). At the end of the 1970s and during the early 1980s, however, this barrier, which had been originally sufficiently dimensioned at a width of 50 m, had diminished to half of this width owing to its high

K_2O content (Fig. 14). To restore the necessary hydraulic barrier effect, backfilling took place to the maximum possible degree, directly at the boundary safety pillar, of those mined-out cavities that had been identified by the team of experts (Fig. 14, see purple zone). For this purpose, approx. 0.8 million tons of rock salt were used: as onsite backfill. As final step, in addition, the backfill sector situated in front of the safety pillar was sealed off. One further focal-point measure is also noteworthy for the work conducted before flooding to stabilize the Bischofferode mining area. In the north and northeast fields of this area, one difficulty was that the workings had been conducted extremely close to the main anhydrite seam, which had restricted water flow and from which slightly mineralized water had penetrated the seam (Fig. 15). Due to prompt backfill of the sufficiently dimensioned infill fields, it was possible to prevent spreading of the weak zones and thereby to avoid potential uncontrollable flooding of the mine.

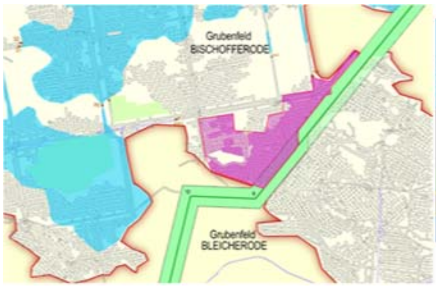

Figure 14 Backfill at the boundary safety pillar between the Bischofferode and Bleicherode mines

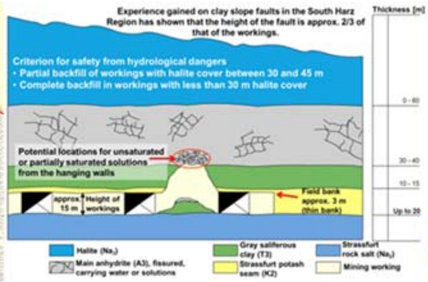

Figure 15 Hydrological danger due to solution streaming to the hanging wall

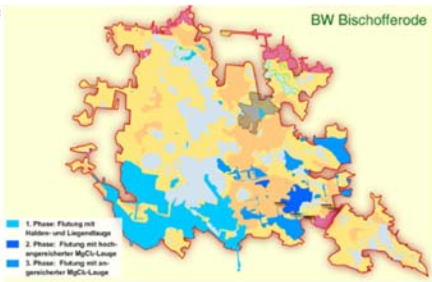

Figure 16 Focal points of measures to secure mines at Bischofferode

For hydraulic stowing performed at the Bischofferode mine, it was important to consider that it was necessary for those parts of a mining field with exposed carnallitite to be flooded with MgCl2 leach solutions and the other sections of the field (as a rule, hard salt sections), flooded with NaCl solutions. Moreover, the general slope to the south of approx. 4 ° of the potash deposits and, consequently, of the workings, was essential to determine the chronological sequence of the flooding of individual sections of the field. On this basis, and on the basis of a series of mine-specific general conditions, design was developed of a program known as “Guided Flooding for Bischofferode”. The flooding process for Bischofferode – with its highly sophisticated and demanding technical aspects, particularly involving the kinematics of the solutions – can roughly be classified in three phases and spatial areas (Fig. 16): flooding of the west and southwest fields by underlying inflow containing NaCl and by flooding with the leach solution obtained from the Bischofferode potash waste dump, also containing NaCl; flooding with highly concentrated MgCl2 leach of the main basin in the southeast field, which borders the backfill field of the mine boundary safety pillar; and flooding of the remaining areas in the east field with enriched MgCl2 leach solution. The flooding process is being supported and controlled by an extensive monitoring network.

3 Privatization of backfill mines

As part of rapidly and simultaneously securing several mining sections by backfilling, and at the same time exploiting the possibility of using officially approved industrial waste as backfill, GVV privatized some of its mines. With transfer of the Mining Operational Planning Procedure, legally binding under German mining law, and in close coordination with the German Federal State of Thuringia and its State Mining Office, the Sondershausen mine was sold to GSES in 1995; the Bleicherode mine, to NDH-E in 1996; and the Sollstedt mine, also to NDH-E, in 2008. These two companies have invested several hundred million euros to execute the underground backfill project, rapidly and according to high technical standards. Also worthy of mention is a special development in the process of hydraulic stowing, whereby officially permitted industrial waste, in accordance with safety law, is prepared and converted into backfill material by means of a patented technique. Within several days after installation, this backfill hardens in the mining cavities (4). The complete backfilling of the mined cavities thereby results in rapid and strong bonding between the fill material and the surrounding strata. So-called big-bag stowing has also been applied: suitable fill material is prepared in surface treatment plants and placed into strong plastic bags of up to 1.2 m^3 capacity that are stacked in the underground cavities. In these three potash mines, a total of 8.5 million tons of rock salt and more than 8 million tons of nonmined construction materials have been backfilled to stabilize the South Harz potash mines. In addition, the Bischofferode and Volkenroda mines have been flooded with a total of 6 million m^3 of NaCl and 2 million m^3 of $MgCl_2$ leach solutions.

4 Long-term stabilization of surface shafts

In the course of around 100 years of potash mining in the South Harz Potash Region, over 40 large surface shafts were sunk, 30 of which were connected to the six closed potash mines, and 19 of which have by now been secured by GVV. In collaboration with its engineering experts, GVV has continued development of its security concept for surface shafts in salt and potash mines (5) and has consequently raised its concept to a new level of sophistication (Fig. 17). This concept basically provides total backfilling of the shaft column, in the form of a layered fill column. From hydrological aspects, the fill column contains in every case a sealing element to separate the groundwater storey from the lower capping strata, as well as an additional seal in the top section of the salt-bearing strata horizon as protection of this horizon. Finally, an optional third sealing element is installed between the worked-out mine cavities and the filling column to account for rising leach water or effluent potentially containing pollutants from former mine workings.

5 Covering and vegetation of potash dumps

More than 85 % of the crude salt extracted from this mining region was not economically exploitable and was therefore stockpiled as industrial waste in dumps on the surface – insofar as it was not used for hydraulic stowing in underground workings. These dumps consisted of 95 % soluble salts and covered an area of 350 ha, with a volume of 170 million m^3, in six potash dumps in the South Harz Mining Region. As a result of the action of precipitation over the years, some 500,000 tons of salt have entered the groundwater and watercourses. Effective measures were necessary to counter the resulting negative effects on the environment.

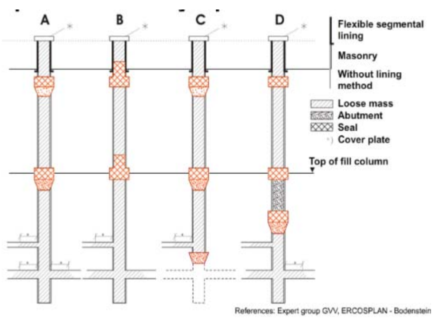

Figure 17 Concepts for shaft stabilization in potash mines

Figure 18 The Bleicherode potash dump in 1995

Figure 19 The Bleicherode potash dump in 2007

The initial remedial task was to construct leach water catchment channels to minimize entry of leach run-off into the ground water. At the same time, it was necessary to cover and vegetate the dumps, to reduce – to as great a degree as possible – dissolution of the salt from precipitation. Immediately after German reunification, various research projects to investigate the most suitable variety of grasses and plants commenced at German universities in Clausthal-Zellerfeld, Freiberg, Göttingen, and Kassel, as well as at the German Environmental Foundation, K-UTEC, and GVV mbH. These studies examined the basic conditions involved in the planting of various grasses and other plants. Project development involving the basic principles of soil and recultivation measures in the context of extremely aggressive, salty soil conditions was likewise initiated. The photographs in Figs. 18 and 19 depict the distinct transformation at the Bleicherode potash dump from 1995 to 2007. By today, more than 40 % of the surface of the South Harz dumps – except for the Bischofferode dump – have been covered and vegetated with a total of 27 million tons of material.

As Fig. 20 makes clear, this development has until now reduced the salt burden in the River Wipper by half: a notable success for scientific and operational measures taken to reduce environmental damage.

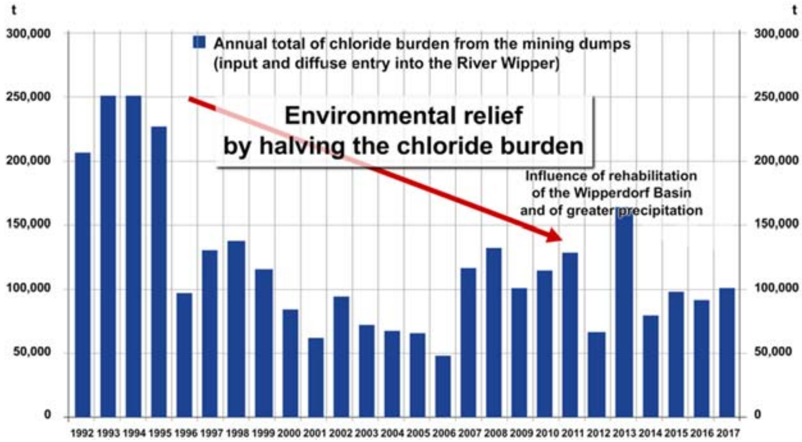

Figure 20 Reduction of chloride burden at Hachelbich (on the River Wipper)

6 New infrastructure in decommissioned mining areas

The total closure of potash mines in the South Harz meant loss of employment for around 12,000 miners: a dramatic development for this mono-structured mining region. GVV therefore established a goal of rehabilitation as quickly as possible of the surface areas of the mines to provide areas for new development and job creation (6). The demolition and removal of redundant plant facilities was rapidly executed and, in collaboration with the local communities, plans for new infrastructure were developed and implemented. As a result, GVV has succeeded in settling around 200 new companies on the former locations of potash mines: businesses that have invested until now 225 million euros and created employment for over 3,600 men and women.

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In-lake Neutralization of Lignite Mining End Lakes

FC Benthaus *Lausitzer und Mitteldeutsche Bergbauverwaltungsgesellschaft mbH (LMBV), Germany*,

O Totsche *Lausitzer und Mitteldeutsche Bergbauverwaltungsgesellschaft mbH (LMBV), Germany*

Abstract

Groundwater inflow into the lignite mining end lakes in East Germany is rich in iron and sulphates. Due to this fact, the majority of the pit lakes and their run-off waters do not meet the national water quality requirements. Hence, water treatment is required for the lake water bodies. In-lake neutralization of the entire water body is the preferred option with regard to cost efficiency, water quality, and ecological effects. Over the last 15 years, LMBV has developed, tested and enhanced different in-lake neutralization techniques. Due to these efforts, the achieved state of technology will be presented. In East Germany, 17 acidic mine lakes have already been neutralized and need regular follow up treatments to stabilize the neutral conditions. At least five more lakes are to be neutralized in the next few years. This makes LMBV the most experienced organization in-lake technology for mine lakes worldwide.

Keywords: *Lignite mining, contamination by sulphide minerals, active water treatment, in-lake neutralization of mining end lakes*

1 Introduction

Lignite mining in Germany has been carried out under soft rock conditions for about 150 years. In order to allow safe mining, the groundwater layers have been dewatered to a depth of about 50 – 80 m. To remove the overburden from lignite seam, the material has been displaced to outer damp sites. In the mined-out areas, large end lakes have been created with a volume of 20 – 450 mill. m³ (LMBV 2017a).

In the phase of mine operation and closure, sulphide minerals (e.g. pyrite and marcasite) in the overburden had been oxidised. The minerals formed water-soluble iron- and sulphate ions, as well as small amounts of other heavy metal ions in some cases. When mining ceased, the groundwater layer outside the mining site was refilled and the sulphide minerals were transported by the re-established groundwater flow. Due to acidic groundwater flow, the majority of the pit lakes and their run-off waters do not meet the national water quality requirements. Hence, water treatment is required either for the lake water bodies or the discharged waters. In-lake neutralization of the entire water body is the preferred option within regard to cost efficiency, water quality and subsequent use.

2 Water treatment principals

In order to comply with German water regulations §§ 27, 44 and 47 (WHG 2009) as well as Article 1 of the European Water Directive (WRRL 2000), the quality of surface and underground water may not be deteriorated by mining activities. To ensure the water from the mining lake as well as runoffs waters does not adversely affect downstream biocenosis, a water treatment according pH values and iron components is necessary. Active water treatment is the most common form of water treatment in mining industry. Because the mine lake waters are acidic (pH values from 3 to 7, iron levels from 1 to 150 mg/l), they require the addition of lime, limestone or soda to raise the pH value (LMBV 2017a). Once the pH value has been elevated, dissolved iron precipitates out of the solution and sinks to the bottom of the lake. As a result of the large amount of water being treated, techniques like ion exchangers, membrane filters or reverse osmosis are not suitable in this case.

In-lake neutralization involves the surface water body in the former opencast mining pit by mixing a neutralizing agent into the water. With this process, the total water body as well as sediment of the lake, erosion material and the water flowing into the groundwater aquifer must be neutralized. The main advantages compared to a run-off treatment are usually the following:

- In-lake treatment is required just periodically; run-off treatments have to operate all the time,
- Degradation of ammonia by microbes in neutral water bodies,
- Iron sludge formed during neutralization settles on the lake bottom, and does not have to be disposed of elsewhere,
- Output of neutral lake water into the adjacent downstream groundwater aquifer and
- High usability of neutral waters (e.g. fishing, recreation …) (to using this style template)

3 Choice of in-lake procedure

Technically, not all treatment procedures are equally suitable for all types of lakes. Lake shore-based stationary water treatment plants would appear to be the preferable solution when continuous treatment cycles are required. They can be automated to a large extent so they can be both operated and monitored remotely. The lime should be introduced into the lake water body at an appropriate distance from the shore using pipes and subsurface turbulent jet technology. The required lime suspension is produced with lake water on the shore. Stationary plants of this kind are well-suited for relatively compact water bodies where good mixing as a result of the convective lake water currents can be expected (LMBV 2017b).

Some German mining lakes are heavily segmented and made up of several sub-basins. Here it is more likely that mobile plants (i.e. water treatment vessels) are capable of distributing the neutralization agent across the lake as required.

4 First Approaches to in-lake procedures

LMBV and her partners tested several in-lake treatment techniques in the recent years. The techniques available for adding lime particle suspensions to acidic post-mining lakes are either the use of mobile water treatment vessels, which cover most of the lake surface during the liming, or stationary plants, spreading the lime with pipes into the lake.

The first trial of a full-scale in-lake neutralisation at Lake Senftenberg with approximately 11 000 tonnes of lime and 3 000 tonnes of caustic soda using hopper barges to distribute into the lake showed, that any efficient neutralisation of post-mining lakes with solid lime products required long periods of reaction with the lake water and intense mixing processes. The lime sank rapidly to the lake bottom in clumps, without dissolving any further into the lake water. In addition, the lime particles became inert in the sulphate-rich lake water, presumably because of the development of gypsum on the particle surface.

5 Lime Resuspension in Lake Geierswalde

In order to overcome this problem, at lake Geierswalde this deposit was collected using a suction dredger in 2004. The suspension was subsequently distributed again across the lake surface by means of ten large sprinklers. The alkaline suspension brought to the lake surface had a solids content of 2 % by mass. While these solid particles were sinking to the lake's bottom, some part of the lime dissolved causing neutralisation in Lake Geierswalde. Wind and density driven convection in the lake water contributed to further dissolution of lime particles, as well as for the intermixing and distribution of their reaction products.

6 Use of Soda ash to Lake Bockwitz

As part of another LMBV project soda ash was added to the water of the post-mining lake Bockwitz to initiate neutralisation in 2004 to 2007. The initial values of the acidic water body of some 18 million m^3 were: pH = 2.7, BNC(4.3) = 4.5 mmol/l, and Fetot = 0 55 mg/l.

The pulverised soda ash was initially injected directly from the silo vehicle pneumatically as a mixture of solids and air into the lake just below the surface close to the shore (Fig. 1). As a result of the input of soda, a temporary pH value in the range up to 7.7 was achieved, Thus, the method proved technically feasible, respecting that soda achieved weak buffering of up to ANC(4.3) ≈ 0.4 mol/l. .

Figure 1 Soda input to Lake Bockwitz (source: BGD/LMBV)

Lake Bockwitz has since been subject to natural succession by continuously groundwater inflow. Thus re-acidified at a relatively slow rate which will cease pH to a value of 3.5. In general, though, the input of soda has proved to be economically inefficient because of the rising price of soda ash on global markets

7 Adding caustic lime to Lake Hain

From 2008, in-lake neutralisation was carried out using a plant (Fig. 2), situated on the southern shore of Lake Hain. The caustic lime was stored in silos and the lime suspension produced in a two-stage process. Lake water from the nearby Haubitz area was used to slake the lime and produce the suspension. Input of the caustic lime suspension to the water body was done by a sprinkler above water at about 2 % by mass. The lime was distributed across the lake by convective lake water currents by wind and density driven flow processes.

Figure 2 Upper left: Lake Hain stationary neutralisation plant and its floating unit for above water distribution (source: UIT/LMBV)

8 Water treatment vessels

The liming process of lakes has been long practiced in those regions in Scandinavia that have been affected by acid rain in soft water areas.

One such Swedish water treatment vessel, the Brahe type, was used for the first time on an eastern German post-mining lake in 2008. The lime-water suspension was spread across the lake surface by two water guns. The vessels could easily transported by road on a trailer from which they can be launched to a lake. One disadvantage was that the relatively coarse-grained pulverised limestone being used being less effective. Another ecological drawback is the risk of the fine lime particles drifting into the reed beds along the lake shore as they are unable to penetrate the air-water boundary.

In this context, the Barbara is another water treatment vessel, using an under water lime distribution technology. The vessel is a catamaran with two tube mixers mounted between the hulls (Fig.3). This allows additional mixing by the vessel's two propellers at the ends of the twin hulls. The vessel has two lime bunkers, each with a capacity of 12 m³, allowing material to be bunkered according to the bulk density of the lime.

Figure 3 Water treatment vessel "Barbara" in operation, and (bottom right) being lowered – showing the distribution system between the vessel's hulls (source: LUG/LMBV)

Positive aspects of this new technology are high effectiveness of neutralization agent and economic mixing technology. This is due to the high turbulence and the low concentration of the solid matter with a suspension of way less than 1 %. The main disadvantage of this vessel is the long loading time of the on-board silo. A further step of development of particular relevance to LMBV is the water treatment vessel Klara (Fig.: 4). It has been designed and built specifically for use at the Lausitzer Seenland, which are former mining pits.

Figure 4 LMBV water treatment vessel Klara during trial operation (courtesy: LMBV)

The Lausitzer Seenland consists of nine former mining pits, which are connected by navigable canals, in the federal states of Saxony and Brandenburg (Fig. 5) between the towns of Senftenberg and Spremberg. The water surface area of the entire lake chain exceeds 55 km², and it has a volume of more than 800 million m³.

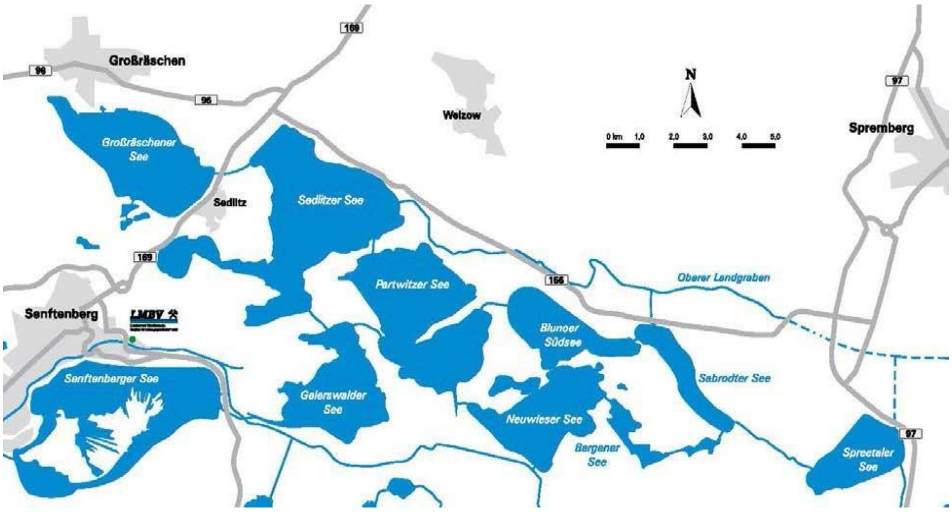

Figure 5 Lausitzer Seenland, former mining pits and Lake Senftenberg – 9 interconnected post-mining lakes (source: LMBV)

The Klara dimensions were defined so that it would be able to pass through all canals, bridges, and locks. Klara vessel consists of a push boat with two silos-barges. The engine, generator, and the bridge are on the push boat. There are two lime silos on each barge, and beneath each of the barges, two discharge units have been mounted between the catamaran twin hulls.This discharge unit arrangements of the water treatment vessel Klara has the advantage that while the first barge is on the lake with the push boat discharging neutralization agent, the second barge can be loaded. It reduces the time between two treatment cycles to about 5 minutes for changing the barges. Klara can distribute caustic lime, pulverised limestone, or calcium hydroxide, and is able to deliver neutralization very efficiently. It reaches high levels of dilution in lake water by boosted the agent by the vessel propellers. The vessel is dimensioned for the discharge of approximately 40,000 t of neutralization agent per year. Klara is therefore able to carry out both the initial neutralization as well as the follow-up for the entire Lausitzer Seenland (Figure 5).

9 Summary

A relevant example of a mobile plant used for neutralization is the LMBV water treatment vessel Klara. It was custom designed and built for the initial and follow-up neutralization of the Lausitzer Seenland, the mining lake. The Klara is the most powerful water treatment vessel built to date, which follows up the development of several in-lake treatment vessels. Other large treatment vessels such as the Barbara are suitable for post-mining lakes with relatively high demands for neutralization agent. They have proved their usefulness.LMBV is able to carry out efficient and very effective in-lake neutralization measures using mobile water treatment vessels and stationary neutralization plants. By now, there are a number of well tested techniques available. The decision on technology and neutralization agent depends on both, technological and economic considerations. These decisions are usually made on a case-by-case basis.

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Mine Closure and Reclamation in Illegal Small Scale Mining Activities - An Example of Amber in Ukraine

C Drebenstedt TU Bergakademie Freiberg, Germany

T Shepel TU Bergakademie Freiberg, Germany

Abstract

Amber is a gemstone from organic origin and attract attention since centuries. Amber mined regular and in Europe, mainly at Baltic Sea region. However, in Germany, Poland, Byelorussia, Russia or Ukraine amber is present in former sea transgression areas in shallow depths.

Illegal mining develops in economic difficult environment. Based on the knowledge of the regular mining and exploration results, people without alternative income start the extraction of amber with primitive tool in relevant regions. Because of high demand and prices, since 2015 the illegal amber mining in Ukraine increased and starts to be organized with hundred "miners" on a claim. The uncontrolled mining disturb the surface, presented here by forest. The use of hydraulic pipe extraction method mix the overlaying soils and slash clay to the surface. Furthermore a surface subsidence is happens.

The illegal mining activities tolerated by the government. Al least there is no responsibility for reclamation. No governmental organisations start to require regulations. In a project proposal, a case study for the reclamation worked out.

Keywords: *amber, illegal small scale mining, Ukraine*

1 The Problem status

Illegal mining let to several problems to the society. To them belongs a set of economic, social, ecological, fiscal, legal and other aspects with high complexity [1]. The amber is mined illegally on a large scale in the northwest of Ukraine (regions Olewsk and Rivne, Figure 1 number 1 and 3).

Mining is motivated by the fact that amber can generate good income. One might get approx. 300€ for one kilogram of amber splinters (16 mm in size) and more than 3,000€ for a single piece larger than 20 g in weight. Amber is thus significantly more expensive than gold (one ounce = 31.1g costs approx. 1000€). Amber is particularly popular in China, where yellow is considered a lucky color.

The poor economic situation in the rural region of western Ukraine is also stimulating people to mine amber.

The illegal mining of amber is estimated at approx. 300 tons per year [2]. Amber can be found either directly below the surface or at the depth of 50 m and more, covered by loosened sediments (sand, clay, silt).

Even before Ukraine became independent, amber had been legally mined in open-cast mines in the north-west part of Ukraine, e.g. in Klessiv. Knowing about the amber deposits, people began the first illegal mining activities in 1992 and the activities have been rapidly expanding since 2014.

The illegal mining of amber takes place either near the surface through shallow pits or at greater depths through flushing boreholes with water. This destroys the surface and makes impossible the further use of land. During the construction of the pits, unordered holes and fills are created. The damaging of trees' roots results in the destruction of forests.

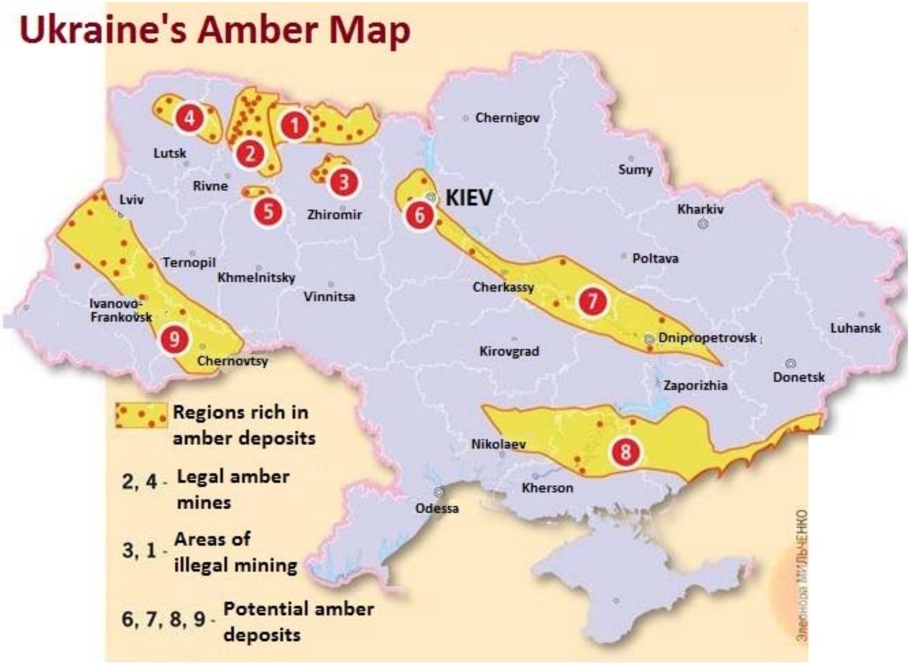

Figure 1 Amber deposits in Ukraine [2]

The flushing of amber with water in underground is used at greater depths (Figure 2). A water jet that is directed vertically into the ground liquefies the sediment above the amber layer. Light components are brought to the surface by the water flowing upwards from the borehole, including amber (density approx. 1.07 g/cm³), which is then gathered with meshes. While large-scale mining, the forest is cleared illegally (Figure 3). The area destroyed during the mining of amber is estimated at 1,700 ha [3].

Since illegal mining is carried out on a large scale in public and several hundred workers are involved, it can only be conducted with the knowledge of local authorities.

Mining destroys not only the landscape, but also the deposits. The uncontrolled, illegal mining activities result in inoperable deposits. No duties or taxes are paid for the extracted amber, but obviously bribes. Millions of euros are lost by the state yearly. The raw amber is usually illegally transported to Poland and then, on a regular basis, reimported for further processing.

Figure 2 Illegal mining of amber by its flushing with water from underground [4]

Figure 3 Illegal deforestation for the mining of amber [4]

The pictures of the illegal mining of amber in Ukraine are similar to those of gold mining in Africa (Figure 4).

Figure 4 Consequences of small-scale mining in Mocambique (left) and in Ukraine (near Olewsk, 2016)

2 Consequences of the mining for the landscape

The influence of mining activities on nature and landscape is briefly described on the example of the illegal mining of amber near Olewsk.

The excavation field is located in a forest area and can be reached by a poorly paved road. The subsoil layer is composed of sand; trees are predominantly pines and oaks. The groundwater level is near the surface.

The degradation causes changes in the landscape (Figure 5), e.g.:

- deforestation
- trenches for the supply of groundwater to pumps
- a big number of holes in soil remaining after the extraction activities
- land subsidence accompanied by the flooding of post-mining areas
- danger from unsecured flushed boreholes
- dumped tailings

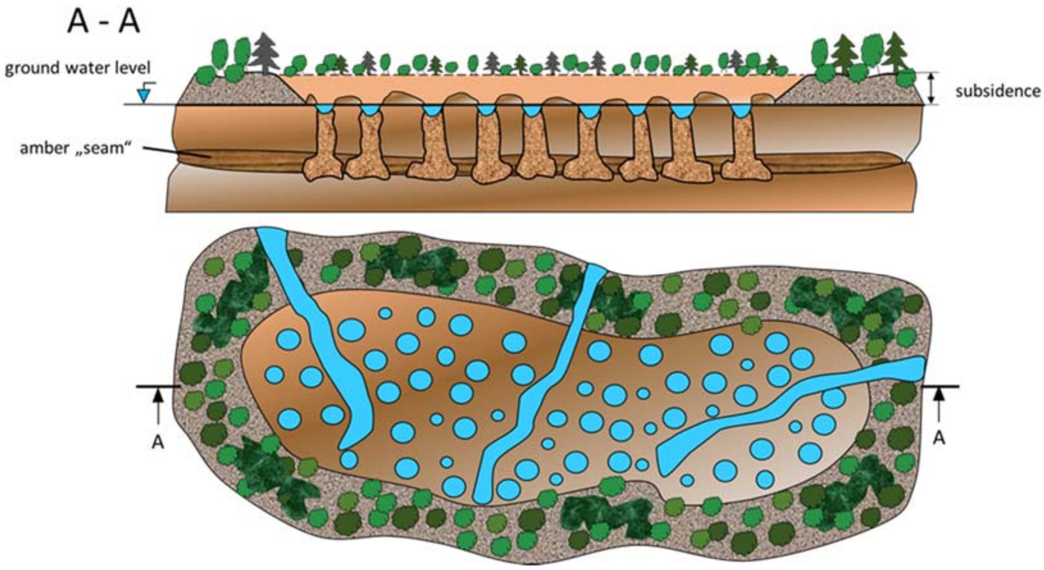

Figure 5 Scheme describing the state of a post-mining area after the illegal extraction of amber

3 Suggestions for the technical implementation of the reclamation

To decide about the right method of reclamation, the primary objectives of reclamation activities must be determined at first. It depends on several internal and external factors.

Internal factors are natural conditions such as morphology, geology, climate, soil, hydrology, etc. The natural conditions are the background for the naturally occurring specific species of plants and animals in this area.

External factors are determined in particular by the society. They include, for example, the land use (agriculture, forestry...), infrastructure and settlements.

Based on the regional planning, the reclamation objectives must be adapted to the land use and coordinated with the local authorities and people in the region.

For the implementation of the reclamation, the following technical proposals are initially suggested, without precise knowledge of planned use of land, geological conditions as well as botanical and zoological details. This is reserved for the subsequent planning.

The following suggestions are based on the impression of the area visited near Olewsk (see Figure 3, right). The basic technology consists of deepening a part of the area to create a water body (pond, lake...) that can be used economically, for tourism or for nature conservation and filling another part, e.g. for reforestation. Of cause the self-healing power of nature can be used (section 3.1).

3.1 Natural succession

A simple method of reclamation is the natural succession. The abandoned area is left to the natural development. Plants and animals reclaim the area. Before that, it must be cleared of the rubbish.

The advantages are the low reclamation costs and a high nature conservation value, but they are offset by the disadvantages such as permanent threats to the public and a lack of economic use of the land.

3.2 Partial filling of the terrain by creating a water surface

In this proposal, a part of the destroyed mining area is dredged. In the area of the dredging, a water body is created. The excavated material is used to fill up the other part of the mining area on the same terrain and can be used for reforestation (Fig. 6). Depending on the size of the area, the excavated material possibly has to be transported (Figure 7).

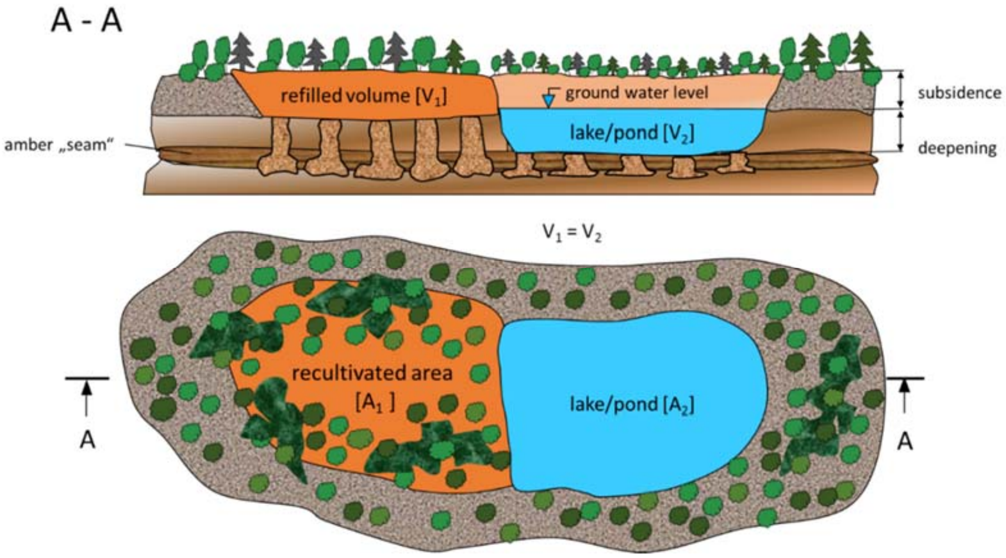

Figure 6 Scheme of deepening a water body and filling the remaining area

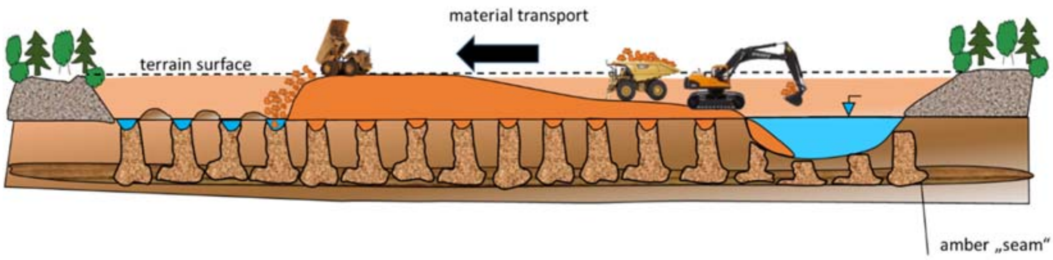

Figure 7 Scheme of the excavation and filling with the use of trucks

3.3 Creation of several water bodies and filled areas

In order to reduce the transport use, it is possible to deepen and fill in strips within the areas reached by an excavator (Figures. 8 and 9). The multi-water landscape is environmentally more valuable than just one water body.

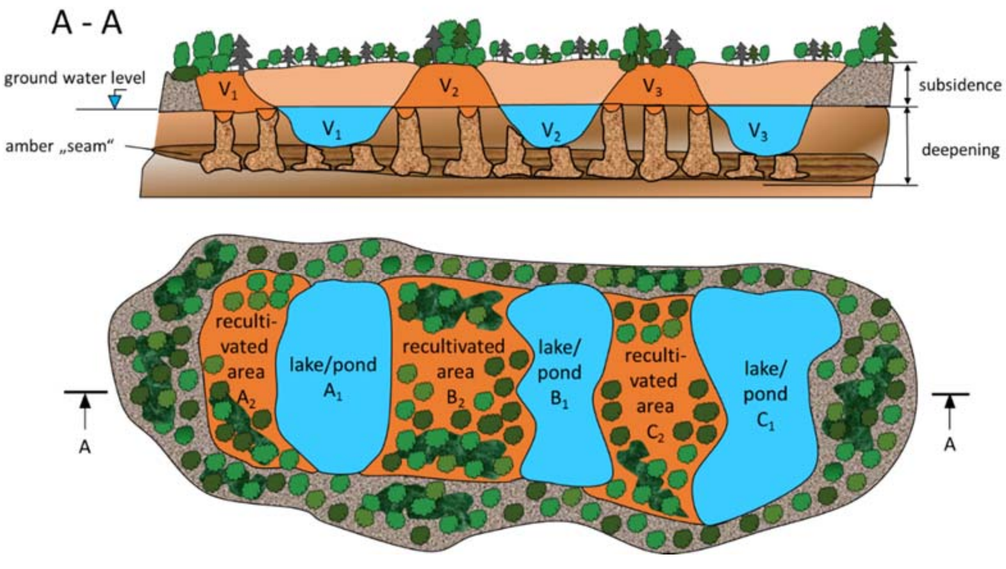

Figure 8 Scheme of creating several water bodies

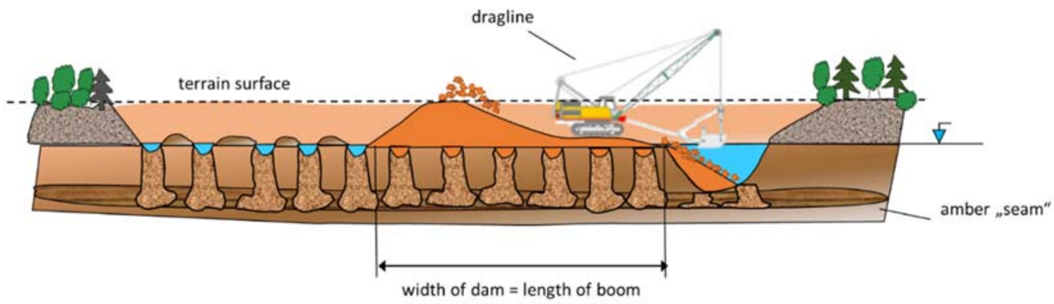

Figure 9 Scheme of excavation and filling of a strip

3.4 Creation of a water body or backfilling

In addition to the partial excavation/ partial backfilling options (see 3.2 and 3.3), the entire area can also be deepened for a water body or completely filled up with soil. This requires appropriate transport over longer distances as well as areas for soil filling or soil removal. In the case of two nearby mining areas, this could be possible avoiding the necessity of using additional land (Figure 10).

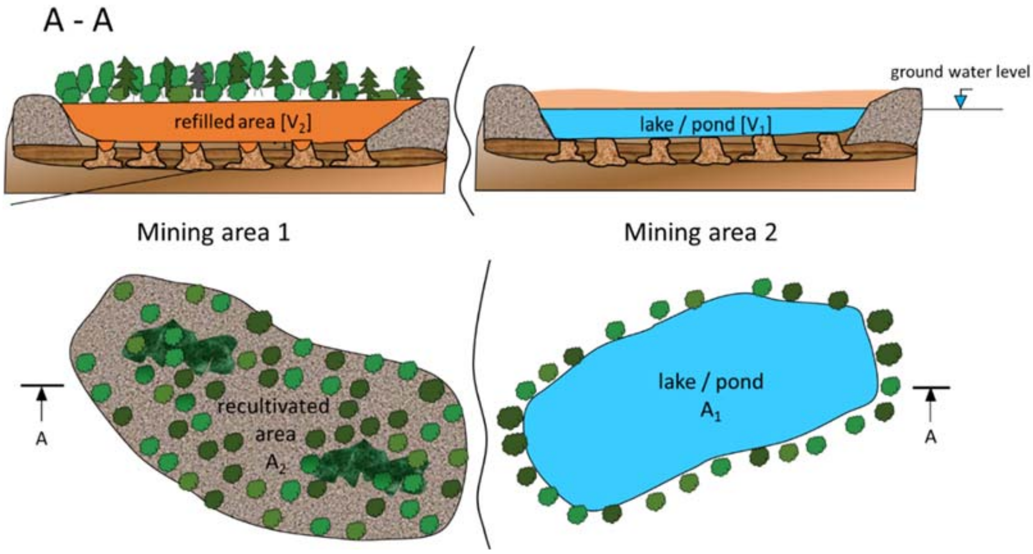

Figure 10 Scheme of a complete refilling by deepening of adjacent mining areas

4 Possible solutions for financing the reclamation activities

In order to prevent further uncontrolled destruction of the landscape and the accompanied damage to the society, the illegal mining of amber must be stopped.

For the calculation of costs for the reclamation, appropriate reclamation measures must be determined (see section 3).

4.1 Polluter pays principle

One way of financing the reclamation activities is to identify the originators and allocate the costs to the people who have benefited from the amber business. Since the extraction of amber is illegal, this can only be done by means of court rulings. The perpetrators are the amber graves and the persons of the state authorities who tolerated the mining activities or accepted bribes.

4.2 Legalisation of mining

It must be examined to what extent the existing operations or new ones receive a permit for the legal mining of amber. Parts of the population could thus pursue legal employment and the state generates tax revenues. Legal mining creates infrastructure and work in the supply and subsequent industries and can support schools and associations. Legal mining would take responsibility for reclamation. When granting licences, it should be defined whether areas destroyed by illegal mining are included for the residual extraction and further reclamation.

4.3 Reclamation under the state responsibility

If the options 4.1 and 4.2 cannot be implemented, it remains for the state to pay for the reclamation activities. This could be done by using tax money or by setting up a fund of mining companies to finance the reclamation of illegal mines.

5 Conclusion

Illegal mining let to several problems to the society. Under them are ecological damages and lack of payments, partly for reclamation. After wild excavation and making business the area is left destroyed. On example of illegal amber mining in West-Ukraine are given suggestions for reclamation and finance. The main problem is, that the government and police tolerate this illegal mining, because they are part of the million dollars business.

Acknowledgement

The article based on a meeting with the NGO "Ecology and World" on 11. /12. June 2016 in Kiev. The meeting include a side visit in Obishe, near Oleswk. The NGO had the target to work out proposals for stopping and reclamation of the illegal amber mining.

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1. Legal, financial, socio-economical and organizational aspects

Innovative Approach to Stakeholder Engagement on the Surface Design for the Closure of Canada's Giant Mine

J Amphlett *Indigenous and Northern Affairs Canada*

L Christoffersen *SRK Consulting*

D Hockley *SRK Consulting*

Abstract

Following the discovery of gold in Yellowknife, Northwest Territories, Giant Mine officially opened in 1948. Mining activities ceased shortly after the mine's owner went bankrupt in 1999. Since that time, the mine has been the responsibility of Indigenous and Northern Affairs Canada (INAC). Historic activities at the mine have resulted in the generation of arsenic trioxide dust disposed of in underground chambers, contaminated soil and waste rock, four tailings containment areas, seven open pits and contaminated water and sediment in Baker Creek, which runs through the mine site. The site has been undergoing rehabilitation and closure activities, with final closure activities anticipated to be implemented in 2021.

The roughly 50-year operating period of the mine resulted in significant disturbance and impacts on the health and lifestyles of local people, especially members of the Yellowknives Dene First Nation (YKDFN) and other Indigenous groups. Giant Mine is within the Akaitcho Dene asserted territory and is close to the YKDFN communities of Ndilo and Dettah, and is within the traditional land use area of the Tlicho, known as Mowhi Gogha De Niitlee. Giant Mine is also situated within the municipal boundaries of the City of Yellowknife.

The Environmental Assessment of the initial closure plan was completed in 2014 and raised many concerns about the surface remediation components. Given the high profile of the mine site in the local community and concerns raised about the closure plan, INAC recognized the need for broader engagement. In 2015, INAC proposed a Surface Design Engagement (SDE) Process that was further defined in discussion with stakeholders. Over the course of a year, this engagement process involved a series of meetings and workshops and included stakeholder preparation, identification of objectives, definition of closure options, risk review, and evaluation of closure options by stakeholders.

SDE results were very influential in the final selection of closure methods for Giant Mine. Decisions made based on SDE were communicated back to stakeholders and engagement on changes to the closure plan is ongoing.

1 Introduction

Giant Mine (the site) is an inactive gold mine located approximately 5 km north of the centre of Yellowknife, Northwest Territories (see Figure 1).

The mine produced gold from 1948 until 1999, after which stewardship was transferred to the Department of Indian and Northern Affairs Canada (INAC), now Indigenous and Northern Affairs Canada (INAC). All mining activities ceased in July 2004, after which INAC reassumed stewardship and a contractor was retained to operate and maintain the site in compliance with current regulations. Final closure activities are anticipated to be implemented in 2021.

The roughly 50-years of mining resulted in significant disturbance to the land and water, and impacts on the health and lifestyles of local people, especially members of the Yellowknife Dene First Nation (YKDFN) and other Indigenous groups. In general, the YKDFN and other local groups were not consulted on the Giant Mine throughout most of its operating life.

INAC developed an initial remediation plan for the site that included containment of approximately 237,000 tonnes of arsenic trioxide dust produced as waste and stored underground and remediation of the surface including the four tailings containment areas, seven open pits, contaminated soil, and Baker Creek.

Environmental assessment of the initial closure plan was completed in 2014, and raised many concerns about the surface remediation components. It was clear that surface remediation planning would benefit from a much broader and detailed engagement with the YKDFN, the City of Yellowknife, and other interested groups. INAC proposed a Surface Design Engagement (SDE) process to obtain stakeholder input and determine what options would best meet stakeholder objectives.

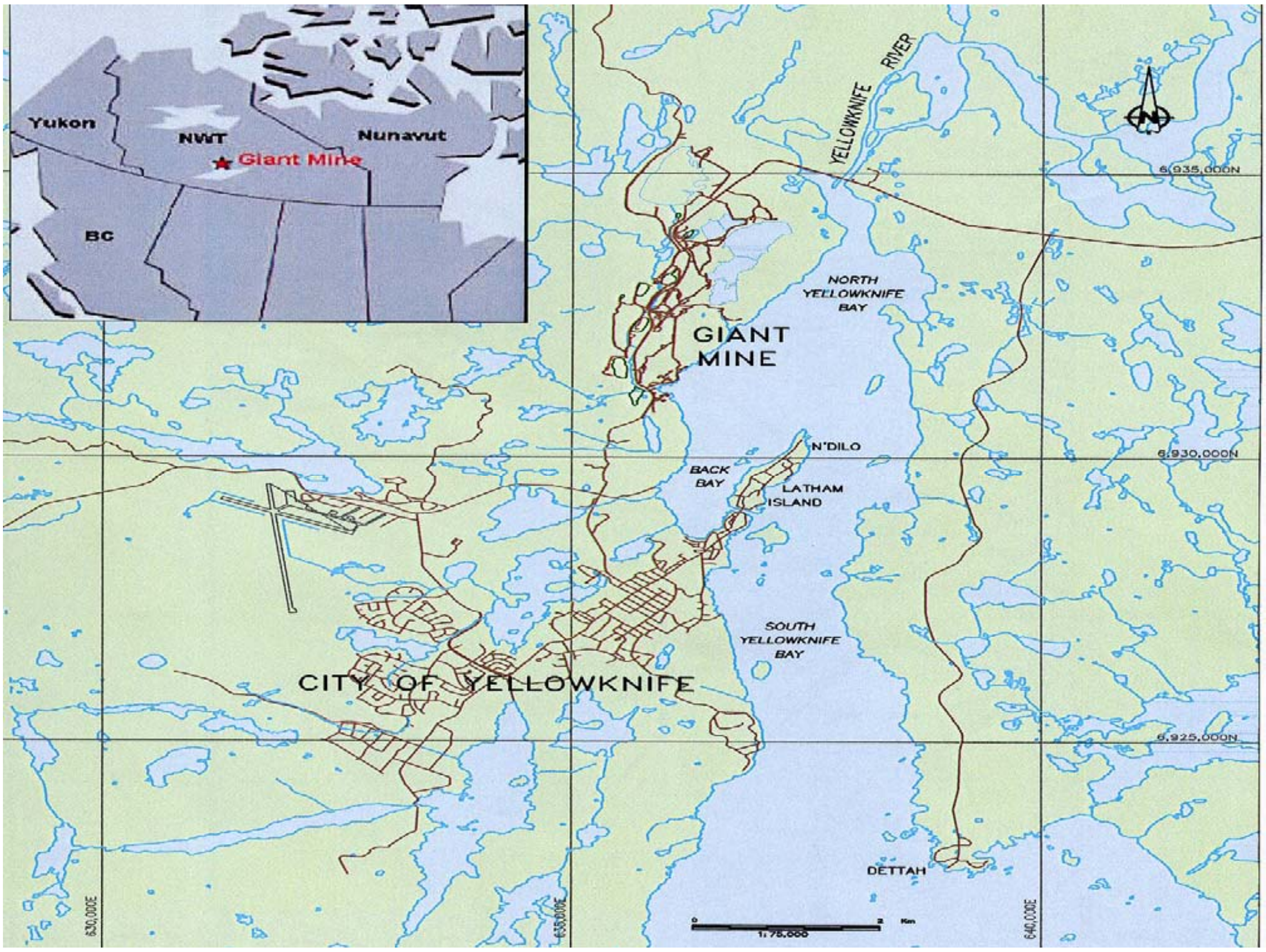

Figure 1 Location of Giant Mine

2 Stakeholder Preparation

In October 2014, a proposed engagement strategy for SDE was presented to the YKDFN and other stakeholders with the goal of ensuring interested groups had a voice in the major decisions about surface remediation. A timeline for the process was developed with specific dates proposed for meetings. Feedback was received on the process through written comments and a series of meetings held in the late 2014 and early 2015. Table 1 presents the major stakeholder groups who participated in SDE. Preparation sessions were completed with each stakeholder group in April and May 2015. For groups not familiar with parts of the site or with the latest studies, the sessions included a general introduction to the site and the available technical information. Sessions also included working through an example of how closure options would be evaluated in the process.

Table 1 SDE Stakeholder Participant Groups

Yellowknife Dene First Nation (YKDFN)	North Slave Métis Alliance (NSMA)
City of Yellowknife	Alternatives North (Social / Environmental NGO)
Government of the Northwest Territories	Environment Canada
Department of Fisheries and Oceans	Health Canada
Fly Kid Foundation (Fly Fishing NGO)	Mining Heritage Society
Great Slave Sailing Club	Giant Mine Project Team

3 Stakeholder Objectives

Stakeholder objectives were critical for the options evaluation held at the end of the SDE process. These objectives were the standard against which participants reviewed each of the closure options. From May 2015 through January 2016, an independent technical advisor to the stakeholders met at least once with each of the interested groups to discuss the following questions:

- What do you want the surface remediation at the Giant Mine to achieve?
- What vision do you have for the site, the environment and the community while the remediation is underway and once the remediation is complete?
- What are the important values that could be affected by the project?
- What outcomes would you like to see for the important values?

The objectives that could directly help to identify preferred remediation options are presented in Table 2 (Slater 2016). Based on feedback from stakeholders, the objectives in Table 2 were reworded into 16 “plain language” objectives used to evaluate the closure options. In general, they were all clarifications or simplifications of the Table 2 objectives.

Table 2 Stakeholder Objectives Developed for Selection of Preferred Closure Options

Category	Objectives
Human health and safety	Eliminate, avoid, and minimize effects on and hazards to public and worker health and safety.
Ecological conditions	Eliminate, avoid, or minimize effects on and hazards to the aquatic, terrestrial, and atmospheric environment.
	Restore the aquatic and terrestrial environment consistent with land use.
Land use and site attractiveness	Maximize flexibility and provide access for a range of future land uses.
	Use surface remediation to define and constraint future land uses and warn about areas where people or wildlife could be harmed by surface or subsurface conditions.
	Minimize or avoid disturbance or contamination of areas outside of the site.
Socio-economic values and conditions	Increase public confidence about site conditions and management.
Long-term requirements	Minimize perpetual care requirements.
Cost	Minimize risks associated with climate change, government instability, and other unforeseen circumstances.
	Use available funding efficiently.
	Minimize cost to future generations.

4 Development of Closure Options

An Option Definition Workshop was held over two days in June 2015 with over 100 participants. The first day of the workshop included presentations to ensure that all participants had a common understanding of the site and the key surface remediation issues. These presentations discussed the status of site buildings, roads, water treatment systems, Baker Creek, the four tailings containment areas, the five open pits, contaminated soils and other wastes, as well as the results of previous human health and ecological risk assessments. One-page handouts were provided as summaries of each topic.

Most of the second day involved workshop activities by the stakeholder participants. Each table of participants was first asked to list all of the surface remediation methods that they thought should be considered. Then each table developed a vision and a complete plan for the entire site. These steps were facilitated to allow each group to report on progress.

After the Options Definition Workshop, five representative options that covered the range of ideas expressed by the stakeholders were developed as shown in Table 3. These representative options were carried forward into option development. For each option, conceptual (scoping level) designs, sketches, cost estimates, and assessment of residual risks were developed. The goal was to compile the information needed to assess the expected performance of each option with respect to the objectives that stakeholders had defined earlier in the process.

Table 3 Closure Options for Stakeholder Evaluation

Closure Option	Vision	Pits	Baker Creek	Contaminated Soil	Tailings
1	Access to the site will be restricted for people and animals.	Blast down steep pit slopes and build barriers around open pits.	Widen Baker Creek channel for flood control.	Remove or cover contaminated soils in the areas disturbed by mining activities.	Cover the tailings on the surface with a layer of coarse rock.
2	Restrict human access to site, but not animal or fish access.	Fill A2 pit with quarried rock. Fill A1 and C1 with South and Central Pond tailings and cap with a rock cover.	Widen Baker Creek channel for flood control.	Determine if contaminated soils present significant human health or ecological risks, and remediate or restrict access if needed.	Relocate South and Central Pond tailings to A1 and C1 pits. Cover remaining tailings ponds with a rock cover.
3	The site will be made safe for industrial and recreational use, but not residential use.	Blast down steep pit slopes and build barriers around open pits.	Widen Baker Creek channel for flood control.	Determine if contaminated soils present significant human health or ecological risks, and remediate or restrict access if needed.	Cover South Pond, Central Pond, North Pond, and Northwest Pond with rock and soil that will support vegetation.
4	The site will be made safe for industrial and recreational use, but not residential use. Baker Creek will be diverted off-site.	Blast down steep pit slopes and build barriers around open pits.	Divert Baker Creek to the north of the mine site and remediate the former on-site channel.	Determine if contaminated soils present significant human health or ecological risks, and remediate or restrict access if needed.	Cover South Pond, Central Pond, North Pond, and Northwest Pond with rock and soil that will support vegetation.
5	The townsite / shoreline will be safe for any use, including residential. The rest of the site will be safe for industrial use and recreational access.	Fill A2 pit with quarried rock. Fill A1 and C1 with South and Central Pond tailings. Cap with rock and soil that will support vegetation.	Widen Baker Creek channel for flood control and remove contaminated sediments.	Remediate soils above residential standards from the townsite / shoreline areas. Remove soil above recreational standards from bedrock outcrops and accessible forested areas across the southern half of the site.	Relocate South and Central Pond tailings to pits. Cover North Pond, and Northwest Pond with rock and soil that will support vegetation.

5 Risk Review

A Risk Review Meeting was held over three days in December 2015. Each stakeholder group had one or more representatives attend the meeting to provide input and improve the options prior to the final evaluation step (Stratos 2015).

Remediation activities in the representative options were evaluated using the same risk rating tools used for project risk assessments. The remediation activity was described, and then participants discussed what concerned them about the remediation activity. Concerns were recorded as a risk statement. The group was then asked to discuss consequence ("how bad could it be?") and likelihood ("could it really happen?") to determine the risk rating (low, moderate, moderately high, high, very high). The risk statement and risk rating, as well as notes on existing treatments and potential mitigation options, were recorded in a risk register.

Assessments of consequence severity and likelihood were based on the consensus of opinion rather than on detailed calculation of probabilities. This approach allowed a much wider range of risks to be considered as efficiently as possible. Differences of opinion among stakeholders about consequence severity and likelihood were tracked. Two types of risks were identified: (1) project and implementation risks, which are associated with implementing the remediation activity and tend to be similar to those of other large construction projects, and (2) residual risks, which will remain following the completion of site remediation activities (e.g., those associated with remaining contaminants or physical hazards). The options were updated to address some of the implementation risks. Residual risks were considered when evaluating the options.

6 Closure Options Evaluation

An Options Evaluation Workshop was held over four days in February 2016 with more than 75 participants. Stakeholders were assembled in tables representing each group to consider the five closure options in Table 3. Technical experts were available during the workshop to answer questions. The process for evaluating each option was as follows:

- Presentation of the option description
- Plenary discussion of pros, cons, risks, and uncertainties
- Evaluation of the option by each table against the plain-language objectives
- Capture of the evaluation results from each group using a colour-coded table, with green indicating the group agreed that the option met an objective, and red indicating the group disagreed that the option met an objective. An example of an option evaluation is provided in Figure 2.
- Discussion of the colour-coded results, especially cases where tables had very different opinions about whether an option met an objective

To provide a check on the group evaluations, each individual participant was subsequently asked to identify his or her preferred option. Finally, to assess how close or far apart the final preferences were, tables of participants were asked to agree on a preferred option, and suggest up to three changes that would make their preferred option even better.

The evaluation results clearly showed that stakeholder groups were more positive towards Options 2 and 5 and much less positive towards Options 1, 3, and 4. Individual polling confirmed the pattern in the group assessments, as did an additional group exercise in which stakeholders were asked to make changes to their favourite option.

- Individual voting: As their first choice, 35 people picked Option 2 and 45 people picked Option 5 (3 people picked Option 3), out of a total of 83 votes. As their second choice, 27 people picked Option 2 and 37 picked Option 5 (2 people picked Option 1, 13 picked option 3, and 1 picked Option 4), out of a total of 80 votes. In total, Option 2 received 62 votes and Option 5 received 82 votes, out of a total of 163.
- Five of the stakeholder group tables picked Option 2 as their favourite option, and the other five tables picked Option 5. When asked to make three changes to their favourite option, many of the changes made the two options even more similar.

Option 1

		YKDFN-1	YKDFN-2	YKDFN-3	YKDFN-4	NSMA	Alt. North	City & LH	Other Govt	Tech Experts	Project Team
1	This option will keep people safe from site contaminants.	Agree	Strongly Disagree	Disagree	Strongly Disagree	Neutral	Disagree	Agree	Strongly Agree	Disagree	Disagree
2	This option will keep people and animals safe from physical dangers such as falling into pits or mine openings.	Agree	Strongly Disagree	Strongly Disagree	Strongly Disagree	Disagree	Neutral	Disagree	Agree	Agree	Disagree
3	This option will keep fish safe from contaminants.	Disagree	Strongly Disagree	Strongly Disagree	Strongly Disagree	Disagree	Agree	Strongly Disagree	Agree	Agree	Strongly Disagree
4	This option will keep fish healthy for eating.	Disagree	Strongly Disagree	Strongly Disagree	Strongly Disagree	Disagree	Agree	0	Neutral	Agree	Neutral
5	This option will keep animals safe from contaminants.	Agree	Strongly Disagree	Disagree	Strongly Disagree	Disagree	Neutral	0	Disagree	Disagree	Agree
6	This option will maximize dust control.	Agree	Strongly Disagree	Agree	Agree	Disagree	Neutral	Disagree	Agree	Strongly Agree	Strongly Agree
7	This option will repair the land and water.	Disagree	Strongly Disagree	Strongly Disagree	Strongly Disagree	0	Disagree	Strongly Disagree	Disagree	Strongly Disagree	Disagree
8	This option will allow for a range of potential future land uses.	0	Strongly Disagree	Disagree	Strongly Disagree	Strongly Disagree	0	Strongly Disagree	Strongly Disagree	0	Strongly Disagree
9	This option will restrict future land uses.	Agree	0	0	0	0	Neutral	0	0	0	Strongly Agree
10	This option will clearly warn future generations about remaining dangers.	Agree	Agree	Strongly Disagree	Strongly Agree	Agree	Neutral	0	Agree	Agree	Strongly Agree
11	This option will minimize disturbance outside the site.	Agree	Strongly Agree	Strongly Disagree	Neutral	0	Strongly Agree	Agree	Neutral	Strongly Agree	Agree
12	This option will maximize public confidence that the site is safe now and in the future.	Disagree	Strongly Disagree	Strongly Disagree	Strongly Disagree	Strongly Disagree	Strongly Disagree	Strongly Disagree	Disagree	Strongly Disagree	Strongly Disagree
13	This option will minimize work to keep the site safe for the environment and people in the future.	Agree	Strongly Disagree	Strongly Disagree	Strongly Disagree	0	Disagree	Strongly Disagree	Agree	Strongly Disagree	Strongly Disagree
14	This option will keep the site safe in the future, for example from climate change, government instability, or other future problems.	Agree	Strongly Disagree	Strongly Disagree	Strongly Disagree	Strongly Disagree	Disagree	Disagree	Disagree	Strongly Disagree	Disagree
15	This option will make the best use of available public funds (taxpayer dollars).	Agree	Strongly Disagree	Strongly Disagree	Strongly Disagree	Strongly Disagree	Disagree	Disagree	Neutral	Disagree	Agree
16	This option will minimize costs to future generations.	Neutral	Strongly Disagree	Strongly Disagree	Strongly Disagree	Strongly Disagree	Disagree	Disagree	Neutral	Strongly Disagree	Strongly Disagree

Figure 2 Example of Stakeholder Option Evaluation

7 Conclusions

Since the completion of the SDE process in 2016, the stakeholder evaluation results have been used by INAC in selecting closure options for Giant Mine. Decisions made based on SDE were communicated back to stakeholders in February 2017 and engagement on changes to the Closure Plan is ongoing.

Input received from SDE (stakeholders clearly preferred Options 2 and 5) has been critical in developing and updating the Closure Plan for the Giant Mine. Key decisions informed by SDE have included the following, many of which differ from the initial closure plan that went through the Environmental Assessment completed in 2014.

- The open pits will be filled: both Option 2 and Option 5 specified that pits will be filled. In the initial closure plan, the open pits were not filled and were stabilized and fenced.
- Baker Creek will be kept within an onsite alignment: both Option 2 and Option 5 specified that Baker Creek would remain onsite. This is consistent with the initial closure plan.
- Tailings from South Pond will be relocated to and consolidated in North Pond: both Option 2 and Option 5 specified that South and Central Pond tailings would be relocated. In the initial 2014 closure plan, no tailings were relocated.
- Tailings on the surface will be capped with rock (no vegetation): Option 2 specified that tailings would be capped with rock (Option 5 did not). In the initial closure plan, tailings were capped with a vegetated cover.
- The townsite / shoreline area will be remediated to meet residential standards: Option 5 specified that the townsite / shoreline area will be remediated to meet residential standards (Option 2 did not). In the initial closure plan, the townsite area was remediated to an industrial standard and did not include a more extensive shoreline remediation.

One favourable outcome of SDE is that while the final plan may not reflect every stakeholder group's first choice for closure, there is an understanding of the many other perspectives that must be considered in selecting closure options.

The revised Giant Mine Closure Plan will be resubmitted to the Mackenzie Land and Water Board for approval in January 2019.

Acknowledgement

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Closure Management in the Company's Strategic Guidelines

TCC Bissacot *Nexa Resources, Brasil*

JR Condor *Nexa Resources, Peru*

BX Silva *Nexa Resources, Brasil*

FF Micaela *Nexa Resources, Peru*

AC A Lima *Nexa Resources, Brasil*

E Huanca *Nexa Resources, Peru*

MA Pereira *Nexa Resources, Brasil*

Abstract

The decommissioning process of a mine and/or mining-industrial facility must be planned as well as their implementation. This includes the elaboration of closure plans whose costs must be duly estimated for the proper calculation of their financial feasibility and the correct provision of funds to be used during the operation of the project, its closure and the monitoring period after the decommissioning. Since the main goal of the decommissioning process is to achieve physical, chemical and biological stability, and reduce negative effects on the social aspects to leave a positive socioeconomic and cultural legacy, addressing these matters should be part of planning and delivering the project, regardless of the legal current demand on the matter. In order to ensure the issue is being addressed within the company's strategic planning, internal policies have been adopted to define the guidelines for preparing, updating and implementing the actions of decommissioning. According to these guidelines, preparing the plans must be preceded by the stage of socio and environmental diagnosis and the study of alternatives for future use. The first draft of documents must be prepared during the phase 2 of Front End Loading (FEL) of new projects and followed by periodic updates after the launch of operation. Periodic follow-ups must be held every five years for operations with a life of mine (LOM) over five years, progressing to a level of detail of a basic plan five years before the end of its LOM and to an executive level two years before its closure. After elaborated, the plans are approved by internal corporate committees and by the company's board of directors. Once validated, they are used to update the accounting records of decommissioning costs (Asset Retirement Obligation and Environmental Liability, when applicable). The amounts provisioned and the disbursement follow-up are included in the company's strategic planning through goals related to the material decommissioning matter. Establishing these guidelines has allowed a proper allocation of technical and financial assets to deliver progressive closures and a strategic view of the company for the implementation of measures. In addition to environmental rehabilitation, these guidelines provide us an improvement in the image of our company and leave a social legacy to the communities where the operations have been implemented.

Keywords: *decommissioning; mining and metal sector; strategic planning*

1 Introduction

In order to ensure a positive process and to leave a sustainable legacy for the communities after closure of operations, the decommissioning of a mine and/or mining-industrial facility must be planned with the same due care as was taken during the operating phase (SANCHEZ, 2013). For this reason, the subject of closure is considered important for the operations of Nexa Resources (Nexa), occupying a special position in the company's business strategy; likewise, the phases of new project design and the operating of mining and metallurgical units are managed with a future vision of mine closure.

In order to obtain licensing in Peru, it is necessary to make a conceptual closure plan at the design phase (Mine and Metallurgical operation) and once the environmental license is approved, a Closure Plan regarding feasibility must be presented. In Brazil, from the legal aspect, the Closure Plan is presented in two ways: Simplified, at the moment the mining operation requires it; and more detailed, two years before final closure of mining activities. There are no formal legal requirements for metallurgical units. Therefore, regardless of the current legislation, for internal guidelines, all operations by Nexa and new projects have a Closure Plan. These plans are technical documents and include the instructions for a safe, complete and efficient deactivation, in which economic, environmental and social actions are considered, with the final aim of guaranteeing a deactivation in line with best practices within the sector and allowing the subsequent reutilization of the areas, delivering additional to the investors and the communities.

2 Methodology

In Nexa, in order to comply with mine closure guidelines, a methodology has been established based on the following criteria and sequences:

- Corporate policy and register of closure
- Approval flow and responsibility of internal and corporate committee
- Closure plan preparation methodology

2.1 Corporate policy and register of closure

Nexa has elaborated the policies and guidelines of Mine Closure, which can be found in the GQI system, where any NEXA employee with the Username of the company can download the aforementioned Corporate Policy and Managerial Procedures. The definitions of the corporate policy and register are based on the description in Table 1.

Table 1 Definitions of the corporate policy and register

Aim	To establish guidelines for the standardized elaboration and revision of documents, based on current best practice.
Application	All Units and refineries of the Nexa Group and new projects.
Responsibilities	The person in charge is the Unit Manager or New project.
Procedures	Should be elaborated by a competent, qualified consultancy and comprise a multidisciplinary technical team with proven experience.
Flow of Approval	Levels of Approval in the Unit, corporate committee and Board of Directors.

In Nexa, in accordance with the international Accountancy regulations, the budgets for the closure plans belong in terms of accounting to two groups: Asset Retirement Obligation (ARO) and Environmental Liabilities. The accounting impact can be seen in Figure 1, where:

Asset Retirement Obligation (ARO): is an accounting procedure established in the international accounting regulations – IFRS - and in the CPC; regarding environmental issues, it refers to future obligations to restore/recuperate the environment. These obligations do not include corrective actions of damage done by environmental liabilities.

Environmental Liabilities: These are obligations acquired as a consequence of previous or present transactions that cause voluntary or involuntary environmental damage to third parties, such as soil pollution, continuous/accumulative atmospheric pollution, pollution of waterways, biota, intervention in Permanent Preservation Areas (PPA).

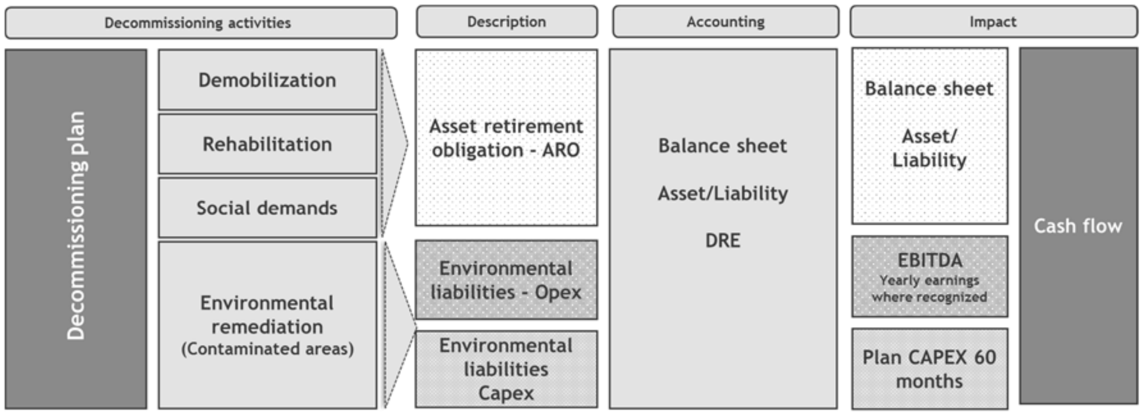

Figure 1 Distribution and Accounting Impact ARO and Liabilities

2.2 Approval flow and responsibility of the internal and corporate committee

The elaboration and approval of closure plans in Nexa follow 5 (five) Macro-phases, which are: i) Contracting and elaborating the document on the responsibilities of the General Manager of the Unit or project; ii) Assessment and elaboration of the Closure Plan by the Unit committee; iii) Assessment and approval of the plan by the corporate committee; iv) Assessment and approval of the plan by the Board of Directors; and v) accounting record. The unit committee and the corporate committee have the role of assessing the Closure Plan, contribute to its revision in such a way as to guarantee that this document meets all applicable technical premises and the guidelines of the company. All phases of assessment of the document must be registered in internal format standardized for this type of activity and the approval duly registered in the records. According to the Nexa's guidelines, preparing the plans must be preceded by the stage of socio and environmental diagnosis and the study of alternatives for future use. The first draft of documents must be prepared during the phase 2 of Front End Loading (FEL) of new projects and followed by periodic updates after the launch of operation. Periodic follow-ups must be held every five years for operations with a life of mine (LOM) over five years, progressing to a level of detail of a basic plan five years before the end of its LOM and to an executive level two years before its closure.

2.3 Methodology of the elaboration of closure plans

All existing undertakings must have an up-to-date closure plan compatible with their expected useful life. Likewise, any new undertaking will be approved only if it includes a conceptual closure plan. Extensions or modifications of already existing processes and installations must be incorporated into the already existing closure plan of the undertaking.

The elaboration of the closure plans must be carried out by a specialized company, qualified in accordance with the technical criteria and experience, that demands: i) Company with proven experience in similar services in the mining-industrial sector; ii) Own workforce or with established link to formal service providers; iii) Multidisciplinary team with professionals and backups specializing in physical, biotic and socio-economic environment, including manager and inspector with proven experience in similar services in the mining-industrial sector; Insurance policy covering technical responsibility; iv) Methodology validated for the elaboration of Study of alternatives of future use; v) Methodology validated for mapping of social impacts; vi) Methodology validated for elaboration of socio-economic profile and monitoring of social indicators; vii) Methodology and database based on validated technical reference and traceable for assessment of closure costs. La assessment of the contractor company must be archived in order to verify compliance with all mentioned criteria (NEXA, 2017). The preparation of the closure plan, in its successive detailed versions, must follow the stages described in Figure 2.

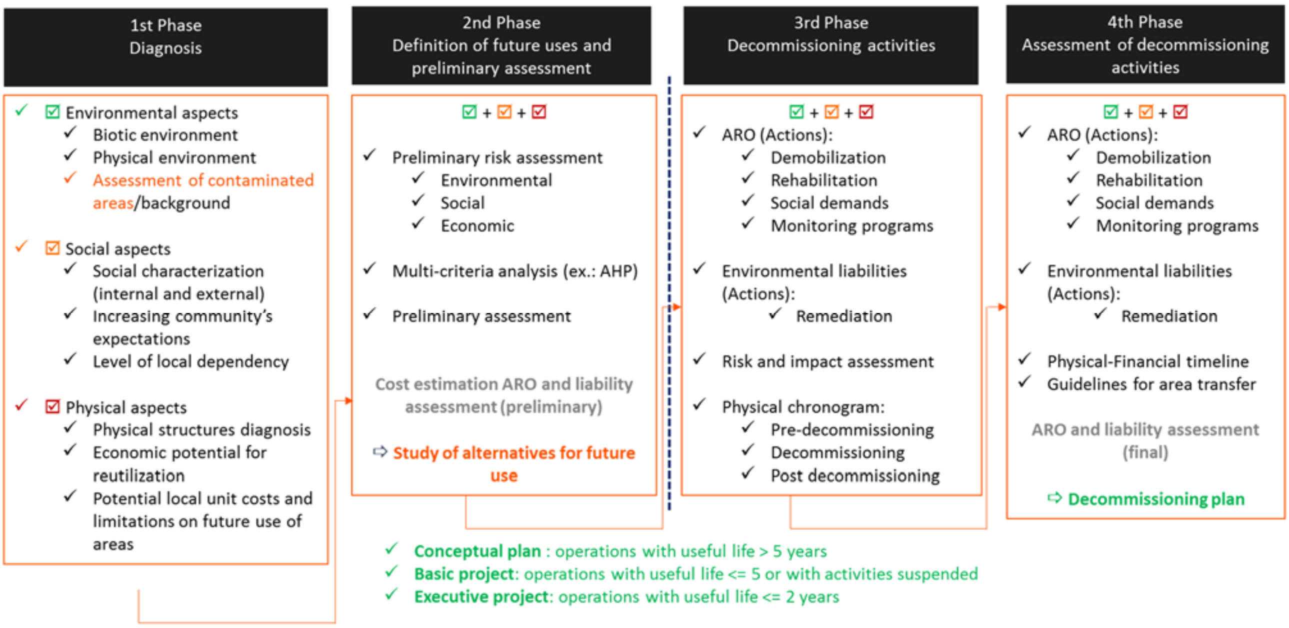

Figure 2 Closure plan preparation stages

3 Data and results

In 2017, Nexa concluded the revision of the decommissioning plans of all units installed in Brazil, and also prepared a study of alternatives for future use for all the units in operation in Peru. Throughout this work, there was also an update in the diagnosis of the area's physical, biotic and socio-economic environment, with the gathering of information on potentials and restrictions in local development in the short and long term. Likewise, an assessment and diagnosis was made of the civil structures and facilities of the unit, verifying which can be reutilized appropriately after deactivation. With this information it was possible to establish a physical financial chronogram for each unit, including the measures for pre-decommissioning, closure and post-closure. All work was accompanied by the Corporate Committee of approval of Closure Plans and Projects, which was restructured in 2017 in order to guarantee the assessment and approval of all elaborated plans and the updated financial resources were included in the company's financial provision. As an example of the progress made in this process, we will present the cases of progress in progressive closure plans of the units of Vazante (Brazil) and Atacocha (Peru).

3.1 Vazante

The evolution of the closure plan of the Vazante Unit, in Minas Gerais, demonstrates how the process was conducted. The start date of the Zinco mining operation in Vazante was 1969 and since then it has been operational with useful life of the Unit. The current forecast, based on probable and proven reserves, has the operation's useful life lasting until 2028, and there are search and quantification activities for more mineral resources that could extend the life of the operation. The current closure plan was based on a diagnosis of the physical, biological and socio-cultural environment that identified the potentials and limitations of the region and began the formulation of a plan for future use of the area. In line with this process, a Social Agenda was prepared, conversing directly with representatives of the communities, public authorities and entities of the civil society, with the aim of preparing a plan of local involvement (this work is can be seen in detail in the chapter on communities).

In the gathering of information, it was recognized that the region had potential for developing activities of ecotourism (taking advantage of the natural potential of caves and grottos of the region), the surroundings (the unit's mining structures) and religious tourism (Feast Day of Our Lady of Lapa). In this context, the current plan envisages an environmental nature (physical, chemical and biological environment) to the recuperative activities of degraded areas, and alternatives of local development after the demobilization of NEXA's assets.

Environmentally speaking, the plan registers constant progress, investment in the last years are little more than 10% of the budgeted value for the next 5 years and have already included (GOLDER, 2018):

- Recuperation of 292 hectares, the equivalent of almost 600 football pitches
- Decommissioning of two old mineral concentrate processing units, including an installation that was not operated by Nexa, but was incorporated in its component area in projects of extension of useful life
- One closed pit and four partially closed, of a total of ten in existence
- Five closed waste rock dumps of a total of eight in existence
- One of the two tailings was closed and de-characterized by the State Foundation for Gerais Mining Environment (Feam)

The vegetation coverage replanted in this area created a favourable environment for the expansion of fauna species and the monitoring of this indicator has shown great progress in the last five years. For example, in the Lumiadeira pit and waste rock dumps LCA 01 to 05, the number of fauna had an increase of 108% for mammals, 140% for reptiles, 174% for birds and 250% for amphibians, between 2013 and 2017. In the case of birds, the number of species almost tripled and currently approximately 17% of all species of the Brazilian mountains of the region are found in this area alone.

3.2 Atacocha

The Atacocha Mining Unit is found in Central Peru, in the Pasco region. It has been operational for more than 80 years and in the last 20, due to the increase in production, it has needed to progressively use tailings, which, at the end of their useful life have begun to be closed. The investment in the progress of closure of these tailings was 35% of the total cost of closure of the Unit. Below is a description of the progress of closure of the tailings at the end of their useful life (GEOSERVICE, 2017).

Malauchaca tailing

The project consisted in the closure of the tailing deposits, where until today the following works were carried out, showing percentage advances.

- Physical stability: 100%
- Hydrological stability: 90%
- Vegetation: 100%
- Geochemical stability: 100%

The project implementation lasted 7 months, starts 02/25/17 and the programed work concluding 09/25/17.

Cajamarquilla tailing

This tailing is completely closed, in compliance with the detailed engineering of Physical, Hydrological and Geochemical stability and vegetation coverage; currently the post-closure monitoring has begun.

Vegetation on basins and slopes:

- Bush vegetation: Chillca (up to 1.00 m in height).
- Creepers: Couch grass (slow-growing and aggressive species).

Species found:

- Species of bush vegetation covering 30% of total Cajamarquilla tailing deposits. Ground-covering or creeper species. Couch grass covers 100% of tailing deposits in the study.

Clover is found in 40% of the total area.

Ticlacayan tailing

The tailing is in the final phase of closure and the Slope has been shaped. The current state of the closure is described below.

Vegetation on berms and slopes:

- Bush vegetation: Chillca (up to 0.70 m in height).
- Creepers: Couch grass (slow-growing and aggressive species).

Species found:

- Species of bush vegetation covering 20% of total dump. Ground-covering or creeper species. Couch grass covering 40%.

Clover is found in localized area, as well as some “ichu” grass, together covering 5% of total area.

Chicrin tailing

The tailing is in the final phase of closure. The current state of the closure is described below

- Vegetation on Slopes, Platforms and Berms.
- Bush vegetation: Chillca (up to 1.00 m in height).
- Creepers: Couch grass (slow-growing and aggressive species).

Species found:

- Species of bush vegetation covering 60% of all Chicrin tailing dumps. Ground-covering and creeper species cover 70% of tailing dumps in the study.

4 Conclusions

The incorporation of mine closure administration in the company’s guideline strategies has standardized the process and methodology of implementation and approval of the Management document, thus guaranteeing the proper closure of each component that is or will be activated (in projects), also guaranteeing the Physical, Geochemical and Hydrological stability and vegetation coverage, which will prevent future environmental alterations. Also included are social issues, aimed at leaving behind a positive legacy after the closure of mining operations. These guidelines define the responsibilities in the elaboration and implementation of the closure plans, which is preceded and directed by the Unit’s highest authority (Unit Manager) and also commits to the revision and contributions to the other areas involved, preventing any greater future alterations of the closure plan. In many cases, objections were raised which undermined the closure; the involvement of the social aspect reduces the vulnerability to social risk that could lead to changes in the closure engineering due to non-acceptance by the surrounding community.

It is also important that the decision to close large scale mining components is made with costs approved by the Board and strategic areas of the company, in order to assess the technical-economic impact this will bring, as well as guaranteeing the best possible definitive closure of the components. Regarding accountancy, the ARO guidelines focus on establishing economic sums that guarantee the closure of components in accordance with the disbursement schedule. These guidelines include legal requirements for mine closure which guarantee compliance with the regulations and avoid financial penalties and fines that would damage the company. The established guidelines define NEXA as being a responsible company, conscious about implementing closures in an efficient and sustainable way. In the coming years, Nexa’s experience could serve as a centre of knowledge and research for other companies in this sector, becoming a model and example at the forefront of mine closures.

It is also important to point out that the guidelines foresee the update of the closure plan with a maximum period of 5 (five) years, giving us the opportunity to update costs and new technologies.

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Benchmarking Closure Provisions

G Byrne *Niboi Consulting Pty Ltd, Australia*

Abstract

Is it possible to benchmark closure provisions amongst mining companies? A high level indicator that can be calculated from publicly reported data has been developed. This indicator, termed the Closure Provisions Ratio (CPR), is a simple measure of the total closure provisions divided by the reported total land disturbance, measured in terms of dollars per hectare. It has the potential to highlight differences in approach and reporting by companies. It also facilitates a focus on what are both real and apparent differences and whether there has been undue conservatism or optimism in developing the closure costs estimates that underlie the closure provisions that have been reported.

A review was undertaken of publicly available data for 57 mining companies, encompassing a range of company sizes, geographies, commodities and mining methods. The data, covering the 2011-2017 period, shows a concentration of CPRs in the $20,000-$60,000/ha range with an median of around $39,000/ha. Notwithstanding, there is a significant range of values, with outliers in the <$5,000/ha and >$100,000/ha ranges.

The CPR is not proposed as a simplistic approach to back calculate closure cost estimates. It is a benchmark and provides a comparison range against which a particular company's CPR can be compared, either with a large population of companies in the sector or a selected group of peer companies. Variation away from the benchmark range does not necessarily indicate that company's closure cost estimates, closure provisions or AROs are in error. What the calculation of the CPR offers is a method to highlight whether questions should be asked or where more detail is needed about a company's closure provisions.

Keywords: *closure provisions, benchmark, closure, rehabilitation, asset retirement obligations*

1 Introduction

Is it possible to develop a useful benchmark for closure provisions amongst mining companies? This paper discusses a high level indicator that can be calculated from publicly reported data. This indicator, termed the Closure Provisions Ratio (CPR), is a simple measure of the total closure provisions divided by the reported total land disturbance, measured in terms of dollars per hectare.

Whilst there are many factors contributing to closure costs, it could be argued that three factors have a major influence for mining and metals companies being, infrastructure decommissioning/demolition, water treatment and earthworks. It can be further argued that earthworks, comprising amongst others, slope reshaping; waste rock and tailings dam capping; and revegetation of all cleared or disturbed areas is the major cost factor for most mining companies. A proxy measure of this cost factor is the total area of land disturbance and hence the basis of the CPR.

The CPR has the potential to highlight differences in approach and reporting by companies. It also facilitates a focus on what are both real and apparent differences and whether there has been undue conservatism or optimism in developing the closure cost estimates that underlie the closure provisions that have been reported. This paper also discusses how a number of variables that influence the data and which may provide reasonable explanations for the provisions varying from the overall median or from selected peer companies.

2 Approach

A web-based search was conducted of 212 companies operating in the mining and metals sector which were considered to have the potential to publicly report the relevant closure data. The search for companies was based on a number of factors, including membership of the International Council of Mining and Metals (ICMM); large well known multi-nationals; mining sector companies listed on the Global Reporting Initiative (GRI) Sustainability Disclosure Database; and companies from a large spread of geographies.

Of these, 57 companies were found to report both the total area of current land disturbance and the amount of closure provisions, or as reported by some companies, their asset retirement obligations (AROs). The remainder did not have relevant data, either because they were not publicly listed, were subsidiaries of publicly listed companies, did not separately report closure provisions or, for most, did not report their land disturbance.

For all of the selected companies the closure provisions or AROs are listed in the financial balance sheet for the particular year of reporting – normally forming a part of the company's annual report. The balance sheet reports total liabilities, both current and long-term. Within the reporting of liabilities there are line items for provisions, which are typically part of long term liabilities although sometimes they are also current liabilities. Included within these provisions are the closure provisions and AROs. For some companies these are alternatively described as environmental rehabilitation provisions or more simply as rehabilitation provisions. Mostly, the closure provisions and AROs are detailed in a note accompanying the balance sheet. For a number of companies, particularly those reporting from North America, the AROs are reported as a separate line item in the main balance sheet.

Reporting of land disturbance figures is typically included by companies in their sustainability reporting for that particular year. For most companies this is a separate report, although there is an emerging number of companies which now publish integrated public reports (that is combined annual financial and sustainability reports). Many companies now report according to the Mining and Metals supplement of the GRI (GRI 2000 and GRI 2013). GRI indicator MM1 requires companies to report on the amount of land disturbed or rehabilitated, more specifically reporting the opening and closing balances for the "total land disturbed and not yet rehabilitated". A number of other companies, whilst not specifically reporting to the Mining and Metals supplement, still report their respective areas of land disturbance.

3 Data

To calculate the range of CPRs, data were collected for the selected companies covering the reporting years 2011 to 2017. Not every company had data covering this entire period for a number of reasons, including their longevity as a publicly listed entity; how long they have been reporting land disturbance figures; and for many companies their reporting year is only current to 2016. However, on average, data are available for a five year period for all companies, with the lowest being two years and the highest being seven years.

Not all data are reported in the same units. For a number of companies, conversions have been made to report land disturbance in hectares. Similarly, many companies report their provisions and AROs in their local currencies. These have all been converted here to US dollars using exchange rates applicable for the particular year of reporting. All financial data in this paper refers to US dollars.

Table 1 summarises the geographic headquarters for the selected companies. These companies range from those with only one operational site to ones with in excess of 100, with the number of operational countries ranging from 1 to 50. Operations cover both surface and underground operations. The average most recent gross revenue is $7.9 billion with a minimum of about $2 million and a maximum of about $153 billion.

Table 1 Selected companies – geographies

Company headquarters	Number of companies
Australia	12
Brazil	1
Canada	12
Czech Republic	1
Hong Kong	1
India	1
Indonesia	1
Israel	1
Japan	1
Norway	1
Russia	5
South Africa	6
Sweden	1
Switzerland	1
United Kingdom	4
USA	8

The company operations encompass both single and multi-commodity organisations, including base and precious metals, coal, iron ore, phosphate, diamonds, rare earths and industrial minerals. Some companies have oil and gas groups, but companies with their primary focus being conventional oil and gas have not been included in this review, mainly because few, if any, of these companies report their land disturbance areas.

A financial factor that is important to note is that closure provisions and AROs are discounted figures. That is, the closure liability estimate for the current disturbed footprint is discounted to the current end of mine life. As such, the closure provision for a particular site is not the same as the closure cost estimate. The implications of the discounting of closure provisions are discussed later in this paper, together with other variables that influence the calculated CPRs.

Similarly, the closure provision is not the same as the regulatory bond or financial assurance that may apply for a particular site. The regulatory bond or financial assurance is an estimate, often using a calculation method required by the regulator, to cover the State's liability should the mining company default on its closure (or more often rehabilitation) obligations. The bond may bear little resemblance to the company's actual closure liabilities.

4 Data Review

4.1 Closure Provisions Ratios

For each company, a CPR was calculated for each year that data were available and the medians were calculated for each company. Figure 1 shows the range of median CPRs for each of the companies with available data. The data shows that the median CPRs range from a lowest figure of \$238/ha to the highest of \$292,742/ha.

The average CPR for all companies over the 2011-2017 period is \$53,990/ha with a median value of \$39,357/ha. Figure 2 illustrates the distribution of CPRs. Despite the significant range of values shown in Figure 1, the distribution of Figure 2 shows that there is a concentration of CPRs in the \$20,000-\$60,000/ha range, with outliers in the <\$5,000/ha and >\$100,000/ha ranges.

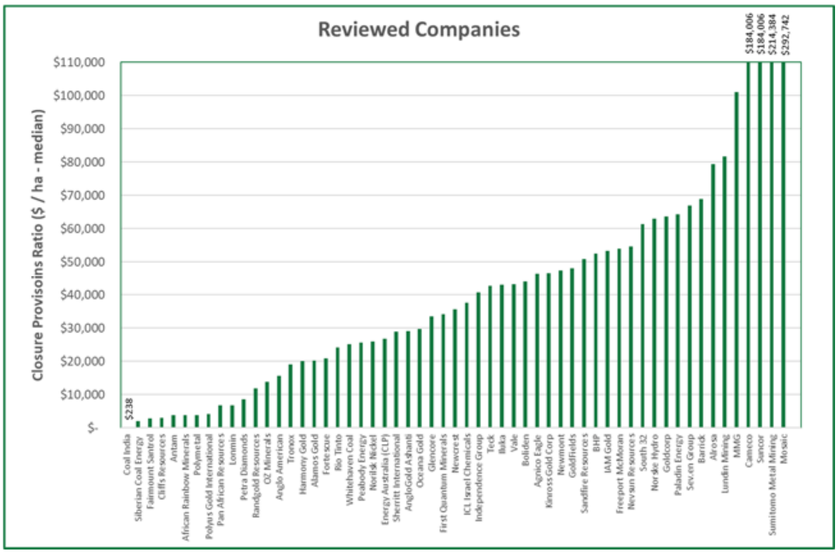

Figure 1 Range of Closure Provisions Ratios

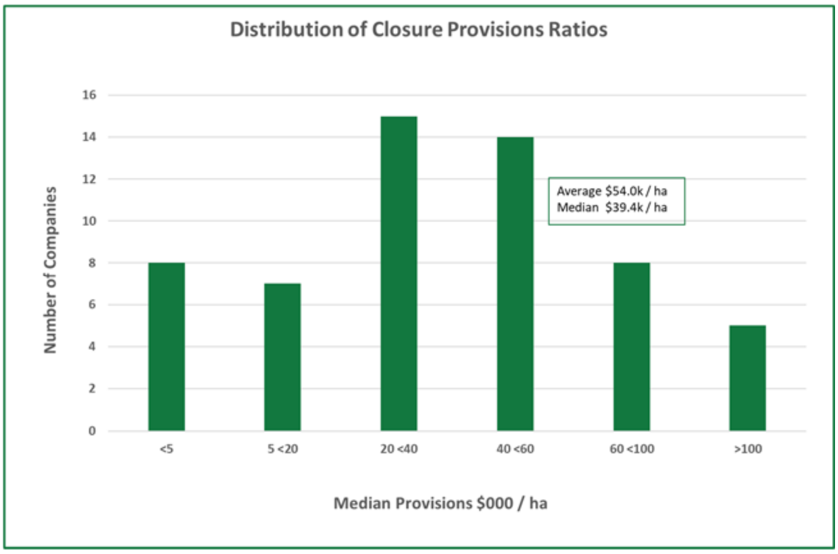

Figure 2 Distribution of Closure Provisions Ratios

4.2 Methodology influences

There are many inputs and variables that form the basis of the calculated CPR. A number of these variables need to be considered when interpreting the CPR values with respect to individual companies. These are discussed in Section 6. There are other variables that have the potential to influence the validity of the methodology for calculating CPRs and include the following:

- Yearly variations.
- Size of the business.
- Number of operations.
- Number of countries.
- Geographic spread.

Because the CPRs have been calculated over a seven year period, the impact on the CPR of cost variations, especially inflation, needs to be assessed. Over the 2011 to 2017 reporting periods the median CPRs for the assessed companies vary between $238/ha and $258,300/ha, but with no consistent increases year on year, which might have been expected if inflation was a factor in the estimate of the closure provisions – see

Figure 3. The variations appear to be more influenced by the mix and number of companies reporting for that year, with inflationary effects either not being a factor or being masked by discounting.

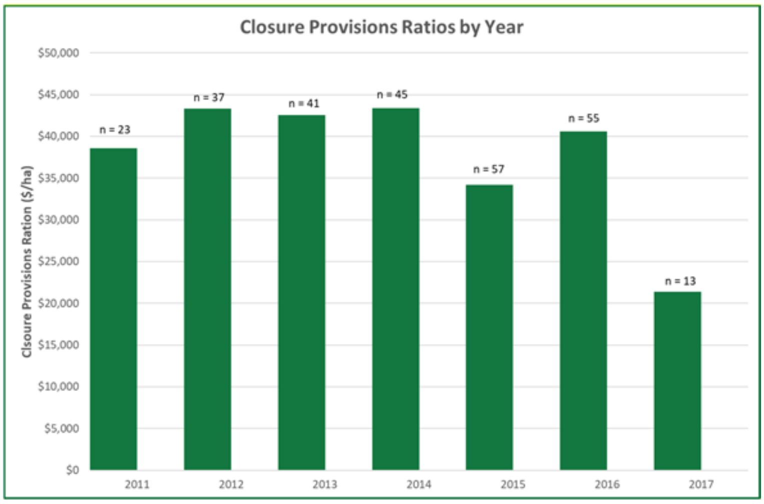

Figure 3 Variation of Closure Provisions Ratios with years

The variation of CPR with the size of business was assessed by adopting the company's most recent annual gross revenue as a surrogate measure of its size. The data are summarised in Figure 4, which show variable median CPRs ranging between around $25,000/ha and $45,000/ha, with no apparent trend according to the size of the business.

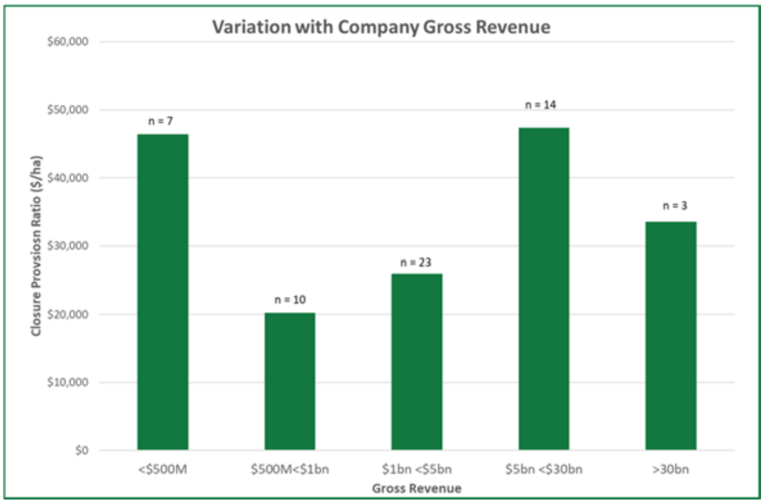

Figure 4 Variation of Closure Provisions Ratios with company gross revenue

Similarly, the variation of CPRs was also assessed against the number of operational sites for each company. The median CPRs ranging between about $27,000/ha and $43,000/ha and with no apparent trend according to the number of operations. Figure 5 shows the results of an assessment of the CPRs against the number of countries in which companies had operations. This indicates that companies which only operate in one country have a lower median CPR than those that operate in multiple countries, although within each grouping there is a large variation, with the highest median CPR for a single country company being a little over $79,000/ha. The lower median CPR for single country operations could indicate a number of factors including economies of scale (if the operations are close to each other) or that international standards of practice for closure are not being factored into the closure cost estimates.

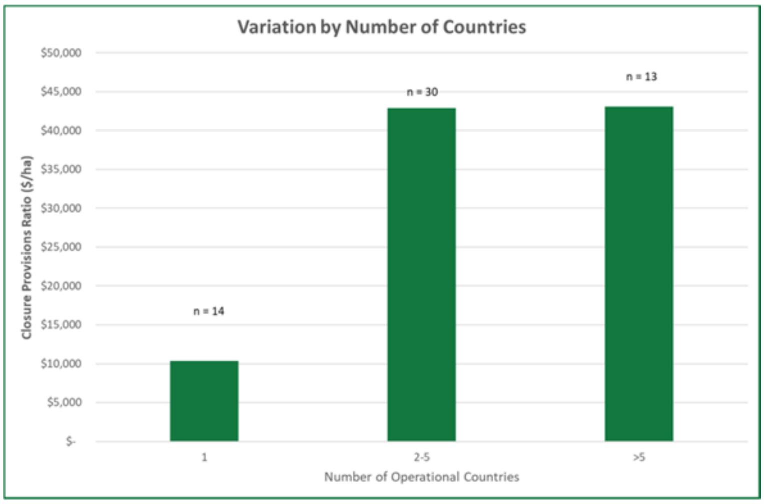

Figure 5 Variation of Closure Provisions Ratios with number of operational countries

A review was also conducted to assess variation of the Closure Provisions Ratio with the geographic spread of operations. This review concluded, however, that such a relationship may not be reliable with the available data. This is primarily because the majority of the companies have operations in multiple geographies and the closure provisions reported in company balance sheets are consolidated, discounted closure liabilities for the entire portfolio of each company's operations. Of the reviewed companies a total of 20 have operations in the same geographic region. Figure 6 compares the Closure Provisions Ratios for these companies. Whilst the sample size is small and therefore reliance on any trends should be treated with caution, it does show differences by an order of magnitude between companies with operations located in Asia and Africa and those with operations in Oceania and Europe.

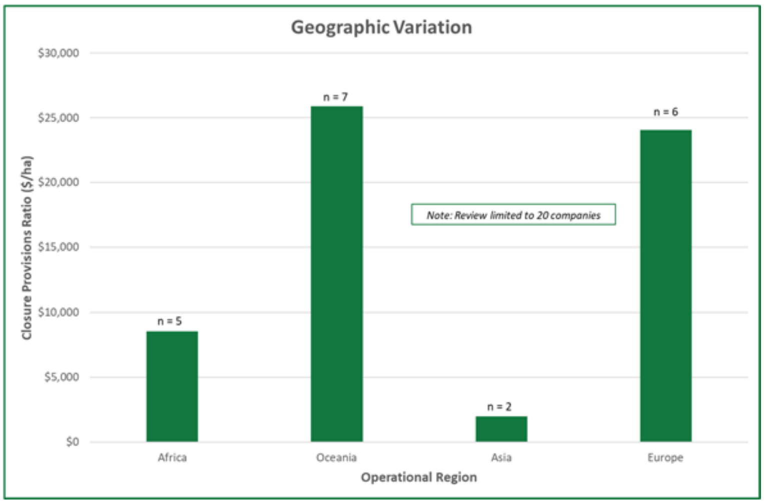

Figure 6 Variation of Closure Provisions Ratios with geographic regions

The data of Figure 5 do raise one obvious question. That is, how can the CPR be applicable to companies with global operations covering many developing countries where costs, in theory, should be lower and therefore the CPRs would be lower? It is considered that theoretically lower cost in developing countries not a valid argument because it is mainly based on the fact that the cost of labour is generally lower. This, however, is not a major influence on closure costs because the latter are heavily influenced by the costs of machinery and equipment. These costs are more influenced by the capital costs of demolition equipment, large earthmoving machinery and water treatment equipment plus the operating costs of fuel, power and consumables rather than lower labour costs. These capital and operating costs are often influenced by global rather than developing country factors. As an indication f that lower labour cost may not be as large an influence as perhaps perceived, of the eight companies with median CPRs of les than $5,000/ha, only three are from countries than might be considered as developing (India, Indonesia and South Africa); three are from Russia; and two are from the USA.

The overall conclusion is that the variables of yearly cost variations, business size, and number of operations do not have any undue influence over the applicability of the CPR across mining companies in the mining and metals sector. There may be lower CPRs for companies with operations in a single country, although the variation in CPRs for those companies is large and therefore it is considered that this variable does not impact the applicability of the CPR.

5 Use of the Closure Provisions Ratio

A relevant question to address is what use is the CPR? Why is there any use in having a benchmark for closure provisions and are closure provisions and AROs important? The mining and metals sector is unique in that closure and rehabilitation obligations form a significant component of the valuation of any company. Of the 57 companies assessed, the closure provisions averaged 12% of each company's total liabilities, with a range from less than 1% to greater than 60%. Clearly this proportion of the total liabilities is influenced by other liabilities, most notably debt, but it can be seen that for many mining and metals companies, closure provisions and AROs are a significant factor in their overall valuation.

Therefore, for those assessing mining and metals company valuations, having a benchmark against which to compare closure provisions and AROs could be a useful tool for analysis, particularly when the detail behind the closure provisions is often absent in the public reports. The CPR could be of use to potential investors, existing shareholders, financial journalists and analysts who wish to investigate the background to mining company valuations in more detail. This is especially the case where the closure provisions are a significant component of that value.

The CPR may also be of use for accounting and financial personnel within a mining and metals company. They may wish to use it as a benchmark to "reality check" their own closure provisions as a means to question site data on closure costs, which could be the case where the company has a multi-site portfolio or where there is complexity with joint venture arrangements. In a similar manner, the CPR may be of value to financial auditors when reviewing company financial statements. Finally, the CPR could be used as a yardstick for advisors and consultants involved in acquisition, divestment and IPO processes, to highlight potential areas relating to closure liabilities that warrant further investigation.

6 Interpretation of the Closure Provisions Ratio

The CPR provides a comparison range against which a particular company's CPR can be compared, either with a large population of companies in the sector or a selected group of peer companies. It does not necessarily mean that if a company's CPR is close to the mean or within the range reported by many others that this company's closure cost estimates, closure provisions or AROs are "correct". Similarly, it does not mean that if a particular CPR is towards the extremes of the range that the closure cost estimates, closure provisions or AROs are necessarily "incorrect".

The CPR is a benchmark. It is not a simplistic approach to back-calculate closure cost estimates. The CPR is designed to be used to a means to highlight whether questions should be asked about the reported closure provisions or whether more detail is needed. It is possible that the answers to such questions might provide perfectly reasonable explanation for any variation from the median value reported in this paper, or a range calculated for a peer group of companies.

How can the CPR be interpreted and what are the factors that might influence its variation? The key influences should be evaluated in a sequence that reflects their potential impact on the CPR, as follows:

- Asset life – are there sites which have short remaining asset lives and therefore result in a higher CPR or conversely are very long life asset assumptions leading to low CPRs?

- Basis of closure cost estimates – are the individual site closure cost estimates based on reasonable assumptions or are they too optimistic?
- Footprint characteristics – have the disturbed land areas been accurately and properly reported?
- Discount rates – do higher or lower discount rates lead to variable CPRs and is the adoption of those discount rates reasonable?
- Financial obligations – what obligations are required to be included in the provisions and have they been appropriately accounted?
- Risk cost accounting – are risks required to be included in the provisions and have they been appropriately accounted?
- Abnormal conditions – have abnormal or unusual circumstances for a particular year or group of years affected the calculated CPR?

6.1 Asset life

Differences in the CPR may be caused by variations in the asset lives of different companies. Two sites with similar current closure cost liabilities may have significantly different closure provisions because one site may be very close to the end of its asset life, whereas the other may have many years, or even decades of remaining life. A longer residual-life site could have a much lower closure provision because discounting over its longer life will have a greater influence than the discounting for a shorter residual-life site.

The lower closure provision clearly results in a lower CPR. It is therefore important to understand the mix of assets making up the company and the influence that remaining asset life assumptions have on the CPR.

6.2 Basis of closure cost estimates

A very significant factor in the variation between CPRs are the data and bases for the closure cost estimates developed for individual sites. It is not common for the closure cost estimates that form the basis of the closure provisions to be publicly available. Therefore, it is difficult to interrogate the validity of those estimates – indeed it is one of the key reasons for calculating the CPR.

The CPR may, however, provide some insight as to whether reasonable assumptions have been made to develop each site's closure cost estimates. For many companies their closure costs are based on detailed closure plans, well considered assumptions, sound judgement and incorporation of risk costs. These closure costs have a level of conservatism that appropriately reflects the uncertainties associated with estimating costs for activities that may be many years into the future and for which little back up information may be currently available. It is unlikely that these companies will have low CPRs.

Sometimes, although not very often, there is too high a level of conservatism built into closure cost estimates. Such conservatism might relate to where uncertainties exist around quantities, volumes, rates and risk events. The person developing the cost estimate might base it on the high end (or even extreme end) of the uncertainty ranges for various cost components and may decide to include the full cost of risk events assuming that they all occur.

There are other companies where their closure cost estimates are influenced by optimism and where there is a likelihood of lower CPRs. They often have closure cost estimates based on assumptions that are unlikely to come to fruition, examples of which are:

- There is sufficient topsoil and/or capping material.
- The tailings storage facility and/or waste rock dumps will only require minimal capping thickness.
- There will be no maintenance required after the closure execution phase and there will be no need for long term water treatment.
- Monitoring will only be required for limited period (~ 5 years) and it will not identify any problems.
- Demolition costs will be offset by scrap values.

- There will be regulator / community acceptance of final landform and/or pit lake water quality.
- Existing mine equipment and contracts will be suitable for closure execution.
- The local community will not remember any verbal closure commitments that have been made over the mine life.
- Social transition costs do not form part of the company's closure liabilities.
- Ignore all closure risks in the closure cost estimate – i.e. assume that none of the risk events occur.

The variation of the CPR away from a chosen benchmark may therefore flag issues caused by an inappropriate influence of optimism or conservatism in the closure cost estimates which underlie the reported closure provisions.

6.3 Footprints

Disturbed footprint is one of the two parameters in determining the CPR and therefore differences in disturbed footprint will be a direct factor in CPR variation. A number of factors can influence the reported disturbed footprint and are discussed in the following paragraphs. The relative proportion of "industrial" (smelters, manufacturing, offshore platforms, etc) assets to mining assets could influence the calculated CPR. These industrial assets might have relatively high closure costs due to high decommissioning, decontamination and demolition costs but have a smaller disturbed footprint compared to a large open cut mine with large areas of disturbance. A company with a greater proportion of these assets within its portfolio might have a higher rehabilitation cost per hectare of disturbance and hence higher CPR.

Companies with significant progressive rehabilitation in progress will have disturbed footprints at various stages of rehabilitation. For example, newly disturbed ground will have a higher rehabilitation liability than disturbed ground that has had earthworks and seeding completed. The CPR will be influenced by the relative mixes of rehabilitation stages within a site and within a portfolio of sites. Different companies may report land disturbance in different ways which could result in CPR variations. This is less of an issue with those companies reporting to indicator MM1 of the GRI, which defines the type and manner of land disturbance data to be reported. Companies having joint venture operations within their portfolio, and for which they do not have operational control, rely on the operating entity to supply them with data, including land disturbance information. For those companies with numerous such operations there may be inconsistencies in the definition and/or time periods of that land disturbance by their joint venture partners. Such inconsistences may lead to some variation in the calculated CPR.

6.4 Discount rates

CPRs may also differ between companies due to the adoption of different discount rates. Sometimes the discount rate that has been used for calculating the closure provisions is reported within the notes to the financial statements. The effect of different discount rates can be significant. Some companies adopt market-based discount rates, others adopt a rate that reflects their investment returns. It is important to note that the discount rate adopted for the closure provisions is not the same as the discount rate that the company might adopt as an investment hurdle for evaluating potential new projects. In the latter circumstance a high discount rate is a conservative approach to measure investment return, whereas when calculating the closure provisions that higher discount rate is likely to be speculative. The adoption of different discount rates could also be due to differing policies and approaches to market risk between companies; different applicable interest rates across different geographies; or different interest rates dictated by different accounting standards (e.g. IFRS vs US GAAP). It is therefore important to understand what discount rates have been used for the closure provisions and whether there have been significant changes from year to year.

6.5 Financial Obligations

Companies reporting to the International Financial Reporting Standards (IFRS) are required to include in their closure provisions present obligations, comprising both legal as well as constructive obligations. There may be differences in the interpretation of the latter, and therefore whether or not they are included in the company's closure provisions. Companies reporting to the US generally accepted accounting principles (US GAAP) could report different elements in their provisions to those companies reporting to IFRS, particularly relating to constructive obligations. There may also be different interpretations by companies about their closure obligations. Some companies may acknowledge that they have closure obligations due to broad corporate commitments or verbal commitments made to various stakeholder groups during the mine life. Other companies may take a less conservative approach. Often companies do not include social commitments relating to closure in their closure cost estimates.

6.6 Risk Cost Accounting

Some companies include risk event costs within their closure provisions, other companies ignore them altogether. Even for those companies which include risk event costs there could be different interpretations as to how probable and measurable those risk event costs are – and therefore whether or not they are included in the closure provisions.

6.7 Abnormal conditions

Within individual years of reporting there may be abnormal activities and/or conditions that have an impact on that year's calculated CPR. These could include for example, the impact of acquisitions and divestments that have been made in the year of reporting. Another cause may be an inconsistency in the reporting periods for provisions and land disturbance, such as the financial reporting year being July to June and the land disturbance reporting being on a calendar year basis. The impact of such inconsistencies is reduced when data, as well as calculated CPRs, are assessed over a number of years, this smoothing out the effect of "one-off" differences.

7 Conclusion

The CPR, is a simple measure of the total closure provisions divided by the reported total land disturbance, measured in terms of dollars per hectare. It is high level indicator that provides a benchmark of closure provisions amongst selected peer or whole of industry companies and is developed from publicly reported data. A review of 57 companies covering the 2011-2017 period shows a concentration of Closure Provisions Ratios in the $20,000-$60,000/ha range with a median of around $39,000/ha. Notwithstanding, there is a significant range of values, with outliers in the <$5,000/ha and >$100,000/ha ranges. The CPRo is not proposed as a simplistic approach to back-calculate closure cost estimates. It is a benchmark and provides a comparison range against which a particular company's Closure Provisions Ratio can be compared, either with a large population of companies in the sector or a selected group of peer companies. Variation away from the benchmark range does not necessarily indicate that company's closure cost estimates, closure provisions or AROs are necessarily in error. What the calculation of the Closure Provisions Ratio offers is a method to highlight whether questions should be asked or where more detail is needed about a company's closure provisions.

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The Development of a "Mine Life Cycle Information System"

P Goerke-Mallet *University of Applied Sciences Georg Agricola, Germany*

A Müterthies *EFTAS Fernerkundung Technologietransfer GmbH, Germany*

C Melchers *University of Applied Sciences Georg Agricola, Germany*

Abstract

Mining processes take place within a framework of processes characterised by exploration, production and decommissioning. The closure or post-mining process typically takes the longest time within this framework. This mining life cycle (MLC) is also characterised by different information requirements. Overall, one can note that the required information needs to be supplied as early, reliably and economically as possible.

Within the phases of exploration and production, the information exchange is defined by the enterprise process, governmental requirements and policies as well as information requirements of the public and involved stakeholders. The availability of expert staff can be assumed as given within these phases. In the post-mining phase these framework conditions change. There is a lack of staff and know-how. The responsibilities are potentially unclear and there is a lack of reliable data.

Since 1865 the Federal Republic of Germany has had a legislative framework for mining processes in place. The entrepreneur's responsibility in the post-mining phase has further been specified by the Supreme Court within the last 20 years. Despite this national framework a number of regions still suffer from a lack of data and unresolved issues related to post-mining.

In many cases, acting responsibly to protect both the surface close to former mine works and the environment, and to create resilient future systems in former mining regions is only feasible through large amounts of funding. Our understanding is that many regions of the world suffer from the lack of usable data, data which would be essential for risk management and rehabilitation processes of former mining areas. This is in parts due to a discontinuous flow of information and insufficient availability of relevant data.

The development of a concept for an MLC information system is therefore deemed viable both from an economic perspective but also with a view to the public understanding and acceptance of mining projects at large. This information system contains all data which has been gathered within the MLC framework – a geo-IT network in which all data has a location and time reference. This database would be populated with all written and cartographic documents as well as monitoring measures and verbal reports. Furthermore, the system should utilise the potential of innovative methods of remote sensing, positioning and space detection and geophysics.

The aim is to provide an accessible database system for all involved actors and stakeholders which will assist the handling of post-mining processes in a successful and economical manner and within an adequate timeframe whilst maintaining general acceptance.

Keywords: *post-mining, geo-data, risk management, closure planning, stakeholder*

1 Introduction

Exploiting the earth's resources by mining, agriculture and fishing is economically referred to as primary production (primary sector) (Ramb 2018). Making use of the earth's surface and depleting ground resources are factors of production. It can be assumed that in nearly every country of the world mining activities are being undertaken at different levels of intensity. Currently, the annual global mining production amounts to c. 35 bn tons. In other words, the specific worldwide production is approximately 5 tons per head per annum.

In Germany, the output of mining resources is around 750 m tons per year (VRB 2018). Hence, Germany is a mining country of a long tradition which began more than 1,000 years ago: such a long continuous period of operation, for example, is said to be true for the ore mine Rammelsberg in Goslar, Lower Saxony (Bergwerk Rammelsberg 2018). This fact also means that Germany is facing a substantial legacy of old mining and post-mining challenges that need to be tackled (Fig. 1). Looking at the global distribution of mining processes these challenges are being faced worldwide.

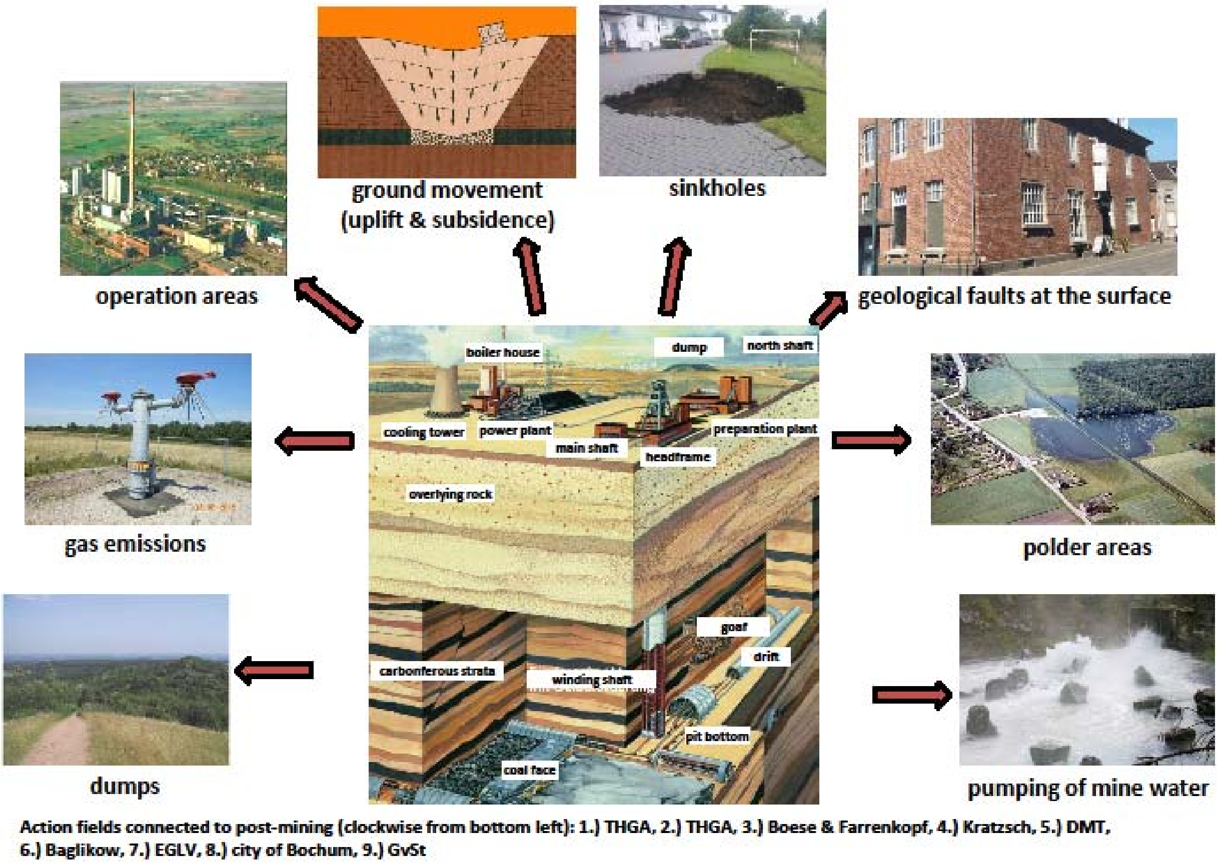

Figure 1 Action fields connected to post-mining

2 Mine Life Cycle

The phase of mine closure and post-mining comes at the end of the mining process. Experience has shown that this phase is the longest-lasting in the mining life cycle; compared to post-mining, the phases exploration and production are usually considerably shorter.

The mining life cycle is characterised by different demands for information. For example, exploration is based on geological recording and forecasting, data of geophysical measurements, drilling results and mining permissions. The data available are particularly characterised by geological information on the deposit and the surrounding rock and strata. Even in the first phase of the mining process there is considerable need to store factual information with temporal and spatial referencing.

The core phase of the mining life cycle is made up of the economic process of exploiting resources. Here, the information need is defined by the entrepreneurial process which mainly consist of an optimal company management regarding economic, ecological and social matters. To achieve that, data on the technical condition of the mine, the deposit, the legal situation regarding permission and the environmental impact have to be regularly updated. Usually, authority requirements and the information demand of the general public and the stakeholders are the major reasons for providing an organised amount of data.

In this context it is notably important that the availability of specialist personnel can be taken as granted during the phases exploration and production; disregarding the technical solutions to ensure access to operational data, the knowledge and experience of staff provide the essential basis of the company's operability (Melchers and Goerke-Mallet 2015).

Principally, we need to state that the required information has to be provided as early and reliably as necessary and as economically as possible. The information demand often follows current issues: long-term perspectives might not be pursued and thus not accepted or perceived as a challenge.

When a mine is closed, those frame conditions change fundamentally. No resources are exploited any longer, and no sponsor is in place. The financial means of a company are then mostly shaped by the provisions it was able to build in the past. Specialist personnel is moving to other countries and industries due to a lack of job opportunities: this results in a considerable loss of knowledge and experience. The changes that come along with that development lead to a lack of clear accountabilities and thus to problems in communication. There is considerable lack of reliable available information, something that hampers the process of finding solutions and leads to a delay and a dilution of decisions.

At this phase of the mining life cycle, sustainable management of post-mining challenges can only be ensured if it is based on a reliable information system. The term sustainability is used on purpose: it illustrates the aim to manage the aftermath of mining taking environmental, economic and social matters into account.

3 Closure planning

Mining processes are not possible without interfering with the environment. We firmly believe that any successful mining enterprise also needs to include an intensive discussion of the legacy and a viable conversion. This process aims at creating new prospects for the affected region and thus has to be discussed at a high level of informal exchange with all stakeholders. Such discussions need to include how to create new jobs in surroundings worth living in, and how to protect the surface of former mine workings and all environmental goods. In many cases, taking on that responsibility of protecting the surfaces of former mine workings, the environment and of creating resilient prospects in former mining regions is only feasible if high amounts of funding are provided. Where the aims of authorities and the general public are not in line with the economic opportunities or ideas of the mining companies, conflicts of interests will occur.

Such conflicts can be observed around the world. In the Federal Republic of Germany, many of those are resolved due to mining law regulations and court rulings. Since 1865, a legal framework specifically defined for mining has been in place, and the entrepreneurial responsibility for the post-mining phase has been rendered even more precise by rulings of the supreme courts over the last 20 years. To tackle the perpetual tasks after the closing of the subsidised hard-coal mines in Germany from 2019 onwards, specific financial means have been provided. For example, the costs of long-term mine water retention in the underground mines of RAG AG and the dry-keeping of the polder areas in the Ruhr area are funded by the foundation RAG-Stiftung which was founded in 2007 (Melchers et al. 2015). The annual expenditure for those perpetual tasks is said to be €220m p.a. Those costs are borne by RAG-Stiftung from its proceedings of its wide range of participation in different companies, most notably in Evonik Industries AG.

Since the 1960s hard-coal mining in Germany has been in the state of continuous decline leading to closure. The insights gained during that long period clearly prove that no sustainable closure and phasing out of mining is possible without a reliable information platform. For example, any safe underground water retention can only be planned and implemented using complete mining charts and map series. Without knowing the mine works and the underground flow paths of mine water, there is the risk that unpredicted accumulations of standing water occur which may lead to sudden water inrushes in operating areas.

In Germany, the mining charts and maps have been managed by mine surveyors over more than 150 years due to legal requirements. Once a mine is closed, the documents are archived and made available either at the responsible mining authority or in a public archive.

Disregarding this particular national resource, there still exist information deficits in certain regions when trying to resolve issues of old mining and post-mining. Thus, at national level too, the request has been brought up time and again to provide an optimised platform for long-term storage and provision of data that are relevant for the post-mining phase. In our opinion, the answer can only be the introduction of a geographic information system, a system that is essential for the successful management of each phase of the entire mining process.

We have noticed that many regions around the globe, e.g. South Africa, Australia and the United Kingdom, lack insights and usable information for the closure and post-mining phase – information that is required for both risk management and the reutilisation of former mining areas.

There are a number of reasons for that; we see the key issue in the fact that the mining life cycle is not seen (or cannot be seen) as a comprehensive whole. However, without taking a holistic view, the missing continuity of information flow and the insufficient recording and availability of relevant information and data cannot be realised.

For that reason, we regard the development of a concept for an MLC information system as paramount, for economic reasons as well as for ensuring a societal acceptance of mining projects. This approach needs to be seen against the backdrop of the growing public information need which goes hand in hand with modern monitoring technology. Looking at recent development in digitalisation and the Internet, it becomes obvious that a very high level of transparency is expected from mining projects exceeding the sphere of the people directly affected, in other words, those living in the mining regions.

The information system to be developed must contain all data that have been compiled as part of the MLC. It is a geo-IT network in which all data are time- and location-referenced.

All information available from written and cartographic documents as well as monitoring measures and oral accounts are entered into the system; for that purpose, the potential of innovative methods of remote sensing, position and space detection and geophysics are to be utilised.

The aim is to create an information platform which is accessible to all actors and stakeholders alike and which can be used to handle the post-mining processes in an economical and timely fashion – if that is done successfully, then general acceptance will be maintained.

4 The Digital Service Archive

4.1 The information base of RAG AG

When subsidised hard-coal mining was being phased out in Germany, the operating range of Germany's largest hard-coal producer, RAG AG, changed significantly. This company is the successor of the former Ruhrkohle AG, which was founded by a merger of 23 mining companies in 1968 to respond to the deteriorating economic conditions in the mining industry. RAG AG is facing issues that relate to developments which occurred in the past 100-150 years. Since the production of hard coal ceased, the operating business of RAG AG has moved on to long-term water retention above and underground, settling mining damage and the reutilisation of former mining areas. At the heart of all those operating activities lies knowledge management. During the next years, this knowledge will be provided by specialist personnel, but their number will decrease: from 2022 onwards, RAG AG will have less than 500 employees. This enormous downsizing will also lead to a loss of specialist knowledge that was acquired over a long time.

Therefore, roundabout ten years ago, the company identified the task to ensure future information and decision-making abilities as a strategic issue. To enable transparency and guaranteed access to existing information, the initiative was taken to set up a platform for future geospatial issues (Fig. 2). This project was called DSA – Digital Service Archive – and has been developed over the last years to become the operating key instrument of efficient and comprehensive data provision across disciplines and across organisations (Koslowski and Vosen 2012).

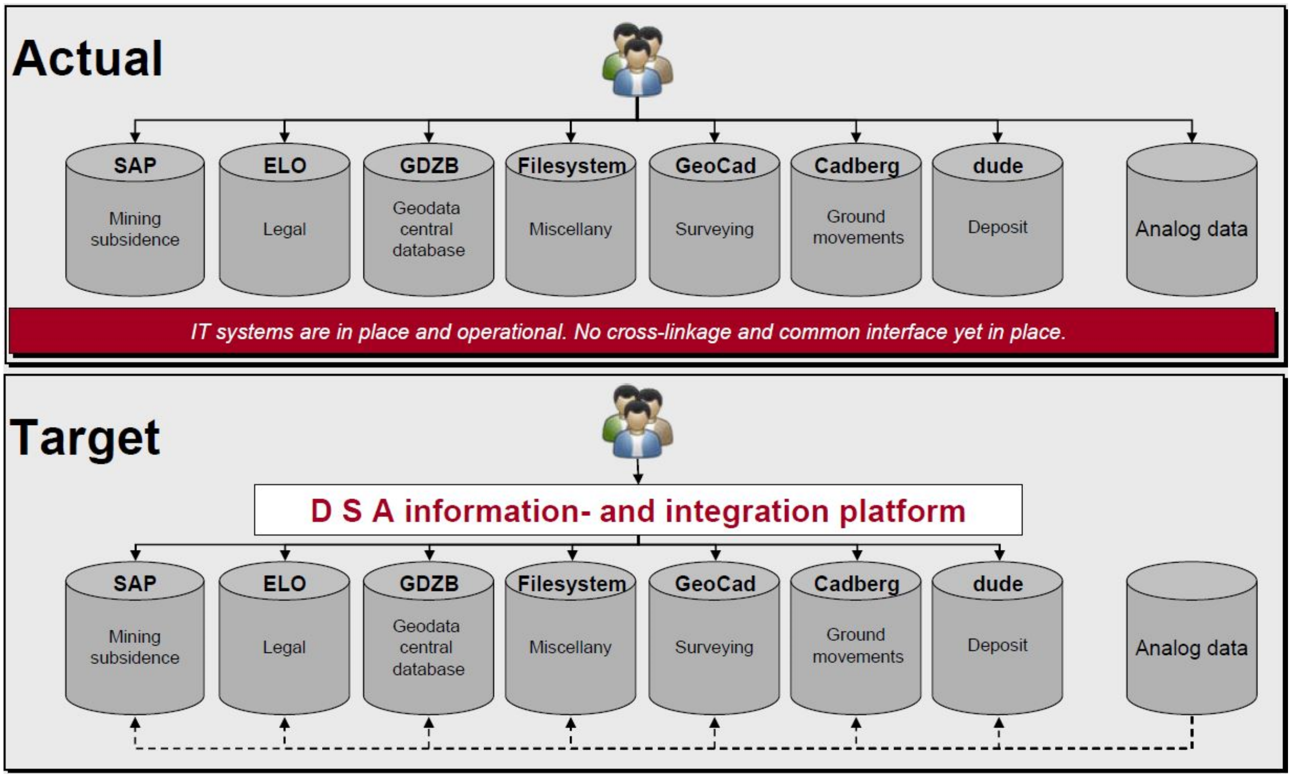

Figure 2 Spatial data of RAG (actual phase and target state) (© Vosen)

The spatial data are used to resolve issues of mine surveying, mining damage, real estate and mine water. The information needed to tackle these issues are stored in different EDP systems at different organisational units as well as in several analogue (paper) archives (Koslowski et al. 2014).

At the moment, the company is administrating a volume of more than 40 terabytes of space-referenced digital data. To this volume we need to add a length of 8km of files which in the future are going to be digitised on demand and integrated into the DSA. For example, the DSA enables access to the archive of charts, maps and aerial images which accommodates more than 100,000 maps and aerial views (Koslowski et al. 2014).

Besides classical GIS data there exist a lot of documents and electronic files which contain spatial references as full text such as the names and addresses of former mine shafts. Currently, the digital service archive (DSA) is the intranet portal of RAG for the long-term use of geo-data and other data sources. As with any other modern map service, the DSA material can be used to carry out spatial analyses and map representations. Moreover, the different data containers of the specialist departments can be searched for full-text entries, too. Not only GIS or CAD data are searched when entering a request, but also other sources such as Office documents, ELOs (electronic archives) or SAP (technical places, real estate and mining damage) (conterra 2018).

The DSA is available to all employees in the group as it has been set up as a web application in the company network of RAG based on existing GIS and search technology (ArcGIS, Microsoft SharePoint), taking into account access rights concepts that were already in place. The special features of the DSA are its flexibility and extensibility and the fact that no new data format was generated. Its major use is to provide structured access to unstructured data (Koslowski et al. 2014).

Discussions with project managers and users emphasise that the use of the DAS has significantly improved the transparency within the company regarding data generation and administration. The exchange of experience has also shown that systems of simple structure lose performance after a short time and are then no longer accepted (and used) by the users.

4.2 New possibilities for data updates and monitoring

The questions remaining are the following: How can we ensure updates of all data to meet requirements of users after hard coal production is ceased and despite limited financial and personnel resources – which include the limitations of expert knowledge? And, on the conditions given, how can we in particular meet the extensive monitoring obligations of the post-mining phase defined as a perpetual task in the former Ruhr coalfield, for example, the observation of ground movements? Linking all existing information, for example, as done by RAG with the compilation in its DSA, with up-to-date information of the new European system for monitoring environment and protection, Copernicus, will provide an important contribution (Fig. 3).

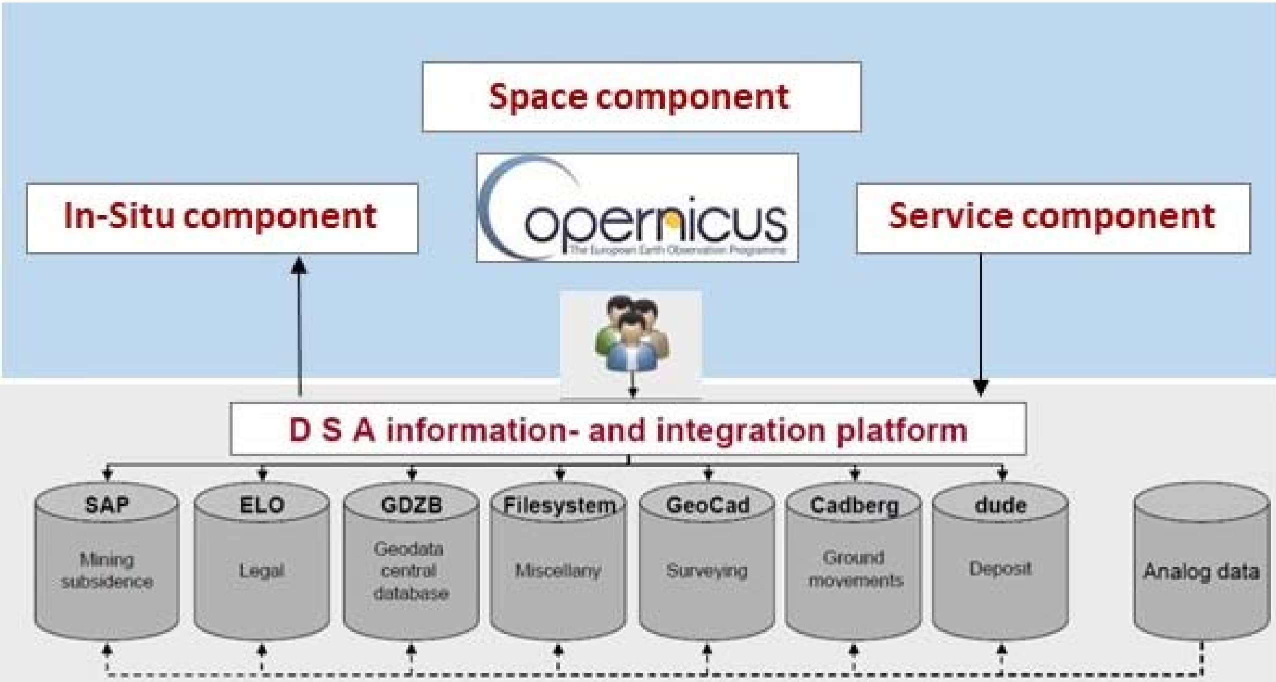

Figure 3 Integration concept DSA-Copernicus (© Vosen, added)

Copernicus is a joint initiative of the European Commission and the European Space Agency and provides a huge number of data and services for environment and protection monitoring free of charge. The up-to-date information needed to do so is provided by the space component which consists of the Sentinel satellites specially built for the Copernicus programme, and other satellite missions which contribute to its services. For example, Sentinel 1 has been providing radar data since 2014 which have been used – among others – by the ground movement office in Germany, part of the Federal Office for Geo-sciences and Raw Materials BGR, to monitor ground movements. In addition to the space component, the in-situ component provides central access to all data not generated by satellite. The service component provides services for joint evaluation of data supplied by the space and in-situ components. During the set-up phase of Copernicus, pilot projects run by companies such as Terrafirma and GMES4Mining helped to early prepare the utility of Copernicus for the entire mining life cycle (Garcia-Millan et al. 2014). A full-scale use of the Copernicus potential, however, requires further development of the downstream services which generate specific information, for example, for the post-mining monitoring tasks, from the core services developed so far. This development also requires cross-linking the mining specific data of, for example, the DSA, with the in-situ component. This link could help, for example, to weekly examine the mining elements (shafts, polder areas) reference in the DSA for ground movements using Sentinel 1 which would allow to early recognise any dangerous situations. In addition to the example of ground movements, such a combination of mining elements, possible incidents per element and the measurable parameters would also allow to identify further potential of Copernicus for the entire mining life cycle which could be used to develop the services further (Goerke-Mallet et al. 2017). Thus, an MLC information system would receive a much higher level of up-to-dateness and generate significant added value for its users.

5 International concepts for Closure Planning

In international mining, reflections of the mining life cycle and a structured management of the closure phase play an important part. With its Mine Closure Toolbox (Anglo American 2013), which has now been released in its second version, one of the globally leading mining groups, Anglo American, shows its awareness of the strategic impact of closure planning. The toolbox, it is claimed, increases the emphasis on the importance of designing, planning and operating a mine with closure in mind. The close consultation with communities, the decrease of closure liabilities and the reduction of overall costs of closure are the targets of the toolbox.

The Mine Closure Toolbox consists of three duties: strategic planning for mine closure, quick assessment of the status of a mine's existing closure plan and filling the gaps in the closure plan. The common thread is formed by environmental and economic knowledge and the permanent risk and opportunity rating. The Mine Closure Toolbox is seen as complement to the existing management processes at the operation. From this point of view, a Mine Life Cycle information system should be put to full use in order to fill or even avoid gaps in the planning of all phases of the mine life cycle.

Another paper describes the point of view of a mining authority. The "Strategic Framework for Managing Abandoned Mines in the Minerals Industry" (Ministerial Council on Mineral and Petroleum Resources (MCMPR) and the Minerals Council of Australia (MCA) 2010) has the aim "to encourage a strategic approach to abandoned mines management, which promotes efficiency, sustainability, innovation and consideration of the unique assets and community values for each mine". The concept highlights the number of thousands of abandoned mine sites of varying size and complexity across Australia. Each site, it is stated, is unique and may present a variety of environmental and safety risks, cultural values and future opportunities.

To promote a strategic approach to managing abandoned mines is the aim of the Strategic Framework. The focus is on risk minimisation, efficient and sustainable management and a recognition of the values associated with these sites. The framework addresses issues such as site inventories and site data management. It is emphasised that the challenges are to find innovative solutions for protecting the multiple values of abandoned sites while ensuring that risks to public safety and the environment are managed appropriately and to implement effective rehabilitation with limited resources.

As the report goes on it points out that site assessment, data collection and data management are perhaps the most important steps in the management process. Knowledge of site history can be an invaluable element in this process. A comprehensive database, incorporating detailed site information, risk data and strategic planning information, is fundamental to the long-term management of abandoned mine sites, so the tenor of the framework.

In connection with Geographic Information Systems (GIS) the paper assumes that geospatial references have to be collected for abandoned mine sites and that GIS is a useful tool for the effective management of large data sets.

These two examples may demonstrate the assessment of two different institutions in terms of closure planning and the management of abandoned mine sites. In both cases the importance of reliable data of the specific site are emphasised. The aim of both institutions can obviously only be reached by a long term and consistent collection of space and time-based data. For this reason, we need to establish a "Mine Life Cycle Information System".

6 Conclusion

Mining undertakings are always both: cost- and time-intensive. In order to design all processes within a mining life cycle effectively, economically and environmentally compatible, continuous knowledge management is to be implemented in addition to operating processes. It can be observed worldwide that the increasingly complexing issues of mining projects need to be addressed timely and purposefully. The successful design of any mining project requires the availability of a Mine Life Cycle information system that will be successively further developed as part of knowledge management.

The data moved within knowledge management are stored with a space and time reference. Given the GNSS methods available today the determination of surface 3D-coordinates does not provide any problem. As for all operating processes, knowledge management should also be handled professionally which means sufficient staffing as well as continuous processing and entrepreneurial appreciation of the task.

This context requires a professional and specialist discussion of the system which Germany's largest hard-coal producer, RAG AG, has developed over the last years. This Digital Service Archive (DSA) is to provide data with 4D-reference on a permanent, cross-disciplinary, timely and reliable basis. As mining activities are always relevant to the space around them, high-quality answers to spatial questions have to be found in the long run. The principal ideas of the DSA architecture are trailblazing and can be put to use when developing similar systems.

The Mine Life Cycle information system is to ensure the ongoing and timely information and decision-making abilities of any mining company based on resilient data. Such a system is important in all phases of the mining project. Looking at the impact which any mining project has on its surroundings, its economic success needs to be seen against that backdrop: because the post-mining phase can only be managed successfully if planning and operation are based on facts which have been compiled in the previous phases. The Mine Life Cycle information system can be compared to the foundation of a building: if you fail to build strong foundations, there will be no way or only a very expensive one to correct such mistakes later on.

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Achieving Sustainable Outcomes of Mine Closure in Developing Countries through Inclusive Agribusiness

MJ Kauthen *Business for Development, Australia*

Abstract

*As part of the mine closure process, one of the most important legacies a mining company can leave a local community that has productive agricultural capacity is linkages to a commercial market, independence from the mining company, and the governance structure to be scaleable and self-sustaining. This paper aims to build knowledge on the potential role that Inclusive Agribusiness can play in the mining industry's community development programs. It proposes that establishing an Inclusive Agribusiness as part of the partnership dynamic between the farmers, buyers and the mining company is a means to ensuring the sustainability of the mining company's community investment once the mine closes. An Inclusive Agribusiness benefits poor farmers by providing access to markets, services and products in ways that improve farmers' livelihoods, while being a profitable commercial venture in and of itself. Business for Development has worked with a number of mining companies to develop Inclusive Agribusinesses for communities impacted by the mines, founded on its **L**ong-term **IN**clusive **C**ommercial (LINC) enterprise model. The paper will outline the value of the LINC Model in developing non-mine related businesses, and provide case studies regarding how mining companies have implemented the model to develop new enterprises in complex social and economic landscapes.*

Keywords: *agribusiness, enterprise model, mine closure*

1 Introduction

Many developing countries are endowed with mineral resources. It is in their interest to maximise the exploitation of their resources in order to generate income for the country, and provide benefit to the local communities that are proximate to the mineral deposit. Mining companies have both the expertise and funding needed to extract and process these resources, and deliver the end product to the international market. Through careful planning and implementation, such activity can also deliver benefits to the host country, particularly the impacted local communities. Recognition of the interests of all stakeholders is critical for the long-term success of such mining ventures. Most mining companies have three key concerns when running a site: safety, volume and costs (PwC 2013). Communities that benefit from the mine pose less risk to these three. To benefit from mining, communities need to see improvements in the basics: food security, water, health care, infrastructure, education etc. They also need to be able to benefit economically. This is where many mining companies struggle with their being limited jobs for unskilled people.

The LINC Model helps mining companies manage this risk by addressing local interest, knowledge, expertise and resources and generate sustainable employment through Inclusive Agribusiness. This paper focuses on strategies which aim to not only establish local community agribusinesses during the course of mine operation, but also how best to ensure self-sustainable performance once the mine has ceased operation. Establishing an Inclusive Agribusiness, which is standalone to the mining venture and brings requisite knowledge and skills, training, financial resources and viable linkages to broader markets beyond the boundaries of the local community, is the basis for continued viability once the mine has ceased operations. This link between agriculture and the markets is the key to long-term sustainability.

2 Impact of Mine Closure

Establishing a mining venture in a developing country involves many activities which impact on local communities. This includes the building of roads, water supply, power supply, waste disposal, as well as employment. Local communities may gain mutual benefit from these facilities and many benefits will remain once the mining company has departed the area. The viability and usefulness of these residual impacts must be explicitly addressed as part of the process of shutting down a mine. Complete rehabilitation of the mine site, leaving it in a safe and non-polluting condition, is critical to the local community. It is not just the environment that must be considered, but also the economic and social impact the mining company leaves.

For example, the mine's operations may have provided employment for the local community. When the mine closes, this labour force is no longer required, and securing alternative employment for these people may become an important part of the mine closure process. Mine closures without a post-mine economic plan may result in a significant and immediate decline of local economies. The flow-on effect is a decrease in the local population, subsequently affecting social services, schools, labour markets, employment, housing prices and other impacts (Kemp et al 2006). The key to a successful outcome following mine closure is to have established industries which are viable independently from the mining venture; and developed through support from the mining company. This should be the aim of all stakeholders in their efforts to help local communities shift themselves from small, family-oriented farming activities to a cohesive market-oriented Agribusiness. Beyond the mineral resource, for some communities its greatest assets are the land and its people, and the LINC Model leverages these assets to enable the community to achieve independence from the mining company. Mine closure is often viewed as an expense which has no financial return, when really it should be considered an investment – an investment into the business' reputation, ensuring a smooth exit from the community, reducing social and environmental risk, and improving the business' social license to operate.

3 The Opportunity for Mining to Facilitate Agricultural Development

Given the close proximity of most mine sites to smallholder farmers in developing countries, there is clearly potential for both the agriculture and mining industries to work together to alleviate local poverty. Cross-sectoral partnerships between mining and agriculture are being recognised as virtually a prerequisite for creating positive mutual benefits from their activities (International Mining for Development Centre 2014). The reality with agriculture is that most farmers in developing countries are smallholder and subsistent. Subsistence farming means to produce enough food and fibre for the needs of the farmer and their family only (Spedding, 1979). If agriculture had stronger returns and links to market, it would be a more attractive proposition. Typically there are four key impediments to smallholder farmers becoming profitable producers:

- **Lack of access to credit and finance** – Finance is needed to access better tools and technology, to smooth and normalise income, and to enable better market access.
- **Lack of connection to markets** – Less than 10 percent of smallholder farmers are aggregated into producer or other organisations that effectively connect them to markets (Wiggins & Keats 2013). Farmers are often reliant on local middlemen to sell their product – these middlemen usually take a high margin and offer low returns. Major barriers to the rural poor participating in formal markets are low farm gate prices, insufficient focus on high value crops, high input costs, and poor productivity and yields.
- **Lack of diversification** – These farmers often lack the knowledge, land and resources to diversify, and do not take advantage of unused/under-utilised land and/or resources to diversify risk. Many grow unsustainable crops, purely because they have been grown for generations.
- **Lack of access to inputs and agronomic training** – Most farmers achieve poor yields due to poor use of inputs and outdated farming practices. Few farmers have adjusted their farming strategies in response to climate change, owing to limited resources and capacity.

When a mining company is considering agriculture as an investment area, especially with line-of-sight to closure, each of these barriers needs to be addressed. Importantly, expertise on how to resolve these impediments can be harnessed through partnering with inclusive agribusinesses, that are driven by long-term sustainable commercial opportunities.

4 What is Inclusive Agribusiness?

Inclusive Agribusiness is a strategy aimed at improving the subsistent agriculture sector by creating positive impact partnerships in the private sector, as this sector is well-positioned to play a significant role in poverty alleviation (Woodhill 2016). It also recognises that the support of donors, Non-Government Organisations (NGOs) and organisations such as mining companies, can be used as a catalyst to execute strategies for poverty alleviation, by achieving scale through the pragmatic use of market solutions. Inclusive Agribusiness goes beyond philanthropy and corporate social responsibility. It aims to integrate inclusive approaches into the core commercial operations of an agribusiness. It recognises that smallholder access to broader markets is the key to tackling rural, developing country poverty and inequality, while also creating opportunities for business growth (Woodhill 2016). Business for Development has been involved in applying Inclusive Agribusiness strategies in developing countries for the past ten years. The "Long-term Inclusive Commercial" enterprise (LINC) Model specifically aims to align the interests of the three key stakeholders – namely the mining company, the farmer and the buyer of the farmed product(s).

5 What is the LINC Model?

The LINC Model combines a "for purpose" social enterprise model with a "for profit" Inclusive Agribusiness strategy. A farmer-owned social enterprise (LINC enterprise) is created to interface with private sector partners, who are pursuing Inclusive Agribusiness engagement with low-income communities. What is unique about the LINC Model is that projects are designed to empower aggregated smallholder farmers to engage more effectively as a single commercial entity. It seeks to significantly improve farmer income and thus take farmers out of poverty on a long-term sustainable basis. The result is a LINC enterprise, which is ideally 100 per cent farmer-owned. The LINC Model also reviews the value chain and assesses who are the middlemen, what value do they add, where the margins are between each middlemen, and how they can be potentially skipped by selling directly to the main buyer. As a result, a bigger margin is reaped at the farm gate. Purchasing costs for each farmer is often high. The LINC Model involves grouping farmers to form a cooperative, so they can not only reduce the cost of input purchases but also aggregate sales into a broader market base, improving loan facilities and utilising better technical expertise. This assists farmers with economising on their transactions costs and gives them greater influence in decision-making.

6 How does LINC help with mine closure?

When building community development programs near mine sites, it is important to develop both mine-linked businesses (e.g., catering and cleaning) and independent businesses that will last beyond the life of the mine. The LINC Model is designed to establish independent agribusinesses by incorporating the following principles: design the project based on community need; utilise a well-planned financial model; build the business small, then monitor and evaluate; align with strong partners; link to the market; create a robust governance structure; develop ownership of the project with farmers; complement existing government-led programs; ensure the process and planning for the LINC enterprise starts as early as possible; make the LINC sustainable once support from the mining company ceases.

6.1 Design the project based on community need

Understanding community perceptions is essential to managing expectations (Kemp et al. 2006). To develop an accurate understanding of farmer needs, a two-pronged approach is utilised. First is an agronomic assessment of the region (e.g., soil testing) to provide hard data on which to base decisions, to ensure the most efficient and effective economic inputs are implemented. The hard data coming from the agronomic analysis must be augmented with softer insights on farmer habits and motivation through an ethnography analysis. Experience in working directly with farmers shows that rational argument based on quantifiable data is rarely enough to ensure engagement and uptake. Understanding the drivers of adoption and perceived risks in new initiatives is critical to the process.From this information, modelling is used to understand the dynamics of the various agricultural value chain participants, and a review is conducted to determine which value chain participants have the potential to create the greatest impact for smallholder farmers. For example, a lack of capital may have historically held farmers back. Modelling may show that increased lending by banks may have the potential to unlock farmer productivity, subsequently attracting other value chain participants to support these farmers. The use of modelling also assists with optimising outcomes across multiple facets – the commodity selected is the one likely to have the biggest uptake by farmers, as well as being the most profitable based on farmer capabilities. The right training is provided, the optimum governance structure is implemented to meet the community's social and cultural requirements, and therefore programs are more likely to achieve the desired scale and impact.

Case Study: Harmony Gold, Papua New Guinea

Harmony Gold's Hidden Valley operation employs about 2,000 people directly and another 1,000 people indirectly as a result of the mining company's activity. Harmony Gold is conscious of providing an alternative income stream for these people when the mine closes. As there is little economic activity around the mine, Harmony also wants to establish sustainable agriculture programs for villages that border the site, so that other programs that have been established by the mining company (e.g., education and health) are sustained.

Coffee is currently grown in the district so there is some production knowledge, but farmers only harvest beans when money is needed. Productivity and commercial farming are viewed as Western concepts. One of the key barriers for farmers moving from subsistence farming is culturally driven, and the program design must take this into account to be successful. The project involves slowly introducing a new mindset to the community. Communication is key, as is building an understanding of the benefits of planning for the future (a foreign concept to many who live from day to day). With a strong hierarchical culture, the project is designed so that it is open and encourages participation from all in the region, not just those at the top of the hierarchy.

6.2 Utilise a well-thought-out financial model

Starting any enterprise is difficult. Starting a LINC enterprise in a remote rural region in a developing country is a lot more difficult. Robust financial modelling is essential to forging a path to sustainability and financial independence. Sustainability through modelling is achieved when the yields and returns are used to determine which are the right activities for achieving the desired results, and how the business should be developed. Financial modelling also assists with risk management, so that potential surprises can be identified beforehand and mitigated where required.

6.3 Start the business small, then monitor and evaluate

Farmers are generally wary of trying new things. Demonstration plots are critical for training farmers in optimal crop management. For these demonstration plots, it is best to select farmers who are entrepreneurial and demonstrate that they are *positive deviants*. The term 'positive deviance' refers to 'a departure from the norm' which results in a positive outcome (Spreitzer & Sonenshein, 2004). These are the people or groups who are willing to try new approaches and also invest the time needed to make a crop work. These positive deviants can be used to demonstrate to the rest of the community that they too can generate greater earnings if they adopt the new approach/crop. It is important to test crops, to determine ideal seed varieties and demonstrate to the buyer the community's capacity to commit and produce a high-quality product that meets the buyer's specifications. Although developing a proof-of-concept takes longer, it does enable mining companies to engender the trust needed from all stakeholders, including the government. By also applying a robust monitoring and evaluation approach, the program designer can understand how to improve the design for impact before it goes to scale.

6.4 Align with strong partners from the value chain

The World Bank and International Finance Corporation (2002) highlights that "if partnerships have been developed and implemented during (mine) operations, then the opportunities for handling assets for community use and for maintaining social services successfully after closure will be greater." Modelling can reveal relevant stakeholders to partner with across the value chain. It is important to understand the strategies, issues, and needs of each stakeholder; to develop a value proposition which aligns with their interests while also meeting the community's needs.

Case study: Ok Tedi Development Foundation, Papua New Guinea

Ok Tedi Mining Limited's (OTML) mine is in the Western Province of PNG, and currently the only major economic entity in the region. The mine is likely to close within the next ten years. The Ok Tedi Development Foundation (OTDF) is the legal entity that manages community development benefits from OTML's operations on behalf of the 147,000 residents spread across 158 villages throughout the Community Mine Continuation Agreement (CMCA) corridor in PNG. OTML started over 40 years ago and most of its community funding was put towards a number of annual compensation packages. With the establishment of OTDF as an independently operating foundation in 2010, one key objective is to shift the community's mentality from reliance on the mining company to the vision *"to improve self-sustainability and quality of life of Western Province communities"*. A key part of achieving this is shifting the cultural attitude from one of minimal food security to building long-term capacity to develop economic security through commercial agriculture practices. OTDF is investing in those who are willing to sweat, take control of their lives and actively participate in its rubber, rice, agar wood and poultry projects.

OTDF has established a LINC enterprise as part of its strategy for achieving sustainability. Key to the LINC enterprise are partnerships across the value chain. OTDF has partnered with commodity trader Olam with respect to rubber production and purchasing. Olam (2018) has agreed to apply its Livelihood Charter to the project, and provide assistance and guidance to OTDF to promote and develop the rubber production in Western Province. For rice, OTDF has sought technical assistance from Trukai Industries, a leading supplier of rice in PNG, and Innovative Agro Industries to develop a holistic agribusiness master plan. Other partners across the value chain include government agencies, NGOs, private sector service providers, bilateral and multilateral development agencies, universities and research organisations, all of whom are working towards building resilience.

6.5 Link to market

Many community development teams at mines build agriculture capacity by focusing on increasing production. This approach works well if the primary concern is food security and if a buyer is readily available for any surplus (e.g., a mine's canteen). However, increasing supply often only works for a limited period, with local markets becoming oversupplied. Rapid oversupply in the market leads to falling prices and reduces farmer income. Lack of attention to markets and their dynamics frequently results in farmers being left with unwanted produce that they are forced to sell at low prices.

Community programs are more likely to be sustainable if the mining company's investment is the catalyst to establish other non-mine-related income sources. An important way of achieving this is to foster market linkages between communities and external partners. The LINC Model achieves this by ensuring that poor farming communities are connected to the supply chains of buyers (e.g., multinational food and retailers) who are seeking to become Inclusive Agribusinesses. Connecting farmers to markets on an equal footing requires trusted intermediaries, as well as sustainable and scaleable business models that generate sufficient wealth for the farmers. The LINC Model addresses this by ensuring that farmers and buyers mutually benefit from growing their businesses together. By building strong buyer relationships, farmers are more likely to generate good business and growth, create a new source of income, and secure market demand. To achieve such outcomes, farmers often need better tools, training, credit, and improved quality of inputs. All these elements can be supported by a mining company who has a vested interest in building community capacity to meet commercial buyer requirements. Buyers seek to generate strong business growth, expand into new markets, and reduce their supply chain risk and/or cost. The LINC Model can support the buyer's Inclusive Agribusiness through improved supply chain efficiency, via the disintermediation of non-essential middlemen, improved quality, and a long-term partnership with farmers based on mutual benefit.

6.6 Create Good Governance

Being an owner of a business gives people motivation and a stake in its success. The LINC Model achieves this through developing an owner-shareholder structure. The choice of which shareholder structure to apply depends on the specifics of the scenario, such as: (i) negotiations between communities and companies (one community may be interested in an equity stake, while another may prefer a different arrangement); and (ii) considerations concerning commercial viability, which may vary from crop to crop (Paglietti & Sabrie 2013).

The LINC enterprise trades commodities from a group of farmers to a buyer. The dividends are paid either in profits to the farmers and/or reinvested into farm and community programs. The model is scaleable and grows organically by engaging new farmers – new farmers can join the LINC enterprise as suppliers with the same rights as existing farmers. The model is designed to be sustainable through sale margins, negating the need for ongoing benevolent funding.The LINC enterprise's Board can consist of farmer representatives, commercial experts from the buyer, agricultural advisors, and NGO representatives. Sometimes the mining company takes on a Board role to support governance and capability development.

Case Study: Base Titanium, Kenya

Base Titanium Ltd (BTL) commenced mining operations in Kwale, Kenya in 2013. BTL engaged Business for Development to design a community development program that would outlast the life of the mine.

Initially the project involved 20 farmers who grew a combination of cotton and potatoes. Since then, a strong long-term buyer has partnered with the project – namely Cotton On Group (a multinational retailer). Sorghum is also produced by the farmers which is purchased by Diageo, a multinational alcohol producer. By 2020, the project aims to impact 10,000 farmers; however, to achieve this, a strong governance structure is needed.

The LINC enterprise is called the Pamba and Viazi Cooperative Society (PAVI) and is owned by the farmers. PAVI has appointed a CEO, Administrator, Accountant, Technical Manager and Field Extension staff – all local staff have a vested interest in the cooperative succeeding. PAVI farmers subscribe to membership by paying a membership fee and purchasing minimum shares. PAVI has a Board comprised of Kenyans, who have the knowledge and capacity to guide the cooperative. The Board is also supported by a committee made up of key funders and stakeholders. The PAVI cooperative is being guided along a path towards independence, and the ultimate goal is for the project to be self-sustaining within a five-year period. This means that a livelihood micro-economy will have been established which will outlast the life of the mine and will continue to impact thousands of community members for decades to come.

6.7 Develop ownership of the project with the farmers

Increasingly, mining companies are looking to communities to own the post closure projects and be the key instigators in the development of their goals (International Council on Mining and Minerals 2008). It is their energy and ownership that will drive sustainability and profit from the projects when the mine is closed. To establish farmer ownership of the project, a participatory approach should be utilised. The Asian Development Bank (1996) states that "participatory development is a process through which stakeholders can influence and share control over development initiatives, and over the decisions and resources that affect themselves." Development expert Freire and Freire (1994) argues that people who engage in an approach where they are active participants, link knowledge to action and work to actively change their societies.

Enabling participants to build/grow something for themselves can lead to the 'IKEA effect' (Norton et al 2012), a cognitive bias in which people place a disproportionately high value on products they partially created. As many mining companies can attest, when a company builds, for example, a water pipe for a community, often it can be viewed as the company's pipe; when it breaks, it is seen as the company's responsibility to fix. However, if the farmers were involved in building the pipe and are taught how to fix it, they are more likely to feel a sense of pride and take more care in looking after it.

Farmers also need to contribute towards the purchase of inputs (e.g., seeds, fertiliser, tools), so that they place a greater value on the outcome. This is known as the 'endowment effect', which is the hypothesis that people ascribe more value to things they view as their own (*Beggan, J K.1992).* Farmers participating in the project may be offered 'soft loans' so they can access high-quality agricultural assets to increase their incomes, while ensuring that they also own the end results. They repay these loans by deducting repayments from the sale of the harvest – a percentage of the harvest goes to the LINC enterprise or a percentage of farmer yield is paid to the LINC enterprise for member activities, e.g., training. The capital for the loans is raised either through donor funding (e.g., the mining company), seed capital, a revolving fund, farmer contribution or a dividend from sales from the enterprise(s).

6.8 Complement existing government-led programs

It is typically not possible to replace the economic benefit of a mine completely once a mine closes (World Bank & International Finance Corporation, 2002). To mitigate the impact, it is important to co-create any program with the regional government, and design programs that complement their existing policies and strategies. This not only secures a social license to operate, but it also reinforces the likelihood of the government adopting any initiative developed by the mining company post mine closure.

6.9 Ensure the process and planning for the LINC starts as early as possible

To build a farmer enterprise which has links to a sustainable Inclusive Agribusiness and is also commercially viable takes time. If a mining company is planning to create a social business when it is close to mine closure, it is probably too late. A mine closure plan is usually developed at the time of mine licensing. It is at this point when a mining company can take into account longer-term social and economic considerations (e.g., the size and location of townships and other infrastructure), and how this can be used once the mine closes (World Bank & International Finance Corporation 2002). Often over the life of the mine, the people that were employed at the start of the project are not the same people who are employed when the mine closes. As a result, community programs can be plagued by short-term thinking, when long-term impact should be the priority. To achieve this, a value proposition that meets the community's needs is required. This provides the focal point needed to ensure that year on year, a small number of projects are developed, resulting in greater impact and sustainability over the longer term.

Case Study: MMG LXML, Laos

As part of its community development plan, MMG LXML (MMG) worked in Sepon in Laos at the local level, to achieve development outcomes for important issues such as poverty, food security, health, education and the wellbeing of women and girls. Over time, as the mining operations in Laos matured, the company looked to transition its approach from supporting these essentials programs to focusing on long-term economic development that was not solely reliant on MMG. MMG wanted to work with communities to be resilient and sustainable beyond the life of its mines. After preliminary research, it was identified that many farmers in Laos struggled to grow enough rice to feed their families. Growing citrus was recognised as a way of providing farmers with an approach to exiting poverty for good, as it would net a tenfold increase in income over traditional crops. A partnership was established with Ironbark Citrus, an Australian grower, who was looking for counter-seasonal opportunities. The project currently impacts 80 farmers but it did not achieve the reach and scale that was initially intended, as citrus takes a minimum of four years before any commercial fruit comes to bear – too long for farmers to survive without an income. Although the project is still having a profound impact, had MMG started earlier, it would have meant that the project would have had a chance to achieve scale and sustainability.

6.10 Make the social enterprise sustainable

To be an Inclusive Agribusiness and work with a social business, a project will typically not succeed unless all three of the following elements are addressed. Firstly, it is important to ensure that you have the right value proposition that resonates with all stakeholders involved; that the right crop has been selected for the situation (agronomics, culture, etc.), in order to achieve the greatest outcome. Secondly, if the value proposition is 'right' but the approach taken towards achieving the mission is ineffective or inefficient, then the model is unlikely to succeed. Finally, the right people must be embedded within the governance structure; people who are passionate and have the knowledge and capacity to execute the project strategy.

7 Conclusion

Even though mining companies are not solely responsible for addressing the socio-economic impacts of mine closure, there is no question that they are the key player with significant power, influence and resources to impact a community's future livelihood. All four case studies in this paper highlight the challenges associated with developing regional economies and cohesive communities in remote areas, and how they have overcome these challenges by systematically designing commercial LINC enterprises. The LINC Model provides a framework for developing a scaleable, sustainable agribusiness that is founded on evidence-based data analysis, blended with the local social and cultural dynamic. A LINC enterprise builds upon success to support smallholder farmer development that is clearly linked to external markets. This provides a level of certainty in what is a difficult and potentially risky enterprise. Mine closure and creating social legacy in developing countries requires creativity, cooperation and leadership. Although implementing the LINC Model can be complex, it is a long-term and effective solution to developing a sustainable post-mine closure economy. As a result, mine closure will not be seen solely as the end of mining activities, but also the fulfilment of the social stimulus needed for communities in remote regions to engage in Inclusive Agribusiness, that will lead to long-term economic security and sustainability.

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Probabilistic Based Cost Estimation for Mines - Probabilistic Cost Estimating as a Guide to Effective Mine Closure Planning

M Nahir *Indigenous and Northern Affairs (INAC), Government of Canada*

I Hutchison *SLR Consulting, Canada*

J Ankersmit *Indigenous and Northern Affairs (INAC), Government of Canada*

Abstract

The industry standard "single point" or determination cost estimates for mine closures, etc. are commonly used but provide very little information on potential financial risks or cost savings opportunities and hence are not good planning tools and may not be good budgeting tools either. In this paper, the authors outline various probabilistic-based methods of estimating closure costs and discuss how these can be used for mine closure planning, development of risk management plans, financial reserve estimates and budgeting. These tools include decision trees to track alternative outcomes, Monte Carlo simulations to capture cost variability, as well as risk and opportunity identification and management strategy development. Since mine closure at abandoned sites incorporates much uncertainty, these tools provide the ability to isolate key uncertainty variables, which in turn facilitates strategic planning, focused investigations and provides focus on cost effective solutions. It is important to recognize that these probabilistic estimates serve a greater purpose other than providing financial information. As demonstrated in this paper, these estimates also provide a basis for strategic planning and risk management of closure. These methods and how they can be used to improve closure planning are outlined in the paper.

A case history is presented to illustrate the application of these tools. It involves a mine in Canada at which preliminary closure approaches and cost estimates were developed. Decision trees were established to represent the feasible alternatives for closing the Tailings Storage Facility, the underground mine and open pits, the waste rock piles, as well as the site facilities and associated impacted soils. Estimated costs, probabilities and alternatives for these major features were applied to develop the 80% confidence of each cost level to be used for budgeting purposes, the most likely closure approach and cost, the potential maximum and minimum costs, and the breakdown of costs for these features. These data were then used to identify strategies and data collection and evaluation plans for minimizing the potentially more costly approaches, and identifying strategies for minimizing closure costs. This approach supports, but does not replace the formalized decisions analyses recommended for closure planning, which are the subject of another paper by two of the authors. Finally, the paper concludes with a discussion of how INAC proposes to apply the above tools and procedures to improve both its forecasting and budgeting, as well as the mine closure planning process.

Keywords: *cost estimating, cost forecasting, budgeting, risk management, strategic planning, cost savings probabilistic methods, decision trees, Monte Carlo methods*

1 Introduction

1.1 General

Generally, for closure of the site, costs are estimated "deterministically." This type of estimating provides costs for one specific closure approach based on the details developed by the design team. While this approach is commonly used, it does not accommodate the uncertainties that exist when estimating costs, or by the wide range of closure alternatives that still exist.

There are many sources of uncertainty: “closure scope uncertainty” is associated with not knowing what closure elements will be included in the final plan and is largest during the planning stages when alternative approaches to closure are still being considered. This uncertainty generally decreases as the closure approach and design evolves and drops significantly after the closure permitting process is complete and approval for a single closure approach is obtained; “implementation uncertainty” persists during the detailed design and construction phases as unforeseen changes in site conditions are encountered and as schedule delays occur; “schedule uncertainty”, associated with overall project schedule delays such as increases in the number of years of the care and maintenance costs during the design and permitting and construction phases; and “long-term uncertainty”, which are the activities needed for the long-term Care Phase that are difficult to predict at this early stage.

Typically, a contingency is applied in deterministic cost estimates. This is intended to account for uncertainty in field conditions and construction costs, which are part but not all of the implementation uncertainty outlined above. This contingency can also be applied to deal with scope of work and schedule uncertainties to some extent, but cannot effectively deal with the other uncertainties discussed above.

1.1.1 Probabilistic Cost Estimating

Probabilistic estimating is aimed at quantifying the uncertainties discussed above. Generally two methods are used. These include the use of decision trees to map out all possible outcomes and Monte Carlo techniques, which apply statistical distributions to the quantity and unit costs used in deterministic estimates and which can be used to add up any individual statistically determined cost estimates. These are discussed further below.

1.1.2 Decision Tree Approach

Decision trees are ideal where closure approaches and elements, and/or closure schedules haven’t been finalized or are not known with certainty. All possible reasonably feasible alternatives are considered and built into a decision tree, such as the one shown on Figure 1 for the Case History Site care and maintenance costs. As shown, probabilities are provided for each one of the branches in the decision tree and estimated costs are also assigned to each branch.

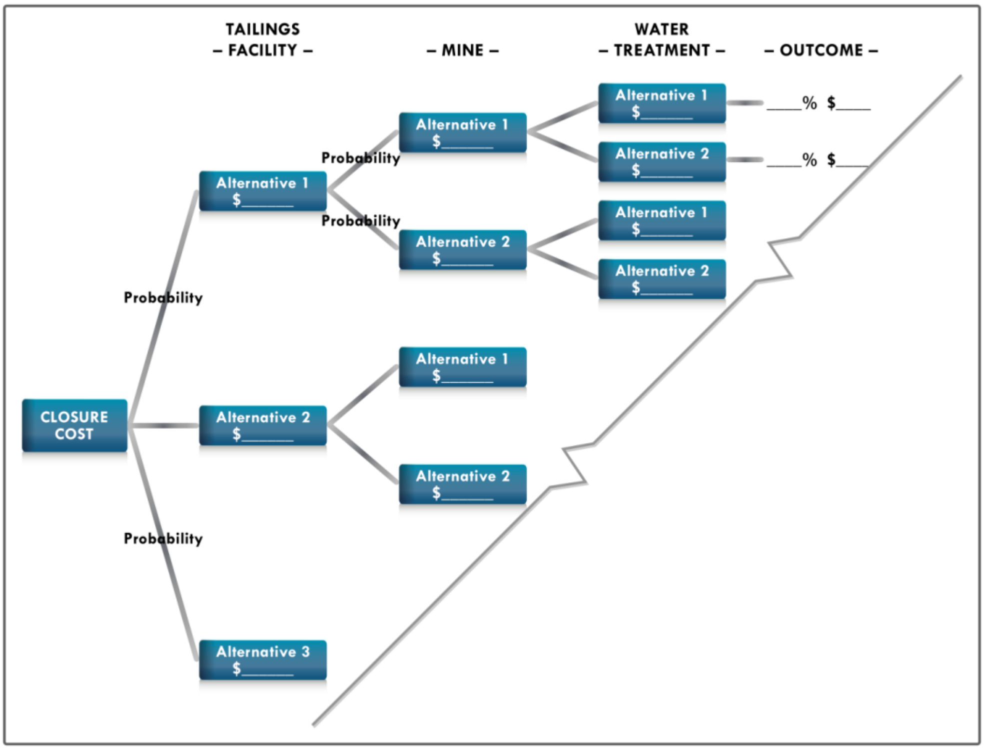


Figure 1 Typical mine closure decision tree

A decision tree deals with each of the uncertainties identified above as follows:

- **Closure scope uncertainty** by incorporating a range of feasible closure plans and components into the analyses;
- **Implementation uncertainty** by considering a range of site construction activities such as different water management strategies, lower or higher implementation costs than contained in the deterministic analysis, higher or lower volume estimates, etc.;
- **Schedule uncertainty** by considering a range of schedules for specific activities; and
- **Long-term uncertainty** by considering the lowest possible (minimum) number of activities and costs and the highest number of activities and costs (maximum).

The benefit of the decision tree analysis is that it incorporates all, or most, of the possible alternatives that could occur and hence removes the potential for large cost estimating errors associated with a single scenario deterministic estimate, particularly before a closure plan is permitted. As can be expected, the decision tree does not provide a single cost estimate, but rather a probability of non-exceedance versus cost curve (referred to as a probability-cost curve), such as the example shown on Figure 2. This curve provides the flowing useful information and insights into the site closure costs:

Minimum and maximum potential costs as represented by the 10% and 90% confidence levels (CLs). These are more representative than the absolute minimum and maximum values since these absolutes are extremely unlikely. The minimum and maximum costs are useful in determining the cost risks associated with a particular site. The larger the relative difference, the higher the cost risks. High-risk costs usually indicate that more emphasis needs to be placed on closure planning and engineering. The decision tree can be interrogated to determine what the underlying causes of these high cost risks entail. The costs associated with, for example the 70% or 80% CL cost can be used for budgeting purposes. This significantly reduces the possibility of the closure project running out of funds, and at the same time avoids the overly conservative approach of using the absolute worst-case cost.

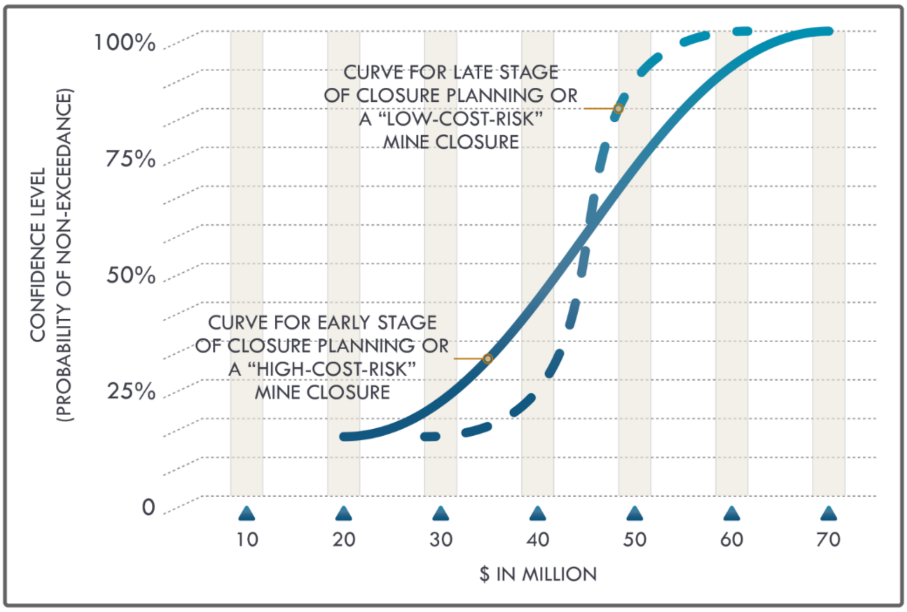


Figure 2 Typical mine probabilistic cost curves

In addition, the following useful statistically based individual cost estimates are obtained:

Most likely cost estimate, which is based on the decision tree branch that has the highest probability of occurrence. For purposes of this report it is always selected along the branch that has the highest probability of occurrence assigned to first branch in each tree. The most likely cost and the activities on the branches that contribute to the cost, provide information on what activities are likely to be required and aids in planning of future activities. It can also be used, with appropriate caution, as a budgeting tool; and **Median cost estimate**, which is like to be ultimately exceeded 50% of the time.

1.1.2.1 Monte Carlo Approach

The Monte Carlo Method is aimed at developing a probability cost curve for a particular closure scenario and accounts for a subset of the implementation uncertainty described above. This subset includes the variability in the actual construction quantities that can occur when construction actually occurs (e.g. the amount of tailings or contaminated soil actually excavated, the amount of rip-rap needed, etc.), as well as the unit cost assigned to various activities (e.g. the cost of excavating and hauling a tonne of tailings to a specific location). This approach involves applying a range of costs and an associated statistical distribution to each of the major quantity and unit cost items in a deterministic cost estimate. It can also be developed for one of the branches on the decision trees described above and is frequently used for the most likely cost scenario.

For the purpose of the analyses presented in this paper, a combination of decision trees and the Monte Carlo approach have been used. In order to provide realistically sized decisions trees (i.e. typically less than 30 to 40 end nodes) it was necessary to generate three separate trees as described in the following section. The Monte Carlo method was then used to add these three probability cost curves to each of the trees to produce a cost probability curve for the entire mine site closure.

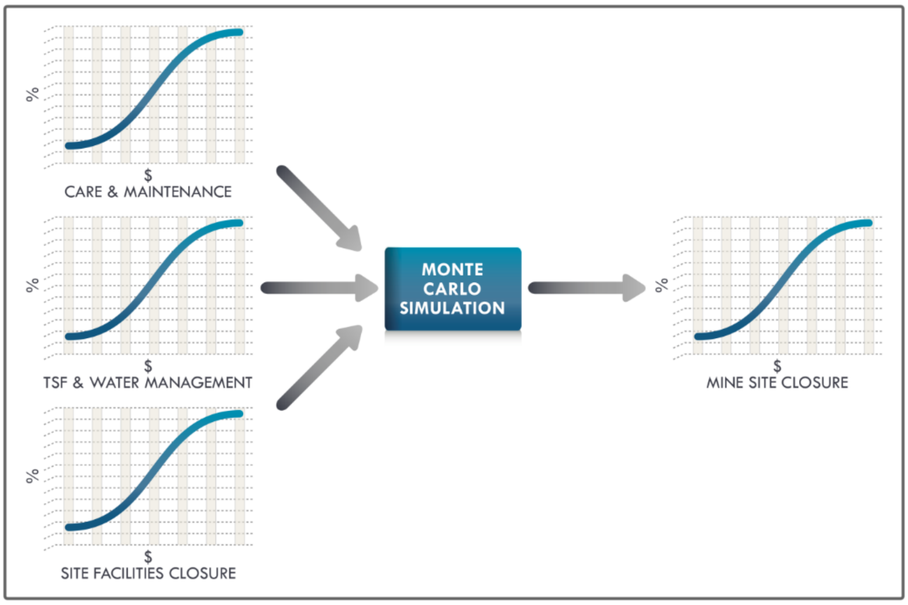


Figure 3 Use of decision tree and Monte Carlo simulations

2 Case History

2.1 Description of the Site

The Case History Mine is located in the Yukon, Canada. The current site infrastructure is depicted in Figure 3.The mine operated from 1987 until November 1990 when the mill was closed. Following the mine closure, further exploration was conducted intermittently between 1994 and 2011. Since 2012, only care and maintenance work has been conducted at the mine site. The Government of Canada is responsible for the financial costs and is considered the "funder". The Government of Yukon (YG) is responsible for the care and maintenance of this abandoned site and is considered the "implementer". Together, the two governments and affected First Nations are working on closure and remediation plans for the Case History and other mine sites.

Description of Closure Approaches

The alternative closure concepts are summarized below. Since the closure planning process is still underway, and since closure permitting has not yet commenced, these alternatives will likely continue to be considered in the future and the appropriate alternatives will be selected as part of the final permitted closure plan.

Figure 4 Case history overview

Table 1 Closure alternatives for different mine site facility/ closure components

Mine site facility/Closure component	Closure alternatives
Open Pits	Access controls, and/or very little to insignificant amount of backfilling
Underground Mines (portals, shafts and raises)	Adit plugs and shaft caps Since the 1430 level portal experiences groundwater outflow at certain times of the year provision is made for an alternative that creates a drain and infiltration zone that would convey the outflow under cover and re-infiltrate it to groundwater
Tailings Storage Facility (TSF)	(1) Consolidation and cove; providing for seepage collection (2) Closure of the TSF in place using a cover and minimizing tailings regrading (3) Relocating the tailings to a new lined storage facility somewhere on the site
Rock Piles	(1) Flatter, vegetated slopes (2) More extensive grading, covering and vegetation
Buildings and Equipment	Range of costs associated with decontamination, demolition, landfills and site remediation
Chemicals and Contaminated Soil Management	Range of costs associated with removal, land treatment, soil excavation, and on-and off-site disposal
Surface and Ground Water Management – Passive (Bioreactor) System – Physical/Chemical System	(1) Both biological and physical-chemical treatment generating for 18 and 8 years respectively. (2) A new physical-chemical treatment plant only and its operation for different periods of time.
Interim Care and Maintenance	Provision is made for care and maintenance during the following four phases of mine closure: • Design and permitting; • Construction of the closure measures; • Adaptive management during which the performance of the measures are evaluated and adjusted, as necessary; and • Long-term post closure Different durations are assigned to each of these phases. The total duration for all phases and for all alternatives is set at 25 years
Mobilization/Demobilization	Provision is made for cost variability in the future and a range of costs is considered
Engineering Project Management	A minimum to maximum cost range is specified
Health and Safety Plans, Monitoring, and QA/QC	A minimum to maximum cost range is specified
Bonding and Insurance/ Contingency	A minimum to maximum cost range is specified
Cost of Regulatory Applications	A minimum to maximum cost range is specified

3 Decision Tree Analyses

3.1 Cost Estimates

All cost estimates presented in the report are considered to be unescalated 2016 cash flow costs for a period of 25 years, starting in January 2018. They are estimated in $ Canadian.

Decision Trees

Closure plan decision trees were developed to illustrate the selected alternatives as described above. Mine facilities and features were grouped under three categories to streamline the decision trees and to group direct costs (i.e. construction) and allow indirect costs (i.e. management, technical studies, etc.) to be determined based on percentages of the direct costs. Decision tree costs and probabilities are captured under the following headings:

Care and maintenance, which includes care and maintenance during the project phases, are represented by the following sub-branches:

- Design & permitting;
- Construction;
- Adaptive management; and
- Long-term care.

TSF closure and water management, which includes the following sub-branches (Figure 4):

- TSF closure construction;
- Water treatment plant (WTP) Construction;
- WTP operation, and
- Indirect costs.

Site wide closure costs, which include the following sub-branches:

- Buildings, equipment and impacted soil;
- Pits;
- Adit closure;
- Rock piles; and
- Indirect costs.

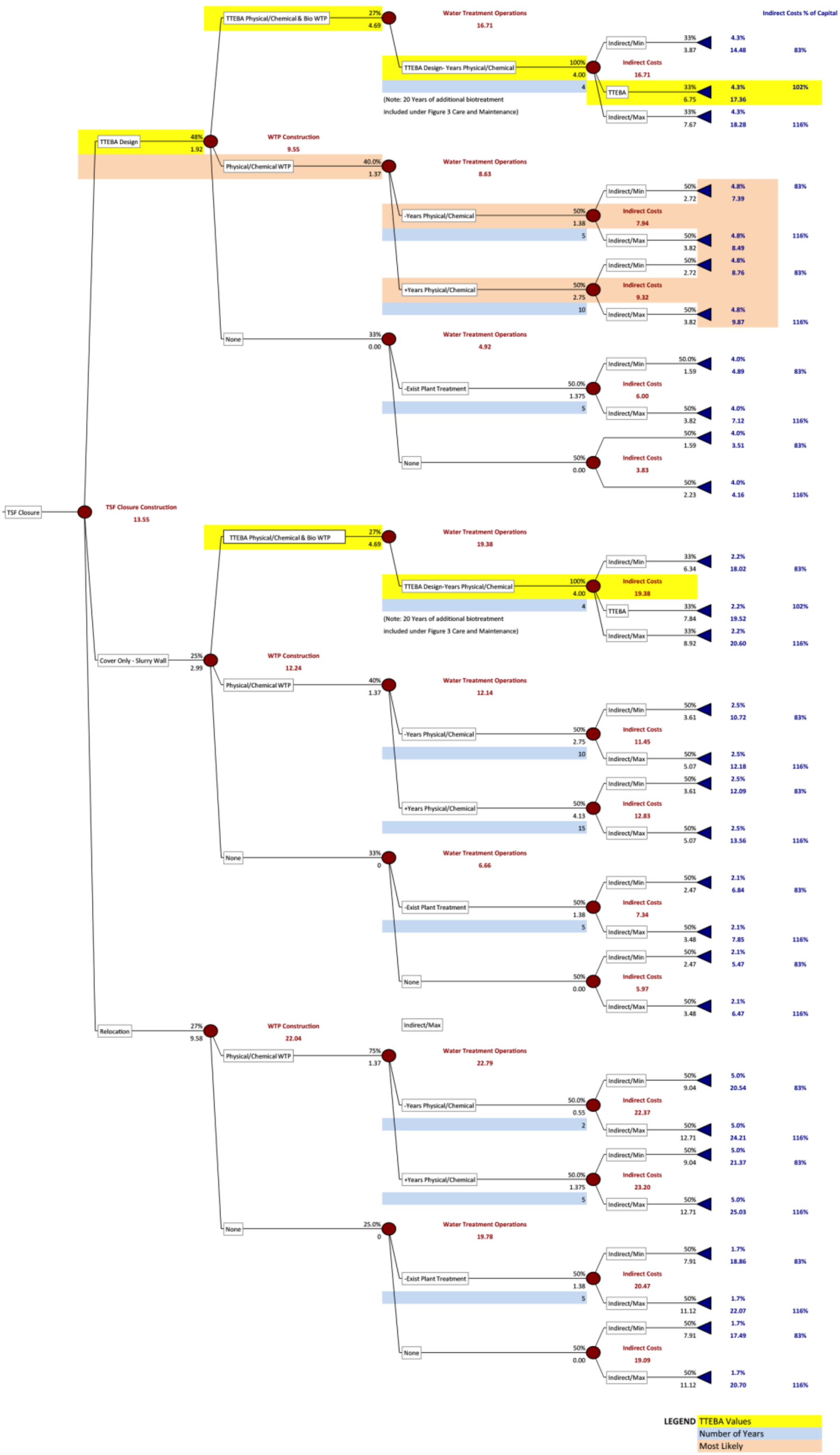


Figure 5 Decision tree – closure and water management

The probabilities assigned to the various sub-branches were determined as follows:

For the TSF closure alternatives, the WTP alternatives, the five pits, and the adit and rock pile closures; the probabilities were based on the consideration of anticipated preferences of stakeholders, the regulatory agencies and the technical merits. The individual and combined probabilities are summarized on Table 2.

Table 2 Mine closure calculated probabilities

Tailings Storage Facility						
Options	1	2	3	4	Select for Decision Trees	Rationale For Probabilities
	Stakeholders	Regulatory Agency	Technical / Engineering	All Interests Combined	Option #	**Stakeholders**
Weights	5	5	5		4	Preference for relocation out of creek. Ambivalent on closure engineering.
TTEBA	25%	50%	70%	48%	48%	**Regulatory Agency**
Cover Only	25%	20%	30%	25%	25%	Preference for consolidation in place. Somewhat interested in re-location.
Relocation	50%	30%	0%	27%	27%	**Technical / Engineering**
Total	**100%**	**100%**	**100%**	**100%**	**100%**	Preference for consolidation in place. Somewhat interested in cover in place.

Water Treatment						
Options	1	2	3	4	Select for Decision Trees	Rationale For Probabilities
	Stakeholders	Regulatory Agency	Technical / Engineering	All Interests Combined	Option #	**Stakeholders**
Weights	5	5	5		4	Want treatment as a safeguard, even if not needed for risk management. Ambivalent on treatment type.
None	0%	20%	80%	33%	33%	**Regulatory Agency**
Physical/Chemical	50%	50%	20%	40%	40%	Preference for treatment, particularly biological since it may be more sustainable in the long-term.
Bioreactor	50%	30%	0%	27%	27%	**Technical / Engineering**
Total	**100%**	**100%**	**100%**	**100%**	**100%**	Likely not needed. If needed, prefer mechanical/chemical.

Results

The three decision trees described in Section 3.2 were processed individually to produce three cost probability curves. Relative costs for each component for the most likely scenario in each of the decision trees were also generated. Examples of the cost probability curves and the reflective component costs for the TSF-Water Management decision tree are shown on Figures 5 and 6.

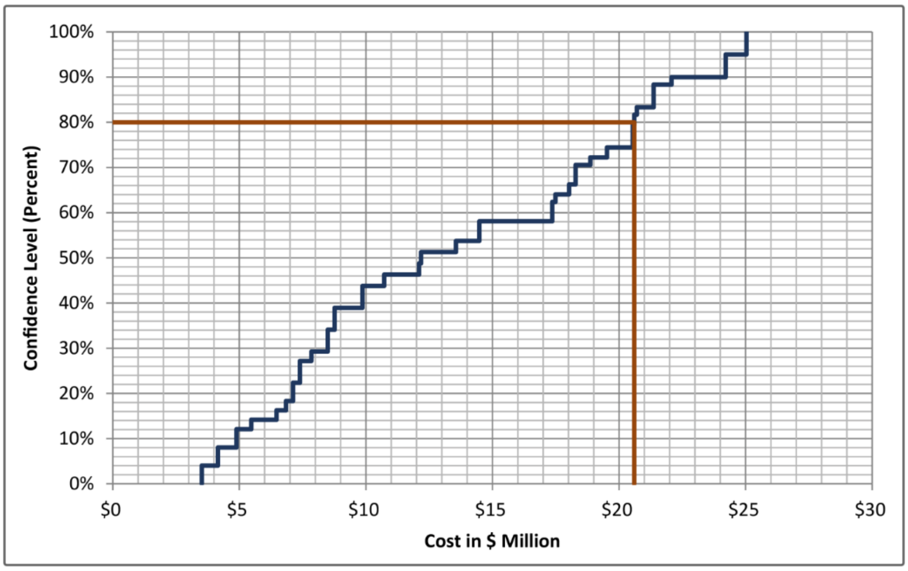


Figure 6 Cost probability chart for TSF closure

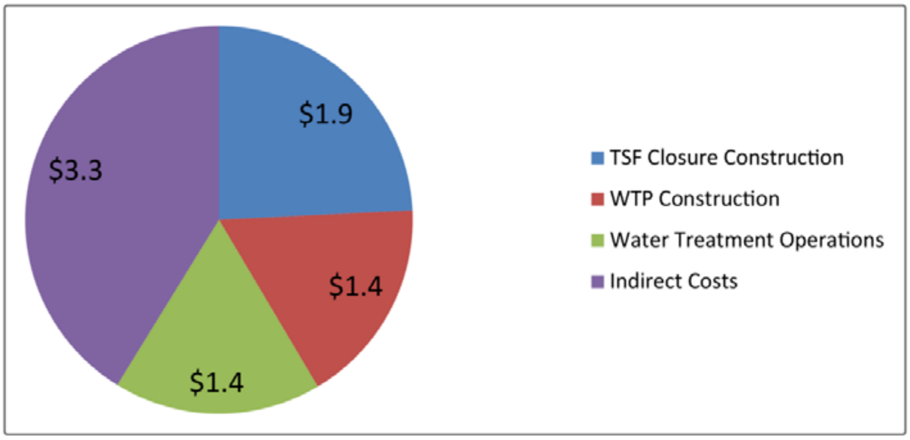


Figure 7 Most likely TSF closure and Water Management cost components

The three individual cost probability curves were then added using the Monte Carlo approach, as discussed in Section 1 and as illustrated in Figure 7. Using 500 simulations to add up the three probability cost tables, a single mine site closures cumulative cost probability curve (Figure 8) was generated.

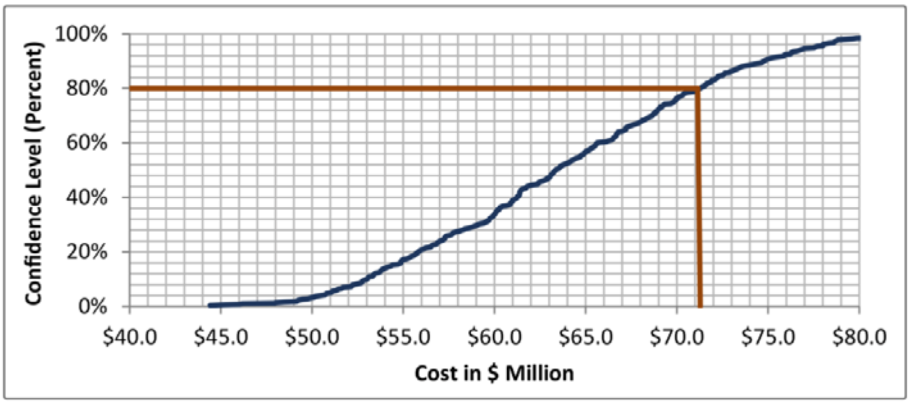


Figure 8 Mine site closure cumulative cost frequency curve

Figure 9 provides the relative costs of the three major components of mine closure:

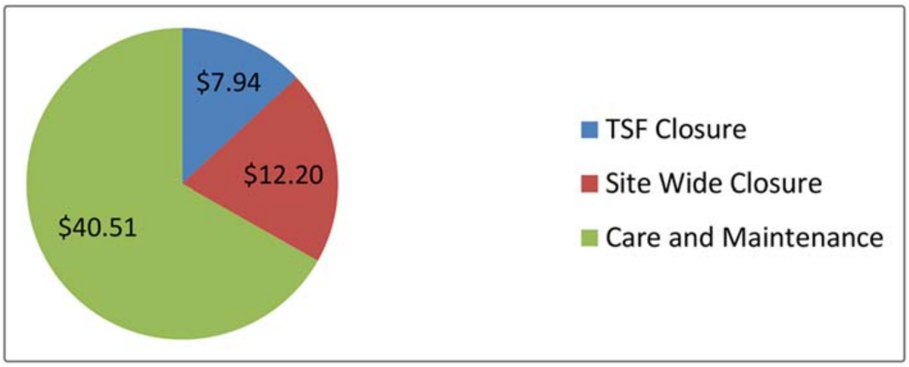
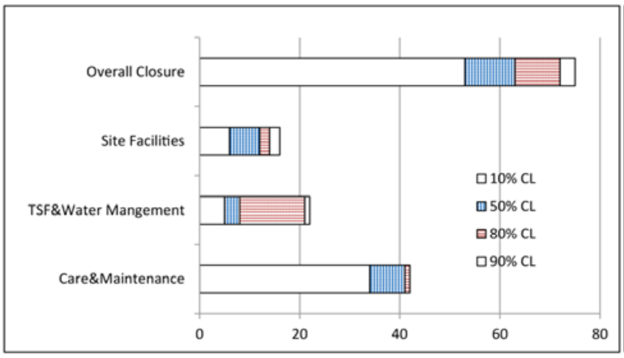


Figure 9 Most likely mine site closure cost components

A summary of the 10%, 50%, 80% and 90% CL costs for the three sets of decision trees and the overall site closure is provided in Table 3.

Table 3 Summary of costs and cost risk ratings



Ratio of 90% to 10% CL	90% - 10% CL Cost	Cost Risk Category [1]
142%	22	Low
267%	10	Moderate
440%	17	High
124%	8	Low

NOTES: (1) Based on the following scale
Low Cost Risk: 100% to 150%
Moderate Cost Risk: 150% to 300%
High Cost Risk: > 300%

Using the ratio of the 90% CL cost to the 10% CL cost as a measure of cost risk and the following cost risk scale, it is evident that the Tailings & Water Treatment Plant component has a high risk cost, the site facility closure has a moderate risk cost and the care and maintenance component has a low cost risk. The overall site closure is considered a low cost risk, as the predominant costs are site care and maintenance, which has a low cost risk.

Table 4 Ratio of the 90% CL cost to the 10% CL cost

Ratio Between 90% CL Cost and 10% CL Cost	Cost Risk Categories
100% to 150%	Low
150% to 300%	Moderate
Greater than 300%	High

4 Conclusions

The overall projected cost spread for the Case History Site is considered to have a moderate cost risk, with a 142% ratio between the maximum and minimum total cash flow costs and reflects uncertainty in the cost estimates for the following (in order of importance):

- TSF Closure and Water Management with a potential spread of approximately $17 million;
- General Site Closure costs of ($10 million); and
- Care and Maintenance costs of ($8 million).

The 50% and 80% CL total cash flow costs for closure of the Case History site are $53 million and $75 million respectively. The 80% CL could be used for budgeting purposes.

INAC now proposes to expand its closure cost estimates to include the above approaches. Through this process, INAC expects to be able to improve the accuracy of closure cost forecasting and also to identify key cost risk and cost savings opportunities the various closure teams should be focusing on in order to develop more effective closure plans and designs. INAC manages a portfolio over 20 mines in the Yukon and Northwest Territory with a total budget of over $2 billion.

Understanding Closure Cost Models and their Ongoing Viability as a Tool for Calculating Closure Liabilities

AK Richards *Jacobs Group, Australia*

R Miller *Jacobs Group, Australia*

DP Murphy *Jacobs Group, Australia*

MA Smith *Jacobs Group, Australia*

Abstract

Historically mine closure cost estimates have been prepared to determine financial assurance payments to regulators or to provide information for company balance sheet provisions. Increasingly there is concern that estimated closure costs are significantly lower than actual costs. As the realities of on-the-ground closure implementation become more and more apparent, resource companies and regulators alike are increasingly looking to more robust and defensible mechanisms for understanding closure liabilities. Closure cost models are often preferred tools for calculating closure liabilities due to their non-reliance on specialist skills and user-friendly interfaces. As a result, there are numerous models available to operators with varying levels of detail and input requirements, resulting in markedly different outputs. This paper presents a comparative analysis of several representative cost model tools – using worked examples and real-world data – to examine the elements required for an effective closure cost model. The same input data has been used to develop a 'professionally prepared' estimate from first principles to determine whether cost models can represent a viable alternative to a traditional estimating methodology. We also explore the question as to whether there is a sufficient knowledge base of real-world cost data available to adequately define an industry-preferred approach, and outline practical approaches that will assist in developing fit-for-purpose costings.

Keywords: *mine closure liability, cost estimate, cost model*

1 Introduction

There is an increasing focus on improving the reliability of mine closure cost estimates for the purpose of finacial assurance to regulators, provisioning in line with International Financial Reporting Standards, and reporting to shareholders. Numerous methods for calculating closure costs are used in the mining industry; from factoring estimates from similar sites, to parametric models (i.e. range analysis), simple or more complex cost models and site specific, first-principles cost estimates. Benchmarking of closure costs is problamatic given the lack of full site closures that have been completed as well as limited publically available actual cost data for those closures that have been undertaken. For this reason, factored estimates are not considered further in this study.

For the purposes of this paper, a 'cost model' is defined as any tool (e.g. Microsoft Excel spreadsheet) where internal functionality – as a whole or in part – is used in the place of compilation by a qualified estimator. A significant body of literature exists regarding the mechanisms for providing financial assurance and accounting approaches to calculate provisions for mine closure. This paper is not intended to add to that literature base but rather to address fundamental questions regarding the adequacy of closure cost models in meeting the increasingly stringent requirements of operators and stakeholders. Through comparative analysis of several representative cost model tools, the elements required for an effective closure cost model are examined to provide a clear set of considerations for the effective utliisation of such tools.

1.1 Terminology

The following table provides a brief glossary of key terminology used throughout this paper.

Table 1 Glossary of Key Terms

Term	Definition
Accuracy	Reflection of the maturity of the project scope, calculated on the Base Estimate, which includes growth, but excludes contingency, owner's costs and escalation.
Contingency	A specific cost provision to cover for unforeseeable items of work (the unknown) that will have to be performed or elements of cost which will have to be incurred within the defined project scope of work but that cannot be explicitly foreseen or adequately described at the time the estimate is being prepared because of lack of complete, accurate and detailed information.
Direct Costs	Direct costs are those that are directly attributable to the closure of specific facilities of the plant or associated infrastructure and rehabilitation and revegetation of existing landforms. These include all associated labour, equipment and material costs together with associated contractor distributable costs and provisional sums.
Indirect Costs	Indirect costs include temporary facilities and services, insurances, management services, site accommodation, travel, mobilisation and demobilisation, and consumables associated with direct costs.
First-principles	The calculation of project-specific costs based on a detailed study of the resources required to accomplish each activity of work contained in the project's work breakdown structure (DOT 2017).
Specific Risk	Assumptions potentially representing scenarios relating to specific events that may or may not occur but nevertheless form a part of project risk profile.

1.2 What Makes a Cost Estimate?

When embarking on a closure cost estimate and selecting the estimating approach, the purpose – or end use - of the estimate is of primary importance. Parshley et al (2009) identifies three common purposes for closure cost estimates, namely: financial assurance; current liability reporting; and planning and budgeting for the full cost of closure. Many of the publically available cost models are principally designed to inform financial assurance for regulators, however operators are increasinly looking to more detailed versions to prepare estimates for full, life of mine closure liabilities. While these models impart the benefits of accessibility and simplicity, these cost tools often do not adequately account for the full suite of elements required of a mine closure cost estimate. Although owners and regulators typically have differing perspectives on what should be included in a closure cost estimate (Brodie 2013), industry guidelines for project cost estimating (AusIMM 2013) identify key requiremnts of a cost estimate including:

- A documented basis of the estimate (i.e. the scope of work that has been costed) and associated assumptions.
- Project-specific work breakdown structure (WBS).
- Site-specific labour and equipment rates and productivities tied to the intended owner-operator or contractor closure execution approach. Indirect costs associated with these direct costs also need to be included.
- Allowances for costs outside of execution including pre-closure engineering studies, community consultation, human resources and post-closure monitoring and maintenance.
- Uncertainties and risks associated with gaps in the knowledge base, confidence in engineering designs as well as labour and equipment rates (i.e. growth and contingency).

When applied in a closure context, the latter of these points is typically the most significant driver of shifts in costs between estimates prepared at the concept stages of mine development and those prepared for a fully developed operation when the nature and extent of mining disturbance, closure risks to be managed, and the objectives for closure are better understood. Methods of combinging risk assessments with standard cost models have been proposed by others (de Plessis & Brent 2006, Hutchison & Dettore 2011) to provide a distribution of probable closure costs and better undersand their risk profile and associated cost impacts. Regardless of the cost estimating methodology employed, it is essential to understand the scope of closure and the associated uncertainties, risks and inherent sensitivities that impact on reliability of an estimate. Without a documented basis, interrogation of closure costs to determine their robustness and understand temporal shifts in liability estimates difficult – if not impossible.

A theoretical open pit iron ore mine site has been developed to illustrate how, using the same closure strategy as a basis, different cost models can produce vastly different estimates of closure costs. This conceptual assessment demonstrates the importance of understanding the core principles of cost estimating when using cost models and calculators to estimate closure liabilities.

2 Methodology

2.1 Conceptual Mine

The Barnaby Iron Ore Mine can be classed as a simplified small-to-medium open cut mine, with the following key assets and features:

- Open pit
- Processing plant
- Accommodation camp and airstrip
- Landfill
- Tailings storage facility (TSF)
- Waste Dump with discrete cell of potentially acid forming (PAF) material
- Miscellaneous infrastructure and disturbance (roads, borefield, laydown areas etc.).

A conceptual site layout illustrating key closure domains is provided in Figure 1. Closure commitments at the Barnaby Mine include backfilling of below water table (BWT) areas of the pit with inert waste material and installation of a store and release cover on the waste dump which contains a zone of PAF material.

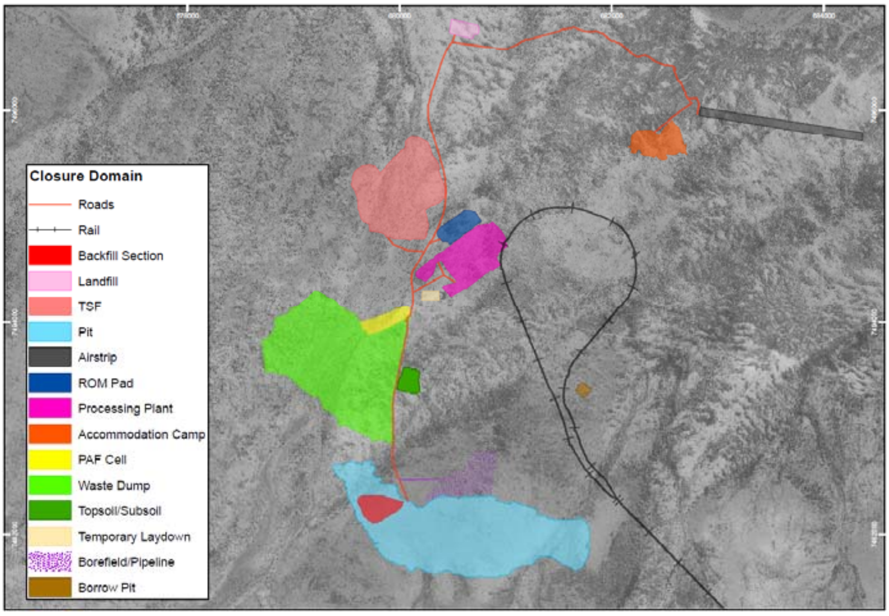


Figure 1 Barnaby Conceptual Mine Site Layout (not to scale)

Costs for the Barnaby Mine were developed from first-principles by appropriately qualified closure and estimating professionals. This 'Prepared Estimate' is used as the basis for evaluating the cost models identified in the following section. Key inclusions of the Prepared Estimate are:

- Direct costs for demolition and rehabilitation based on:
  - quantities derived from site-specific closure strategies and designs
  - crew rates built from first-principles (labour, equipment and material plus distributables) which are adjusted for material densities, haul distances, grades etc. which impact productivity
  - Allowances for pre- and post-closure requirements, as well as community costs
- Indirect costs applied as a percentage of direct costs
- Deterministic contingency.

2.2 Cost Model Simulations

The underlying cost build-up data (i.e. quantities, provisions and percentage allocations) from the conceptual estimate was then input to the following publically available cost models of differing levels of detail currently utilised in Australia:

- **Mining Rehabilitation Fund (MRF) Calculator**: The MRF Calculator assists tenement holders to estimate their rehabilitation liability and the associated MRF levy (Western Australian DMP 2017). The MRF applies to rehabilitation only.

- **Rehabilitation Cost Estimation Tool (the RCE Tool):** The objective of the RCE Tool is to provide exploration and mine operators with guidance on calculating an appropriate RCE for their operations by assisting in the assessment and quantification of rehabilitation risks and liabilities (New South Wales Department of Planning and Environment 2017).

In the case of the MRF, rates are 'hardcoded' and therefore no further adjustment was undertaken. In the case of the RCE Tool, there is the capacity for rate overrides which provided opportunity to test model sensitivities and accordingly two scenarios (hard-Coded rates and overridden rates) were modelled.

These two cost model examples have been selected for use in this study as they represent the scale of available cost models, from the very simplistic to more detailed models with greater flexibility for users to specify site-specific input data. Other cost models with more complex functionaltity, including detailed equipment rate buildups, are also available however have not been utilised in this study as it is our opinion that a professional estimator would need to be engaed to take advantage of the rate buildup functionality and so these models lean more towards a professionally prepared estimate. It should be noted that this analysis was undertaken purely for the purposes of illustrating the key precepts of this paper and is not an assessment of the viability of either tool. Further, the assessment and its outcomes must be considered in the context of the end-purpose of these tools (i.e. financial assurance calculators).

3 Results

3.1 Outputs

A summary of the professionally estimated cost for the Barnaby Mine is provided in Table 2, with further detail regarding the Rehabilitation breakdown by domain provided in Table 3. Outputs of the MRF and RCE Tool are presented in Figure 2 and Table 4 respectively, with RCE Tool outputs under two scenarios (hardcoded and manually adjusted rates).

Table 2 Barnaby Mine Prepared Estimate Summary

Closure Element	Estimated Liability ($AUD)
Pre Closure	$6,000,000
Demolition	$19,758,461
Rehabilitation	$44,612,073
Community Support	$100,000
Closure and Post Closure	$7,201,646
Indirects	$9,977,433
Contingency	$16,970,593
Total	**$104,620,207**

Table 3 Barnaby Mine Prepared Estimate - Rehabilitation Breakdown

Domain	Estimated Liability ($AUD)
Laydown Areas	$90,581
Pipelines and Bores	$26,191
Topsoil/Subsoil Stockpile	$71,699
Airstrip	$888,855
Borrow Pits	$64,320
Plant	$662,959
Haul roads	$212,207
Camp	$762,060
Rail Loop	$132,171
BWT Pit	$24,871,067
AWT Pit	$418,211
Landfill	$1,346,671
TSF	$7,475,761
ROM Pad	$260,277
Waste Dump	$5,480,316
PAF Dump	$1,848,723
Total	**$44,612,069**

Mine Activity Type	Disturbance Category	Disturbance Total (ha)	Land Under Rehabilitation Category	Land Under Rehabilitation Total (ha)	Total Area of Activity (ha)	RLE ($)
Laydown or hardstand area	C	4.99	E	0.00	4.9900	89,820.00
Borefield	C	1.44	E	0.00	1.4400	25,920.00
Topsoil stockpile	E	3.95	E	0.00	3.9500	7,900.00
Airstrip	C	44.79	E	0.00	44.7900	806,220.00
Borrow pit or shallow surface excavation (with a depth of less than 5 metres)	C	3.24	E	0.00	3.2400	58,320.00
Plant site	B	31.29	E	0.00	31.2900	938,700.00
Transport or service infrastructure corridor	C	10.02	E	0.00	10.0200	180,360.00
Building (other than workshop) or camp site	C	35.97	E	0.00	35.9700	647,460.00
Transport or service infrastructure corridor	C	28.75	E	0.00	28.7500	517,500.00
Mining void (with a depth of at least 5 metres) - below ground water level	B	15.00	E	0.00	15.0000	450,000.00
Mining void (with a depth of at least 5 metres) - above ground water level	C	180.00	E	0.00	180.0000	3,240,000.00
Landfill site	B	8.36	E	0.00	8.3600	250,800.00
Tailings or residue storage facility (class 2)	B	46.00	E	0.00	46.0000	1,380,000.00
Run-of-mine pad	C	10.00	E	0.00	10.0000	180,000.00
Waste dump or overburden stockpile (class 2)	B	225.80	E	0.00	225.8000	6,774,000.00
Waste dump or overburden stockpile (class 2)	B	4.44	E	0.00	4.4400	133,200.00
	Total:	654.0400	Total:	0.0000	654.0400	15,680,200.00

Remove All Print List

Figure 2 MRF Calculator Output

Table 4 RCE Tool Outputs

Domain		Security Deposit ($AUD)	
		Hard-coded Rates	**Customised Rates**
Domain 1: Infrastructure		$29,678,700	$21,483,076
Domain 2: Tailings & Rejects		$4,377,243	$7,279,563
Domain 3: Overburden & Waste		$5,968,125	$7,804,915
Domain 4: Active Mine & Voids		$16,110,595	$25,289,279
Domain 5: Management Activities		$7,511,500	$7,511,500
Subtotal (Domains and Sundry Items)		**$63,646,163**	**$69,368,333**
Contingency	$12,729,233	$13,873,667	$12,104,406
Post Closure Environmental Monitoring	$3,182,308	$3,468,417	$3,026,101
Project Management and Surveying	$12,411,002	$13,526,825	$11,801,795
Total Security Deposit for the Mining Project (excl. Tax)		**$91,968,705**	**$100,237,241**

3.2 Observations

3.2.1 MRF Calculator

The MRF Calculator accepts hectare-based quantities and allows domain selection from a drop-down list. With the exception of the waste dump containing PAF material, all domains were considered to be reasonably represented by the available list. Based on the input data, the MRF output estimated rehabilitation costs to be 64.5% less than the Prepared Estimate, although costs for some individual domains were greater than associated areas in the Prepared Estimate. The most significant point of variation was BWT pit backfilling, accounting for $24.4M of the $28.9M difference (refer to Section 4.3). Only three domains were predicted with less than a 15% variation from the rehabilitation components of the Prepared Estimate.

3.2.2 RCE Tool

The RCE tool contains an extensive pre-loaded domain-based activity list encompassing a range of standard closure activities (including alternative levels of effort). Input units of measure are hardcoded and the Cost

Schedule cannot be modified – as such, rate overrides could only be completed for easily convertible units of measure (e.g. $/m^3 to $/ha). Quantities and associated rates representing rehabilitation activities were easily translated, however decommissioning activities required conversion to 'floor plan' values; as a result, rate overrides (per hr) were not undertaken. Key criteria and assumptions for each inbuilt rate are provided, however detailed build-ups (i.e. productivity calculations) are not presented.

Modelled outputs of the RCE Tool were $13.5M (12.1%) lower than Prepared Estimate costs using inbuilt (fixed) rates. Where domains could be aligned, most were observed to be under-predicted with the exception of Infrastructure (which comprises primarily decommissioning costs). Using rate overrides, the RCE Tool outputs were a good match to the Prepared Estimate, however differences in the bitumen removal rate of up to $17/m^2 between modelled scenarios was largely responsible for the downward shift of infrastructure costs which accounted for the overall $5.2M (4.2%) difference between Scenario 2 and the Prepared Estimate. An increase in backfilling rate from the Hardcoded scenario ($3.90) to Overridden ($6.28), to account for site-specific haul distance and gradient) resulted in a $9.4M increase in backfilling costs, which represented the single largest difference between the modelled scenarios.

4 Discussion

4.1 Building a Cost Basis

As the MRF Calculator and RCE Tool contained limitations, such as pre-defined rates or specific quantity requirements, assessing their reliability depends on the level of alignment with the stated closure requirements of the conceptual site.The MRF does not prompt or require a cost basis to be documented, however the RCE Tool includes a table to document rehabilitation requirements and assumptions which serves as a prompt for users to record some aspects of the cost basis (i.e. rehabilitation scope). To allow the model outputs to be interrogated and to understand shifts in closure liability estimates overtime, cost model users should document a detailed estimate basis which supports the cost model outputs. Conversely, care should be taken when interpreting costs presented without a documented basis.

Despite limitations in the underlying model compositions, the assessed models were prepared from the same costs basis as the Prepared Estimate. An effective cost basis requires a thorough understanding not only of the constructive and legal obligations that impact on closure, but also on the requirements of closure project execution. In essence, a cost basis must fully define the site-specific scope that will be priced, as well as providing some treatment of the risk profile that may impact on the estimate. This study has been carried out on a relatively simplistic cost basis as the Barnaby Mine's closure commitments are not overly onerous. As the following sections outline, cost models that enforce simplification of site-specific closure requirements may inherently under- or over-estimate the true cost for closure, particularly for sites with more complex closure requirements.

4.2 Closure Scope

The full scope of closure for the Barnaby Mine was broken down into a Level 4 WBS in the Prepared Estimate. A site-specific WBS ensures that the estimate addresses each element of the project scope and should be prepared to at least Level 3 so that it includes areas, subareas and systems (AusIMM 2013). Both the MRF Calculator and RCE Tool divide the estimate up into Domains - a Level 1 or 2 WBS – with further granularity not accommodated. This is a typical limitation of many cost models, although more advanced tools allow scope specificity to be captured via user-defined itemised WBS elements.

In the case of the MRF Calculator, the scope of closure covered by the model is limited to Rehabilitation. The underlying assumption is that all infrastructure is already removed and is not considered in the financial assurance calculation. As indicated above the absence of a documented cost basis could result in this being misinterpreted. The RCE Tool breaks the scope of work down to a higher degree than the MRF Calculator and does include infrastructure removal, but the hard-coding of the model is somewhat restrictive as it does not allow itemisation at the asset or feature level. Beyond the costs of demolition and rehabilitation execution, other closure costs which owners should include in the full cost of closure – including pre-closure data collection and engineering studies, community consultation, human resources and post-closure monitoring and maintenance – are addressed with differing levels of detail within the RCE Tool, with single line item provisions required to capture some elements of the conceptual site. Such costs are not facilitated within the MRF Calculator. This observation is illustrative of the requirement to fully understand the scope of closure so that adequate provisions can be made within a given cost model for all aspects.

4.3 Model Components and Sensitivities

Rates

Both representative models assessed provided outputs of varying alignment with the Prepared Estimate, which highlights the importance of understanding estimate sensitivities in preparing closure cost estimates. The BWT pit domain in the Prepared Estimate involved backfilling ~4Mm^3 of material, making this activity particularly sensitive to rate. The rate for this element was activity specific, accounting for site-specific aspects such as haulage distance and associated road gradients which directly impact on fleet productivities. This specific area of sensitivity was not accounted for in either model until rate override was implemented within the RCE Tool. On a related note, differences in the bitumen removal rate between modelled scenarios was assessed as being primarily responsible for the downward shift of infrastructure costs. The RCE Tool with its ability to override rates, therefore represents a preferred level of robustness in pricing over the MRF Calculator, however without the in-model ability for bottom-up rate preparation its reliability will vary without external validation of rates (in-built or use defined). It must be recognised that the benefits of simplicity in using a model tend to become reduced as the internal functionality is overridden by specialist inputs (e.g. detailed rate build-ups).

Quantities

The MRF Calculator is limited in accepting per-hectare quantities only. Notwithstanding this limitation, this did result in outputs that were reasonably aligned with the Prepared Estimate for simpler disturbance (e.g. laydown areas). However, the inability to accept volume-based quantities limits its reliability for more complex features (e.g. waste rock dumps). In the case of Rehabilitation pricing the RCE Tool provided the required level of detail with regard to input volumes, however some conversion was required (e.g. between plan area and volumes of topsoil at a specified depth); ideally user defined quantities would be included in addition to rate overrides, as well as the capacity to introduce aspects such as growth or complexity factors in recognition of incomplete designs.

The RCE Tool required the input of surrogate quantities (e.g. m^2 floor space) in place of labour-hours for the majority of infrastructure included in the Prepared Estimate. The lack of alignment between infrastructure removal costs are symptomatic of the failure to account for the inherent complexity of fixed infrastructure with the application of duration-based build-ups (i.e. hr). For infrastructure-heavy sites, a professionally prepared estimate is likely to provide the optimal balance of efficiency in preparation and confidence in the output. Generally, it is recommended that cost models, if utilised, are able to accept durations as well as surrogate parameters, and this may represent a potential improvement to existing models going forward.

Indirect Costs

The inclusions in indirect costs should be documented in the cost basis, but generally cover temporary facilities, construction support and engineering, procurement and construction management (EPCM), and can also include owner's costs (AusIMM 2013). These cost are allowed for in the Prepared Estimate as percentage allocations against direct costs. The MRF Calculator does not appear to account for indirect costs, but due to lack of visibility in the rate build this could not be confirmed. The RCE Tool prompts a percentage allowance for Project Management and Surveying to be included but does not provide any guidance on determining the amount to apply. Users of this tool should therefore seek professional input to determine the appropriate allowance for indirect costs to include in the estimate.

4.5 Other Considerations

Uncertainty and Risk

A robust closure cost estimate requires an understanding of the risks and uncertainties that are unique to every project. Uncertainty is reflected in the Prepared Estimate by applying a contingency allowance reflecting an appreciation of the 'known unknowns' within the project scope. The applied allowance of 20% was allocated in consideration of the class of estimate prepared. The MRF does not include a separate contingency allocation, however as there is no visibility regarding the underlying rate build-ups it is unknown if uncertainty is built into utilised rates (e.g. application of growth). The RCE Tool includes a user specified contingency allocation but the tool does not include in-built guidance on the level of contingency that should be applied. In the case of the RCE Tool, users could turn to established capital project cost estimating guidelines to assist in determining the appropriate contingency to apply based on the maturity of their input data, or determine it based on a probabilistic analysis (e.g. Monte Carlo simulation); the critical consideration is that the determination of contingency (and specific risk if considering out-of-scope risks) must occur outside the model.

Accuracy

Inherent in the various requirements of closure cost calculations is an acceptance of the accuracy requirements of the end-use – namely that the estimate provides sufficient accuracy to reliably estimate the scope and assumptions of the project (Drysert 2006). The MRF Calculator and RCE Tool have no stated accuracy range, and indeed there is no cost model that can output the accuracy of a liability calculation; this process requires the specific input of specialist stakeholders and the use of dedicated software (e.g. to perform a Monte Carlo assessment) *after* the estimate is prepared. Thus, an appropriate understanding of the project scope or cost basis will not be sufficient to determine accuracy. It is recognised that accuracy assessments are only recommended for certain classes of assessment, however linking of the required accuracy to the selected methodology – even at a qualitative level – should be undertaken by an appropriately qualified estimator or based on industry-accepted guidance.

4.6 Requirements of a Robust Estimate

At its core the issue of cost models (and which one to use) vs. professionally prepared estimates is one of *understanding*, specifically:

- Is the required level of accuracy of the closure cost understood?
- Is the scope of closure understood to a level sufficient to match the required accuracy?
- Is the underlying costs basis understood and documented?
- Are the specific limitations and sensitivities of the cost model, and how to account for them, understood?
- Is the risk profile of the project outside the defined scope understood?

The requirements of a robust cost estimate have been defined by several industry guidelines and academic papers (Goldstein & Ritterling 2001, AusIMM 2013, DOE 2015, MERN 2017) and adapted in the following table to illustrate both the range of functionality available in closure cost models but also to reiterate the fact that some aspects will always require development outside the model.

Table 5 Robust Cost Estimate Components

Component	MRF	RCE Tool
Documented Estimate Basis	Not inbuilt	Not inbuilt
Itemised WBS	No	No
Project-specific equipment and rates	No	Partial (over-ridable)
Direct costs (as required)	Partial (rehabilitation only)	Yes
Indirect costs	No	Yes
Growth	No	No
Contingency	No	Yes
Assessment of accuracy	Not inbuilt	Not inbuilt

4.7 A Practical Approach

Whilst there can be no definitive rules to dictate which estimation mechanism or model should be employed in calculating closure costs, we posit that a general approach can provide useful guidance to assist decision-makers in selection of alternative methodologies for calculating closure liabilities, and in particular operators seeking to develop bespoke internal solutions. Figure 3 outlines the steps that should be considered in this process.

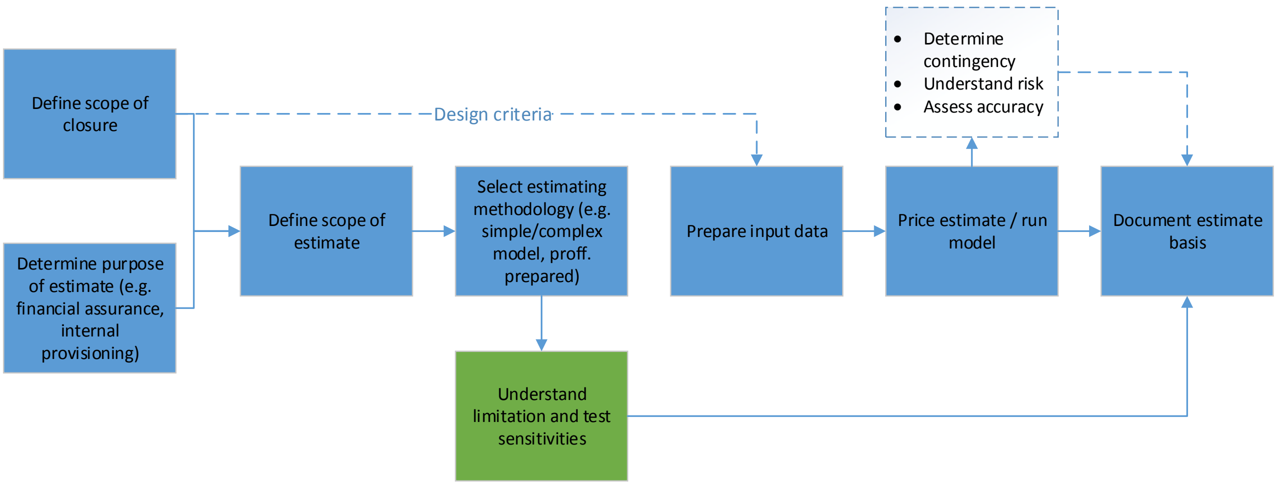


Figure 3 Process Approach to Cost Methodology Selection and Estimate Development

5 Conclusion

Two representative closure cost models of differing levels of detail were compared to a Prepared Estimate utilising the same input data (where possible) representing a simplified conceptual open cut mine. The outcomes of the assessment have highlighted the importance not only of understanding the inherent limitations of a chosen model, but also the site-specific sensitivities represented by the scope of a given closure project.

Cost models represent a trade-off between usability and level of confidence in calculated liabilities; similarly, the more complex the model, the greater the degree of specialist input required. Although no prescriptive criteria have been presented to dictate a 'best-fit' approach to estimating closure liabilities, this paper suggests there is a process that can be followed to have greater confidence in the implementation of cost models.

Ultimately, the realities of closure and the tangible liabilities that they represent are coming into greater focus over time. Regardless of the approach that regulators and owners take, it is recommended that they understand the limitations of the tools they are using to confirm that they are fit-for-purpose. Similarly, model developers should – wherever possible – work with industry to provide updates and add functionality with an aim to maintain the viability of their products in an era where increasing scrutiny is the norm.

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Planning and Implementing Surface Mines Reclamation Works under the New EU Strategy for the Transition of Lignite Intensive Regions to a Post-mining Era

FF Pavloudakis *Public Power Corporation SA, Greece*

CP Roumpos *Public Power Corporation SA, Greece*

EC Karlopoulos *Centre for Research and Technology, Greece*

NK Koukouzas *Centre for Research and Technology, Greece*

Abstract

The implementation of the EU energy strategy towards a low-carbon, climate resilient future poses significant technological, economic and social challenges, in particular for lignite-intensive regions that have to prepare for the reduction or phasing-out of mining and power generation activities, both due to market-driven trends and environmental policies.

This is also the case for the region of Western Macedonia, Greece, which suffers from the highest unemployment rate among the Greek regions, as a result of the gradual reduction of lignite production after the pick of 2004. Therefore, Western Macedonia needs an effective roadmap to make the necessary transition to a more diversified economy.

The present contribution tries a quantitative analysis of the impacts of lignite mining and power generation activities in creating and maintaining direct, indirect and inductive jobs, and producing gross added value at regional level.

It also describes the legal framework that regulates environmental management in Western Macedonia surface lignite mines and the main achievements of the land reclamation works that were carried out in the past, aiming at reforestation and development of farming land on the final surfaces of waste-heaps. Furthermore, it discusses some new ideas about innovative land uses, such as reforestation destined for timber production, livestock farming, herbs cultivations and construction of Photovoltaic Parks, which are considered to be in accordance to the regional strategy for the smooth transition of the local economy to the post-lignite era.

Keywords: *lignite, environment, surface mining, land reclamation, post-mining*

1 Introduction

The lignite surface mines of Public Power Corporation SA (PPC) in Western Macedonia region, which are in operation for 60 years, still play a key-role in the Greek energy system fuelling thermal power plants that meet ca. 32% (2017) of the country's electricity demand. According to the long-term energy plans of Greece, some of the existing or under-construction lignite-fired power plants in this region will be in operation until 2050.

Today, the mines extend over an area of 17,000 ha. Their total annual excavations exceed 170 Mm^3 and the lignite production is 27.2 Mt (2017). The applied exploitation method is based on continuous excavation, transport and stacking systems. This mining method is based on 42 bucket-wheel excavators, 16 spreaders / stackers and 230 km of belt conveyors, which have been installed in four surface mines. Conventional earth moving equipment is used mainly for the excavation of the hard-rock formations that are present within the overburden layers of South Field, the largest mine of the area. Unless appropriate preventive and mitigation measures are applied, the operation of the lignite mines of Western Macedonia will deteriorate the quality of environment in numerous ways due to the scale of the operations and the applied surface mining method (Pavloudakis et al., 2011).

To this context, strategic mine planning, aiming at the exhaustion of the lignite deposits under exploitation, is crucial for the sustainability of the projects considering the time and cost data of mining activities and the way that affect the optimal mine development and plans (Pavloudakis et al., 2009). It requires an integrated approach and optimization based on technical, economic, environmental or social parameters, considering also risk factors and uncertainties related to geotechnical, environmental and other technical parameters but also to changes in the regulatory framework and energy market trends (Roumpos et al., 2016). Emphasis should be placed on the development of a land reclamation model, which should select among various land uses based on a cost-effectiveness approach that meets regional development targets.

2 Environmental management in Western Macedonia lignite mines

In Greece, all mining and quarrying activities work according to the regulations determined in a Ministerial Decision amended in 2011. Moreover, mines and quarries have to meet quality standards and to apply preventive and mitigation measures that are described in numerous National laws and European directives.

Nevertheless, the main legal tool that regulates all environmental management decisions of a mining company is the environmental permit. The first permit referring to the mining activities at the Western Macedonia lignite mining complex was signed in 2001, after a long period of negotiations with all the involved local and National authorities. Since then, additional permits have been signed for all mining operations, as well as for numerous auxiliary activities, such as the ash disposal site of Meliti Thermal Power Plant (2002) and the asbestos cement disposal site (2004).

The main issues introduced by the environmental permits are the following (Pavloudakis & Agioutantis, 2008):

- Development and implementation of a land reclamation programme, according to specific guidelines dealing with the following issues: reforestation, waste heaps topography, landslides prevention, topsoil management
- Management of various waste streams
- Monitoring environmental quality

Environmental permits refer also to the costs of implementing the above-mentioned terms and conditions for the permitting period and until mine closure / rehabilitation (Table 1). This cost includes all the activities required for environmental management during mining operations and land reclamation according to the plans that have been approved by the authorities.

It is worth noticing that, for compensating the adverse impacts of lignite surface mining on the environment and on other economic activities, PPC pays a revenue bond, which corresponds to 0.5% of the company's turnover. The total amount of money that has been paid from PPC since the beginning of this bond is ca. 260 M€. This bond is distributed to the Prefectures, where lignite mining activities are carried out, accordingly to the lignite quantities produced. The local authorities have taken full responsibility for using this bond for financing various development projects.

Table 1 Cost of implementing the terms and conditions of environmental permits

Mine complex	Total area occupied (ha)	Environmental cost until permit expiration (€)	Environmental cost until mine closure (€)
Ptolemais	14,792	25,000,000	90,000,000
Amynteon	5,294	8,000,000	40,000,000

The general planning of land reclamation is based on the map of land uses, which is part of the Environmental Impact Assessment study that has been approved by the Ministry of Environment. Up to now 3,700ha of mine land has been reclaimed, mainly final surfaces of waste heaps, where waste rocks and ash produced from the nearby thermal power plants have been dumped. The usual reclamation procedures that are applied by PPC are: (a) the development of farming lands in horizontal areas on the top of the waste heaps and (b) the reforestation of the sloped surfaces of the heaps' margins. The cultivated land is rented to local farmers at 100€ per ha and year and is seeded with wheat. The productivities achieved are varying considerably from site to site. In general, the productivity of the reclaimed lands varies from 1,000 kg/ha to 4,000 kg/ha (average value is 2,200kg/ha) and is comparable to this reported for cultivations developed in the surrounding areas (Pavloudakis et al., 2011).

3 Effect of mining activities on regional economy

The lignite industry in Western Macedonia strongly affects the regional economy in a multidimensional way, which can be systematized into direct, indirect and inductive effects, as depicted in Figure 1.

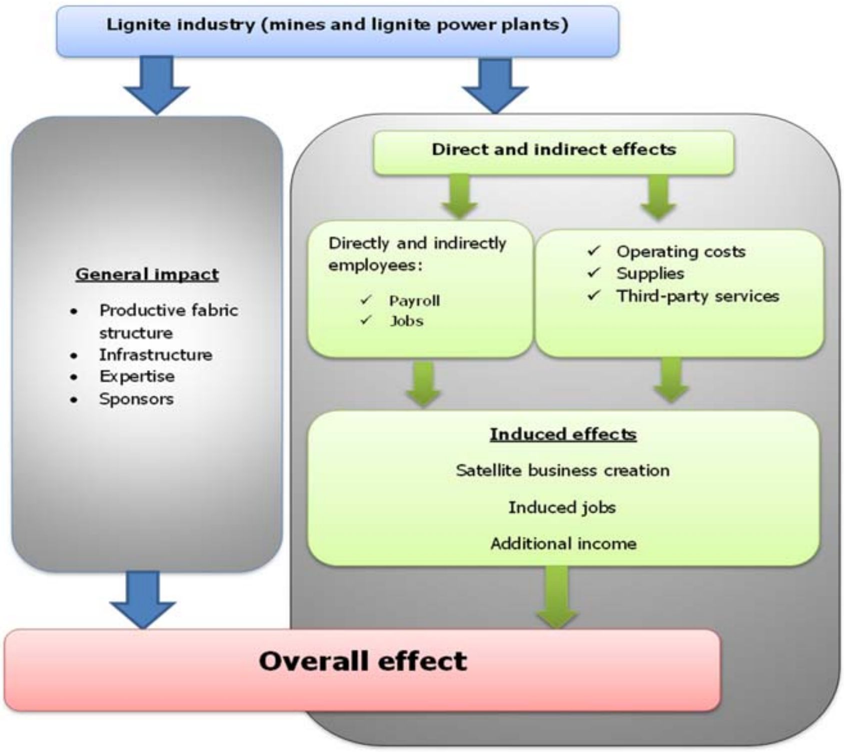

Figure 1 Overall effect of the lignite industry to the regional economy of Western Macedonia

The direct effects are mainly characterized by the effects that arise mainly from lignite industry and include the primary production, jobs and employee salaries. The indirect effects include investment and expenditure on products, services and goods required for the proper lignite industry function. Indirect effects originated from the satellite business as well as from the jobs that are created by the aforementioned requirements. The induced effects are pointed to the wealth and jobs. They are the result of workers incomes that are employed directly or indirectly in the lignite industry.

The quantitative characteristics, emerging with regard to the lignite industry influence on both wealth creation and local labour market, are summarised as follows (TCG/DWM, 2012):

- At the peak of lignite production, more than 34% of the Gross Added Value of the Region of Western Macedonia, about € 1.5 billion, came from the mining and energy sector, wile 22.5 thousand of direct, indirect or inductive jobs are related to the power production industry.

- For each permanent staff position in the lignite mining and power production, 3.28 positions are created and maintained in the local labour market. For each Euro spent by the lignite industry in salaries and sub-contracting, more than three Euros are inductively generated to the local economy cycle.
- Decommissioning of 300 MW lignite power would deprive the local economy by 83 million EUR on annual basis. If 2,400 MW are decommissioning, without equivalent support measures, the results may be extremely catastrophic for the regional socioeconomic status.

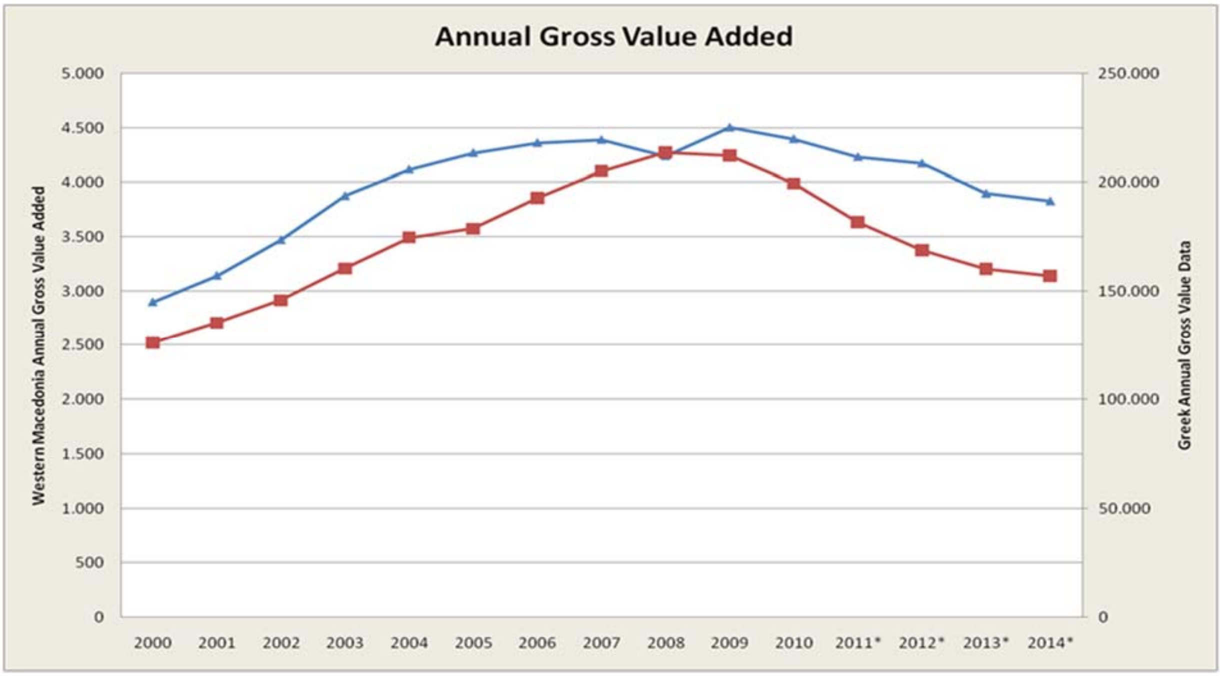

Figure 2 Annual change in Gross Value Added in Greece (red line) and Western Macedonia region (blue line) (2000 is the reference year)

Furthermore, from the comparison of Annual Gross Value Added in Western Macedonia Greece with the relevant figures of Greece, it is concluded that Western Macedonia entered in the economic downturn in 2006, before the start of national economic crisis (2009). On the other hand, the economic crisis effects have milder features in Western Macedonia than in the rest of Greece (Figure 2).

The abovementioned findings are the result of the regional productive model structure. The labour market dependence on the lignite industry is prevailed. This high dependence on lignite industry is a financial mound against the widespread economic downturn.

The Leontief Input-Output Model was used in order to determine the contribution of the mining industry in the regional economy, compared with other productive activities. The model is a linear economic model with multiple sectors. Each individual sector is dependent upon the other sectors in that each one uses the output of another. This technique was developed for the quantitative analysing of the interdependence of producing and consuming units in an economy. The model studies the interrelations among producers as buyers of each other's outputs, as users of resources, and as sellers to final consumers. It also provides a picture of the interconnectedness of the various areas in the economy. All inputs and outputs are expressed in the same units, usually in monetary units per unit of time.

In the examined case, the Leontief model depicts the interdependencies between various economic sectors of regional economy and leads to the multipliers of production, income and employment evaluation. The published catalogues of Greece Inputs - Outputs at the current prices of 2005, 2010 and 2013 years of Hellenic Statistical Authority were considered as the basis of calculation.

As it is shown in Figure 3, a gradual decline in total Gross Value Added at Western Macedonia level has been observed since 2009, with a simultaneous increase of energy sector impact. This means that the relatively stronger shrinkage of other manufacturing sectors in Western Macedonia highlights the mining industry more and more dominant in the local economy. In 2000, only 32% of the Gross Value Added in Western Macedonia came from lignite while in 2014 the percentage rose to 42% (TCG/DWM, 2018).

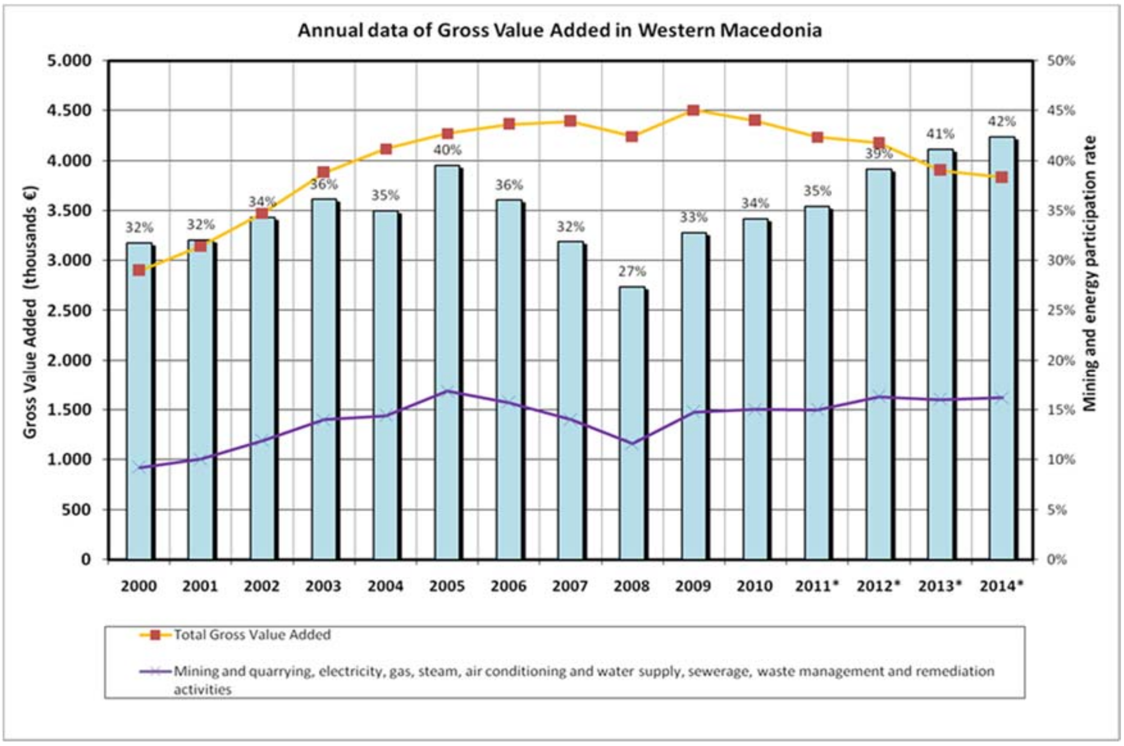

Figure 3 **Annual Data of Gross Value Added and Mining & Energy Production Sector in Western Macedonia.**

A first phase of local lignite industry shrinkage occurred during the period 2010 – 2015, where 663 MW of the oldest lignite-fired units have ceased operation. In parallel lignite electricity production has lost its significant position in the Greek energy mix.

A second, more severe wave of lignite sector reduction will occur in 2020, due to the 6 lignite-fired units planned operation termination dealing with 1812 MW capacity, according to the existing environmental limitations.

Furthermore, according to the proposed National Strategy for Adaptation Measures to Climate Change, Ministry of Energy (2015), where regions vulnerability was examined in terms of economic activity sectors, it was estimated that the local negative impact could possibly be fourfold compared to other Greek regions, mainly derived from the reduction of lignite mining activity.

4 The transition to the post-mining era

The EU policy against climate change is expressed by the *Clean Energy for All Europeans* package. This package is also conducive to jobs and growth by stimulating new employment opportunities in the energy sector and investment in modern technologies. Between 2008 and 2014 the number of jobs in renewable energy sector has increased by 70%.

As part of the *Clean Energy for All Europeans* package, the European Commission launched in December 2017 a Platform on *Coal Regions in Transition* to help regions with coal mining activities identify, develop and implement projects in order to kick-start a viable economic and technological transformation.

Today, 41 regions in 12 Member States are active in coal and lignite mining, providing direct employment to about 185,000 citizens. However, over the past few decades the production and consumption of coal and lignite in the EU has been in steady decline. Planned and ongoing closures of coal mines and the commitment by a number of Member States to phase out coal use for power generation are expected to accelerate this downward trend. In view of this, the Platform for *Coal Regions in Transition* is designed to assist Member States and regions to enable a multi-stakeholder dialogue on policy frameworks and to finance structural transformations, including economic diversification and reskilling, the deployment of renewable energy technologies, eco-innovation and advanced coal technologies.

The Platform on *Coal Regions in Transition* is working on a pilot basis with a small number of regions in Member States on planning and accelerating the process of economic diversification and technological transition through technical assistance, information exchange and tailored bilateral dialogue on relevant EU funds, programmes and financing tools. Based on requests by these Member States, pilot country teams for Slovakia, Poland and Greece were established in the second half of 2017 to assist the regions of Trencin, Silesia and Western Macedonia based on their specific needs.

In case of Western Macedonia region, the total financial resources required to be invested in tackling unemployment from the energy sector are estimated at between € 1.18 and € 3.54 billion, depending on the mix of development and investment policy chosen to be implemented and obviously by its capacity for attracting investment (Giannakopoulos et al. 2018:2). This policy should be based on the following three pillars and their corresponding pilot projects:

- Governance of transition
  - Development of a transition framework based on a holistic approach for interventions
  - Establishment of the portfolio fund "Western Macedonia Development Fund
- Development of low carbon society promoting technical innovation
  - Exploitation of lignite units decommissioning requirements
  - Western Macedonia Regional near zero heating oil dependency until 2025 - A decentralised RES applications Region
  - Upgrade of the building sector towards zero emission in Western Macedonia
  - Development of a New Deal for lignite exploitation in Western Macedonia
- Development of a new sustainable production model
  - Exploitation of land rehabilitation requirements
  - Development of agricultural production chain
  - Development of Education – Training programmes

Regarding in particular rehabilitation of areas where lignite deposits are depleted, the success of this project is crucial for the Region's transition dealing with the form and size of new land to be available, imposing their future possible uses. These land uses should be determined taking into account the existing requirements for mines operation, the related time schedule and the site-specific characteristics of the mining area, based on the following:

- Reduction of environmental impact.
- Adoption of novel concept for forestry creation in terms of environmental – water requirements and management.
- Formulation of RES areas with respect to advanced decentralized concepts.
- Exploitation of depleted mine areas for use of different economic activities (agriculture, recreation, tourism etc.)

The proposed strategy will ensure that land reclamation activities are implemented appropriately, in accordance to the regional development policy and in a cost – benefit base. It will contribute also to new business opportunities, jobs creation and development of technical know-how and experience (Giannakopoulos et al. 2018:1).

It is worth noticing that Public Power Corporation SA (PPC) has already undertaken action aiming at an improved valorisation of reclaimed mine land that is currently not under optimal use.

In order to boost the agricultural economy of the greater mining area, 150 ha of reclaimed waste heaps surfaces will be offered to young farmers for aromatic herbs cultivation. This type of crop is considered as suitable for reclaimed mine surfaces according to a study conducted by the School of Veterinary of Aristotle University of Thessaloniki. The study concluded that the productivity of the reclaimed mine land does not differ significantly to this of the land that was not used for lignite mining. The crops that are primarily recommended are vineyards, edible legumes and aromatic herbs, and marginally cereals. The cultivation of energy crops, rye and oats is suggested only after improving of the soil characteristics in areas where this is economically feasible (Profitou et al., 2010).

Apart from food crops, the cultivation of dedicated industrial and forestry crops and their conversion into added-value products is another promising alternative for reclaimed mine land exploitation. This challenge also includes establishing the required logistics to ensure year-round supply of the produced biomass to combustion plants, biorefineries, etc., providing the structure for a sustainable operation with minimal losses within the value chain. On this matter, it is important to: (i) identify and cultivate the most suitable crop varieties (including forest trees and perennial grasses) and implement sustainable agronomic practices to ensure long term land profitability (ii) understand how such biomass can be best handled, stored and transported depending on the local specificities and the quality characteristics required by the conversion pathways and end product requirements. For ensuring crop productivity with sustainable biomass yields at cost competitive levels in such a 'low margin/ high volume' business case, the following key-parameters need to be carefully managed: reliability, cost control, flexibility, sales volume and stakeholders' awareness.

PPC, in co-operation with the Institute of Forest of the National Foundation of Agricultural Research, investigated the possibilities of developing a new reforestation plan for the mine surfaces that will be gradually available for reclamation until the mine closure in 2050. The total area that will be reforested is 5,381 ha; 80% of this will be planted with various trees, while 20% will be used for the development of infrastructures (e.g. roads, recreational parks). More specifically, the areas that will be reforested are divided in three categories:

- forests of ecological importance (20% of the final reforested area),
- forests destined for timber production (30% of the final reforested area),
- forests destined for livestock farming (50% of the final reforested area).

The plants that will be selected for the reclamation of mines should be perennial, with ability to grow in soils with deficiency of nutrients and should provide enough land coverage and efficient stabilization of soils. Moreover, reforestation with native species will contribute further to the preservation of the diversity of species (Platis et al., 2011).

PPC-Renewables, a wholly-owned subsidiary of PPC, has commenced to develop a power plant project with an intention to construct Greece's largest biomass combined heat and power plant, in order to provide $25MW_e$ of electricity and $45MW_{th}$ of heat. The plant is planned to be installed at an area reserved for PPC Renewables of approximately $58,000m^2$, near the PPC's existing Thermal Power Plant of Amynteon and will be using the existing facilities in order to be connected to the electrical and district heating grids. PPC Renewables has already obtained a Production License from the Regulatory Authority of Energy and has conducted a number of different studies during the past several years.

PPC-Renewables plans to develop a Photovoltaic (P/V) Park on reclaimed waste heaps surfaces of Ptolemais lignite mines. The P/V Park will be constructed in four plots with a total area of 500 ha. For this purpose, PPC-

Renewables carried out an *Invitation for Expression of Interest* procedure for the selection of a long-term strategic partner in the field of renewable energy sources. The main goal of this co-operation will be the construction and operation of a P/V Park in Ptolemais area, with a total capacity that will gradually reach 200 MW, as well as the construction and operation of a plant for solar panels production.

5 Conclusion

The lignite surface mines of West Macedonia play a key-role in the Greek energy system. After 60 years of operation they still are the main pillar of the regional economy while, at the same time, play a key-role in the Greek energy system.

The legal framework that is now in force for the environmental management of lignite mining works requires the issue of environmental permits, which determine a series of terms that regulate the implementation of preventive and mitigation measures for protecting the environment as well as the reclamation of the land that is not used further for mine development.

In this context, the lignite mines of Western Macedonia apply for more than three decades a land reclamation programme, which has given some excellent paradigms of rapid and effective reforestation of waste heap surfaces and development of farming land with similar productivity in comparison with this of land that was not affected by the mines.

Furthermore, trying to use productively the inputs and perceptions from local authorities, public interest groups, universities and research institutes, a new action plan of land reclamation and use, which will drive Western Macedonia to the post-mining era, must be developed. The new plan will take advantage from the participation of Western Macedonia in the European platform for *Coal Regions in Transition* in order to demonstrate and implement innovative land uses, aiming at a rational economic exploitation of the mine land.

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Faro Mine Remediation Project: Working with Indigenous Partners to Achieve Mine Closure

L Spagnuolo *Department of Indigenous and Northern Affairs Canada, Canada*

Abstract

The Faro Mine, located in the Yukon approximately 200 km northeast of Whitehorse, Canada, produced lead and zinc intermittently from the 1960's until 1998 when Anvil Range Mining Corporation was placed into receivership. At one point, it was the largest open pit mine in the world and is now one of the biggest contaminated sites in Canada with over 320 million tonnes of waste rock and 70 million tonnes of tailings - both of which are acid generating and leaching metals into the surrounding environment. Indigenous and Northern Affairs Canada is responsible for funding the remediation of the Faro Mine site and works in close collaboration with a number of partners, in particular the Kaska Nation and Selkirk First Nation.

From 2003 until 2008, the project team completed various studies to characterize the environmental issues at the site which culminated in the development of a number of viable closure options. In 2009, the project team was able to reach consensus on a preferred option known as the 'stabilize-in-place' approach. This plan involves upgrading diversions and dams to ensure tailings remain stable, re-sloping all waste rock dumps to improve long-term stability and installing engineered soil covers over the tailings and waste rock. This option also provides for state-of-the-art collection and treatment systems for contaminated water post-closure.

Since 2009 the project team has been working to further develop the approved conceptual approach and complete a detailed Closure Plan. In 2018, this plan will be submitted to the Yukon Environmental and Socio-economic Assessment Board and Yukon Water Board for review. Following the issuance of all necessary licenses and permits, implementation of the Closure Plan is expected to start in 2022 and take approximately 15 years to complete.

Before mining commenced, the people of the Kaska Nation used the land for subsistence. The abandoned mine site is also upstream of the traditional territory of the Selkirk First Nation. As a result, there is particular interest in returning the site to pre-mining land use and minimizing any further impact to water quality while providing socio-economic benefits to the region. Therefore, through an on-going and respectful nation-to-nation dialogue, the Faro Mine Remediation Project is committed to developing a positive and long-term relationship which will result in their meaningful participation to remediate the site.

Keywords: *zinc, environment, mining, land reclamation, post-mining, dialog*

1 Introduction

1.1 Location

The Faro Mine site is located in the Yukon in north-western Canada, approximately 15 km north of the Town of Faro and 220 km northeast of Whitehorse. The site consists of two areas: the Faro Mine area and the Vangorda Plateau. The Faro Mine area includes the Faro Pit, waste rock dumps, former milling facilities and Rose Creek tailings impoundment. A 10 km haul road connects the Faro Mine area to the Vangorda Plateau which contains two additional open pits, the Vangorda pit and Grum pit.

The Faro Mine site is located in the Kaska traditional territory, as claimed by the Ross River Dena Council, Liard First Nation and the Kaska Dena Council (see Figure 1). Before mine development, people from Ross River utilized the area around the mine extensively for traditional activities (Weinstein 1992). The site is also located upstream of the traditional territory of the Selkirk First Nation. The Ross River Dena Council, Liard

First Nation and Kaska Dena Council do not have a final land claim agreement but several land selections surrounding the Faro Mine site are currently subject to interim protection.

Figure 1 **Faro Mine site**

1.2 Background

The Vangorda deposit was discovered and staked by Al Kulan with the assistance of Kaska prospectors Jack Ladue, Robert Etzel, Joe Etzel, Art John and Jack Sterriah in 1953. While this deposit was considered too small and remote for development at the time, it led to the 1965 discovery of the Faro deposit. The Faro Mine began operations in 1969 and ceased operations permanently when the site was abandoned by the company, Anvil Range, in 1998, leaving approximately 320 million tonnes of waste rock and 70 million tons of tailings that continue to pose risks to human health and the environment (SRK 2010).

Following the final shut-down in 1998, the Faro Mine site entered a care and maintenance phase. Care and maintenance activities are carried out to manage the environmental effects and risks associated with the site. This requires ongoing collection and treatment of contaminated water along with extensive maintenance and monitoring programs. From 1998 to early 2009, Deloitte and Touche Inc. conducted care and maintenance activities at the site, acting as the interim receiver for Anvil Range. In early 2009, Deloitte and Touche Inc. were discharged from these duties and the Yukon Government assumed management responsibility.

Indigenous and Northern Affairs Canada has worked with its partners (Yukon Government, Ross River Dena Council, Liard First Nation and Selkirk First Nation) to establish a joint project Oversight Committee. The committee provides a forum for the direct participation of the affected First Nations in defining, evaluating and selecting remediation options. The Oversight Committee's role is to provide strategic leadership in the identification and development of a recommended approach to long-term site closure and remediation.

In late 2009, the Oversight Committee selected the preferred option that would form the basis for the long-term closure plan. This option considered input from: hundreds of technical studies conducted by a multidisciplinary team of engineers and scientists; consultations with affected Yukon First Nations and communities; an Independent Peer Review Panel, comprised of leading experts in various facets of mine closure; and a multiple accounts-decision analysis that compared a range of options against the project objectives, conducted by a group comprising representatives of First Nation governments, technical consultants, and federal and territorial government representatives (SRK 2008).

The preferred option emphasized the need to stabilize contaminants rather than remove them from the Faro Mine site. Key features of the final closure plan include upgrading dams so tailings remain in place, re-sloping waste rock, installing engineered soil covers over tailings and waste rock, upgrading stream diversions, and upgrading contaminated water collection/treatment systems.

Once the Oversight Committee reached consensus about the main components of the long-term closure plan, the focus of remediation planning efforts shifted to the design, assessment, and permitting for the chosen option. Since 2009, a number of engineering and environmental studies have been conducted to advance the understanding of the final closure plan and associated potential environmental impacts.

2 Approach

2.1 How we engage

Engagement is a critical component of the Faro Mine Remediation Project. Engagement is defined as meaningful ongoing dialogue throughout the project life-cycle between the project and affected and interested parties. Because engagement is an inclusive term, it is used to refer to all engagement, consultation and communications activities. When needed, activities related to consultation or communications are specifically identified to differentiate them from broader engagement activities.

Consultation is any engagement where there is a statutory, contractual or common law obligation to consult and potentially a legal requirement to accommodate. In the case of the Faro Mine Remediation Project, this includes, but is not necessarily limited to, the Crown duty to consult affirmed in section 35 of the *Constitution Act*; section 6.62 and 6.64 of the *Devolution Transfer Agreement*; any requirements to consult noted in First Nations Final Agreements; as well as any consultation required as part of environmental and socio-economic assessment and water licence process required under the *Yukon Environmental and Socio-economic Assessment Act* and *Yukon Waters Act*, respectively.

Communication refers to the one-way flow of information from the project team to affected and interested parties (e.g. newsletters, website updates, media interviews, etc.).

2.2 Who we engage

INAC is committed to engaging with all individuals or organizations that are involved in the project, who may be impacted by the project, who have the ability to influence the project or who have an interest in the project more generally. This is an inclusive term used to refer to all of those with whom the project team engages, including the public, First Nations, and other government departments.

The term “Affected Parties” is used to refer to people or organizations that are directly impacted by the project where there is typically a statutory, contractual or common law obligation to consult. This includes First Nations, but may also include others such as land users and communities (e.g., hunting cabin owners and the Town of Faro).

The term “Interested Parties” refers to people or organizations that are interested in the project, involved in the project or who have the ability to influence the project. Interested parties are generally used to refer to anyone who is interested or has a role in the project but is not directly affected by the project. This includes governments and regulators, non-governmental organizations, contractors, Yukoners and the media.

2.3 Engagement Strategy

Engagement is critical to the overall success of large, complex projects like the Faro Mine Remediation Project. In 2015, following a period of inconsistent engagement, Indigenous and Northern Affairs Canada pursued the developed of a comprehensive Engagement Strategy (INAC 2016) that was adaptable and would guide the project.

Initial interviews were held with all partners to seek guidance and direction on the purpose and content of the Engagement Strategy. Follow-up interviews were then held in order to further gather content and inform the design of a 2-day workshop. This workshop, held in February 2016, allowed for the collective development of key elements of the strategy including: consistent terminology, vision of engagement, a revised approach to engagement; guiding statements; stakeholder analysis; roles and responsibilities; and monitoring and performance.

The Engagement Strategy includes seven core principles that guide behaviour and articulate the approach that will be taken for all engagement activities:

1. Integrated - implement an integrated and coordinated approach to engagement to present a unified front for the project.
2. Formalized - formalize an approach to engagement that is planned, predictable, regular and timely, focusing on small, frequent updates.
3. Respectful - be respectful of the uniqueness of the individuals/groups, tailoring and collaborating as required. Welcome all view points and input and acknowledge parties’ concerns as legitimate.
4. Responsive - meaningfully consider input from engagement activities, communicate how input is used and enable problem solving for issues that it cannot resolve.
5. Transparent - ensure that project information is proactively made accessible through multiple channels and that decision making processes are transparent and effectively communicated.
6. Competent - demonstrate competence and undertake engagement with a positive, confident tone.
7. Relevant - focus engagement activities on the areas of greatest concern to parties.

The vision of the Engagement Strategy is that all parties are well-informed about the project, have opportunities to share their views and contribute to the project, support the approach being taken to remediation and are confident that the project is being well managed. Finally, the strategy includes goals and corresponding objectives which articulate desired outcomes and how these outcomes can be achieved as outlined in Table 1 below.

Table 1 Engagement Strategy Goals and Objectives

GOALS	The integrated project team is well informed about the project, and is coordinated, and confident with respect to the role they play in engagement
	Affected and interested parties are well informed about the FMRP and have regular opportunities to voice their opinions and concerns
	The integrated project team is operating in an open, inclusive, responsive, respectful and transparent manner
	Affected and interested parties have increased trust in the FMRP, the integrated project team and the overall project management
	Affected and interested parties feel increased ownership and optimism with respect to the future of the site and are aware of opportunities to participate in the project
OBJECTIVES	A well-equipped, coordinated, integrated project team is in place
	Project status is proactively and frequently communicated through a range of channels
	Engage-ment is undertaken with confidence, in a professional tone and in plain, meaningful language
	Engagement opportunities are regular, predictable and appropriate for the audience
	Emerging issues are acted on intentionally and effectively
	Feedback is provided on how input has been used and on engagement progress
	Engagement focuses on areas of greatest interest and/or concern to parties
	Opportunities to contribute to the project are proactively communicated through predictable channels

2.3.1 Stakeholder Analysis

As part of the Engagement Strategy, a separate exercise was undertaken to identify categories of affected and interested parties in order to provide high level guidance regarding the specific engagement requirements for each category, as outlined in Table 2 below.

Table 2 Affected and Interested Party Categories

Categories	Description	Engagement Requirements
Affected First Nations	Kaska Dena Council, Liard First Nation, Ross River Dena Council and Selkirk First Nation	-Undertake consistent, meaningful, proactive and tailored engagement -Integrate into project governance -Accommodate where possible
First Nations and First Nation Organizations	Other First Nations and First Nations Organizations	-Provide regular engagement opportunities -Consistently keep informed -Undertake engagement with select groups
Local Governments	Local cities, townships and associations	-Provide regular engagement opportunities -Consistently keep informed -Undertake tailored engagement with groups
Federal and Territorial Regulators	Federal and Territorial departments and regulators (e.g. Water Boards, Fisheries and Oceans Canada)	-Undertake tailored engagement with select organizations -Consistently keep informed
Non-governmental Organizations	Territorial and national groups interested in the project	-Provide regular engagement opportunities -Consistently keep informed
Media / Public	National, territorial and local media and public.	-Proactively engage as required; remain responsive to requests for information
Business Community	The local business community	-Provide regular engagement opportunities -Consistently keep informed -Provide targeted communications materials
Research Institutions	Research institutions interested in the project	-Engage as required
Contractors	Key site contractors	-Ongoing two-way engagement to stay abreast of project activities
Site Users	Those who use the site and represent site users	-Provide regular engagement opportunities -Consistently keep informed; Undertake tailored engagement with select groups

2.3.2 Engagement Cycle

Annual engagement cycles have been developed to guide the timing of activities. Detailed annual plans are also developed as part of the detailed work planning process to provide further direction on engagement activities. The annual calendar and engagement cycle activities are used as a basis for the development of detailed annual project plans. In order to ensure that each task is carried out, a lead is assigned to develop and manage the activities. Depending on the task, the assigned lead will work with other Affected Parties as it carries out each activity. Table 3 below provides an example of some preliminary activities and associated documents that would be prepared to support ongoing engagement.

Table 3 Annual Engagement Cycle

Activity	Timing	Comments
Question & Answer Updates	As required	Key messages for use with media, public and stakeholders
Newsletter	2 per year, or as required	-Combines features with timely project updates, Question & Answer's, etc. -Distributed to mailing list, posted to website, promoted via social media
Website Updates	As required	Critical to keep site up-to-date as it is the "go-to" for many stakeholders
Generic Email Address	Respond to all enquires within 2 business days	Proxy access for staff in case of vacation or absence
Twitter Account	As required	Prepare pre-approved messages to be used during quiet periods
Media Relations (Pro-Active)	As required or as per annual work plan	Includes: media technical briefings, planned interviews, media training for media spokesperson(s)
Media Relations (Responsive)	As required	Project spokespersons are designated, trained and supported with approved messaging
Response To Unforeseen Events	Develop and deliver media messages within 24 hours in cases of emergency and 2-3 days for other issues	Important for both governments to collaborate to ensure consistent messaging
Community Forums And Open Houses	1-2 per year in First Nation communities 1 per year in Whitehorse 1 per year in Town of Faro	Hold community meetings/open houses for general public
Annual Planning	Completed in third quarter	

2.3.3 Governance

A robust governance structure has been put in place to monitor performance and ensure the goals and objectives of the Engagement Strategy are met. The Engagement Working Group is one of the mechanisms for coordinating and integrating engagement activities for the project. The Engagement Working Group serves as the mechanism to steward integrated and coordinated efforts on engagement priorities between the two governments and First Nations. The working group meets quarterly, or on an as needed basis, and: oversees and plans all engagement activities; advances specific engagement initiatives as required; reports directly to the Project Director who provides oversight, direction and approvals for engagement activities; and facilitates knowledge sharing between team members. The Working Group is chaired by the Engagement Lead, who is responsible for coordinating the strategy implementation, developing detailed annual plans, and maintaining and updating the strategy.

3 Results

While there were initial challenges with building the capacity within First Nations to be able to meaningfully participate in the project, the project is generally seeing an improvement to the quality and quantity of engagement activities. For example, in 2017 the project completed over 29 community engagement sessions, reaching 365 people, and managed 181 media events. In comparision, only 2 community engagement sessions, reaching 25 people, and 10 media events were completed over the same time period in 2016. In addition, the number of face-to-face meetings with stakeholders has steadily increased from 3 in 2015 to 40 in 2017.

A recently completed survey of the general public demonstrates that, as a result of the Engagement Strategy, there is a greater understanding of the overall project. In addition, the input that has been received from community engagement has been more comprehensive and detailed – which has been helpful in improving the overall quality of project activities. The stakeholders have also followed up on opportunities to share their views and contribute to the project, support the approach being taken to remediate the site and are more confident that the project is being well managed

4 Conclusion

The Faro Mine Remediation Project Engagement Strategy is a dynamic document, and will evolve with the changes to the project and broader contextual factors. While the principles, vision, goals and objectives of the strategy are expected to remain constant over the life of the five year strategy (and likely longer), the approaches and tools will evolve continually in response to successes, challenges and changes to project and affected and interested party dynamics.

Information overload for communities, particularly for a project of this size, is a constant concern. However, by developing a comprehensive and coordinated overall strategy, the project can provide targeted engagement and more efficient communication of project-related information.

By ensuring all Affected and Interested Parties participated in the development of the Engagement Strategy, the Project was able to achieve a higher level of ownership over the content and deliverables. In addition, integrating the Affected Parties into the Engagement Working Group to develop and distribute content helps to ensure the overall project message is delivered to relevant stakeholders.

Critical to the success of the overall engagement approach has been the integration of representatives of each First Nation into the overall governance of the project. This avoids the challenges associated with the typical engagement approach of developing project documents or strategies in isolation and then seeking support of Indigenous people on pre-developed products. By participating in each level of the project organization, the project has instituted an approach based on cooperation and partnership which ensures all decisions, from day-to-day operational decisions to long term strategic decisions, are made in collaboration with First Nations.

Acknowledgement

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Financial Calculation of Long Term Mine Closure Costs

C Drebenstedt *Technische Universität Bergakademie Freiberg, Germany*

Abstract

Every mine reached once its final stage – the closure of the mine. This is an unavoidable part of the mining process which can occupy a huge lapse of time. Due to that, it is very important to know in before about the tasks and challenges of a mine closure to be able to create a realistic financial calculation of the costs.

This paper introduces typical reasons for a valuation, the valuation model and the conclusions for the model drawn from a sensitivity analysis. Problems arising when the model is applied are highlighted in a case study.

Keywords: *mine closure, financial calculation, remediation, sensitive analysis*

1 INTRODUCTION

Mine closure is the final phase of a mine and summarized all organizational, technical and biological activities, starting with the end of the regular mineral extraction up the achievement of targets of post mining land use. This phase is characterized by lack of income from mineral extraction. There can be an overlap between the closure of parts of the mine and running mine operation. In mines with inside dumps, the reclamation can start early, if the first dump sides are not more necessary for mining and final prepared for land use. This activities not belong to mine closure, but to current reclamation. Mine closure is a process, which can divided into three stages:

- Short term tasks, regular solved within 5 years. To this tasks belong activities (if necessary) like: final mineral extraction, earth movements for land shaping and slope stability/ refill of underground spaces, slope shaping, mining equipment demobilization, clean up surface from constructions (camp, workshops, energy supply, water transport and treatment facilities …), construction of post mining infrastructure, adopted to the land use (drainage system for run of water to avoid erosion, road construction for excess …), start of revegetation …. In this phase dewatering, so relevant, continuous.
- For long-term tasks within 5 to 20 years, depending on project size, typical activities are: soil compaction, decontamination of soils, water pumping and treatment, cover tailings, revegetation with infrastructure and care about still reclaimed sides.
- Very long-term tasks, can last more than 20 years and partly forever. Typical activities are: dewatering to keep areas under groundwater level dry, water and soil treatment, monitoring of activities (stability of dumps and vegetation …), and aftercare of technical and biological measures…

When short term activities in mine closure can be calculated more or less precise and can be organized by the mining company, so, the long- and very long-term activities, mainly harder to predict in amount and time. Because of their long-term nature, the economical evaluation, e.g. behavioral alternatives, are therefore based on an inter-temporal valuation approach. As the evaluated objects usually do not create revenue, the valuation criterion will be the expense parameter that is expressed as the cumulative cash value of all costs and the investments still to be decided upon and thus relevant for the payments to be made. This expense parameter will have to be interpreted as a negative revenue item, so that the valuation approach introduced herein is a special case of the approach used to determine the capitalized value of potential earning, which is dominating in the mining industry.

The research work as well as training and further training at the TU Bergakademie Freiberg have focused for years now on problems concerning the commercial evaluation of deposits, of mining technologies, of mining projects and of mining companies, but the same problems have also been the subject of the consulting services and expert opinions provided by the University on behalf of governments, authorities and of the mining companies themselves (Drebenstedt and Slaby, 2007; Drebenstedt, 2006; Slaby and Drebenstedt, 2000a, 2000b, 2003; Slaby and Drebenstedt and Ohlendorf 2002; Steinmetz and Slaby, 1993; Wilke and Slaby 1993).

If the insights are summarized that have been gained on different objects of valuation, during different occasions for such a valuation and by considering the different valuation targets, the following three conclusions and the recommendations derived from them will turn out to be of fundamental importance:

- The fundamental approach to any kind of valuation in the mining industry is to consider the capitalized value of potential earnings. Alternative approaches to the valuation, such as to consider the net asset value as it is favored elsewhere, are either completely unsuitable for the valuation of deposits, inventories and projects or only partly suitable for the valuation of mining companies and plants.
- The evaluation strategy must take into account the valuation of deposits, projects and companies in their entirety.
- Conflicts existing between a mining company's internal economics (the pursuit of profit), between external effects (caused by interfering in the environment and in natural habitats) and with the duty to protect the deposits (caused by high extraction rates) can and will have to be considered in the decision-taking process to a reasonable extent on the basis of opportunity or alternative cost accounting.

Triggered off by the declining rate of the mining output (e.g. in the hard coal and lignite industry) and by the elimination of entire mining sectors (such as the Wismut), we have been increasingly confronted in recent months with the problem of a commercial evaluation of the ecological consequences of these mining activities as well as with the search for measures required to ward off the dangers arising from this situation and to secure a sustainable development. The relevant efforts have been focused on remediation, post-closure and long-term projects in connection with the Wismut and lignite mining activities. In view of the fact that the problem is of fundamental nature and that it concerns or affects all mining sectors, the work results and the experience gained during this work are to be made known in the following paper.

2 CONDITIONS FOR MINE REMEDIATION

Mining will always affect the environment. Regions where raw materials are produced by surface mining are particularly affected in this respect. The changes in nature caused by mining activities are most varied. They include changes in agriculture and thus to the biosphere, the temporary withdrawal of arable land and living space as well as their devastation, at least for some time, infrastructural changes in the region and the interference in natural and anthropogenic water systems. In order to secure the chances of future generations for a sustainable development, the natural balance affected by mining activities will therefore have to be redressed and the living space once given over to mining will have to be revitalized (Slaby, 1992, 1998; Gerhardt and Slaby, 1994, 2000).

The allocation of the professional, legal and commercial responsibilities will have to be based on the principle of causation. This means that the mining industry, i.e. the mining company causing the post-mining damage, will have to assume responsibility, as it is also stipulated in the german mining law. The general principles of providence and causation will then have to be complemented by the principle of burden-sharing, by the user principle and by the principles of feasibility and reasonableness, depending on the overlapping and distinguishing interests of other parties involved, especially as a result of the ongoing social development processes. One will have to bear in mind that, often enough, the mining companies causing the damage do no longer exist at the time when remediation and post-closure measures will have to be implemented (post-mining reconstruction) and when the contaminated sites will have to be recultivated (long-term obligation).

A major feature of the post-mining consequences caused by the elimination of former mining locations is their long-term character and the special risks as regards the expected and the actual scope of work. This applies particularly to remediation, post-closure and long-term objects in the field of water management, such as to objects for the collection, treatment and disposal of contaminated seepage water from mining slopes, dumpsites and disused industrial facilities, as well as to objects for controlling and limiting the rising ground water levels in old mining locations affected in this respect. Alternative technological and commercial options to solve the problems as well as specific technological and commercial risks are typical of these long-term objects, and they often seem to require an infinite duration to complete them, when one looks at these problems from today's point of view. These specific risks concern the insufficient knowledge of the effectiveness and the reliability of the technological solution applied, the time it will take to reduce the contamination, the required consumption of production factors (such as energy, chemicals etc.) in the course of time, the time involved to treat the relevant quantities of water or the inflow of water and, last but not least, the uncertainties as regards the development of the valuation parameters (such as prices and rates) for the consumption of these production factors during that time. The economical valuation of such objects requires necessarily an appropriate evaluation of the time factor and makes it necessary to take the various risks and trend factors into account. In other words, it is necessary to apply an inter-temporal valuation approach (Slaby and Drebenstedt, 2000a, 2003).

In the current practice of remediation mining, the general problem of the economical valuation of long-term remediation objects is embedded mainly in two fields of the decision-taking process.

First of all, as a pre-requisite for determining the most suitable option of technological and commercial behavioral alternatives. The problem to take a decision in this respect is above all characterized by the fact that the available technological options may oppose each other: one of them may require no or hardly any aftercare, but is cost-intensive, while the other one may require fewer investments, but more aftercare. The problem is here to make an inter-temporal comparison of the expenditure involved (i.e. the investments and the operating costs required), depending on the time when these amounts become due. The problem can only be solved by applying financial and mathematical valuation models.

Secondly, the progress made with the remediation creates the prerequisite for transferring the object into the responsibility of a third party. This transfer often comes along with a change in ownership, i.e. the local authority becomes the new owner, so that the supervision by the mining authority ends, as intended. It might be necessary to pursue the long-term jobs, such as monitoring and water management jobs, also in the future and under the auspices of the new legal owner, in order to contain or ward off post-mining damage affecting the general public.

The readiness of the future owner to accept the commercial responsibility for the project will depend on a reasonable funding. The volume of the funding depends on the services and costs for the relevant object still outstanding at the time of transferring the ownership. The calculation of the amount needed, e.g. a one-off payment to the future owner, will be based on a mathematical valuation model of the financial investments required, i.e. on the calculation of the cumulated capitalized cash value of all outstanding financial obligations.

A suitable approach to a solution of both problems is to mathematically determine the financial investment costs.

3 FINANCIAL VALUATION APPROACH

This approach makes it necessary to establish the cumulative cash value of all financially assessed expenses required for the valuation projects over a limited or unlimited time horizon (T) and in accordance with the required safety and remediation standards. These "mathematically calculated financial investment costs", referred to hereinafter as the expense parameter (AW), act as criteria when the commercial advantages of alternative options are compared and when a one-off payment is made to the future owner after the financial responsibility has been transferred. The calculation of the expense parameter AW is determined by the cash-layout costs (operating costs requiring payments) to be established for the period t. As well as by cyclic and non-cyclic investments that may become necessary. These payments are the input for the calculation. Should payments be received during the period T, such as in the form of revenue or investments, they will have to be offset against the payment made in the same period. Any balances from the liquidation are to be included in the calculation at the end of the project period T.

Calculation of the cumulative cash value of the periodic payments (the mathematically calculated financial investments) related to a base year (0) by taking into account:

- The period required for the relevant measures (T).
- The cash-layout costs at valuation level 0 by taking into account the possibly changing consumption of resources (such as energy, labor etc.) and investments during this period that might become necessary.
- The inflation-adjusted imputed interest (the real rate of interest).
- Trends concerning the changes in the valuation parameters and in the prices for the expense parameter, such as for energy, labor, replacement investments and material.
- A general inflation rate.
- the specific technological and commercial risks concerning the valuation objects.

Investments made and operating costs expended before the base year (0) will be disregarded in the calculation of the cumulated cash value for the payments due, they are irrelevant for the decisions (to be) taken in this respect, they are "sunk costs" by their very nature.

If the expense parameter AW is used as a basis for a one-off payment in the case of transferring the responsibilities, it will be assumed that this capitalized one-off payment made in the base year (0) will be capitalized as an annuity with a safe nominal interest rate over the limited or unlimited time horizon. This periodic annuity is then available with the required amounts to cover the payments, including the calculated trends in the expense and valuation level as well as for specific technological and commercial risks.

$$AW = \sum_{t=1}^{T} \frac{A_{t(0)}}{q^t} \qquad (1)$$

where AW = expense parameter; At(0) = periodic amount for the cash-layout costs and investments in period t at the valuation level in base year (0); q = imputed interest (the real rate of interest).

If AW in equation (1) = constant, the following applies:

$$AW = A_{t(0)} * \frac{q-1}{q(q-1)} = A_{t(0)} * KF \qquad (2)$$

where KF = capitalization factor.

The required cyclic and non-cyclic payments, such as for replacement and one-off investments, are included in annuity At(0) (as an investment annuity) of equation (2). The capitalized expense parameter AW will then be determined by the product of the largest period annuity of all payments and of the capitalization factor. The valuation model shown in figure 1 illustrates the suggested valuation strategy.

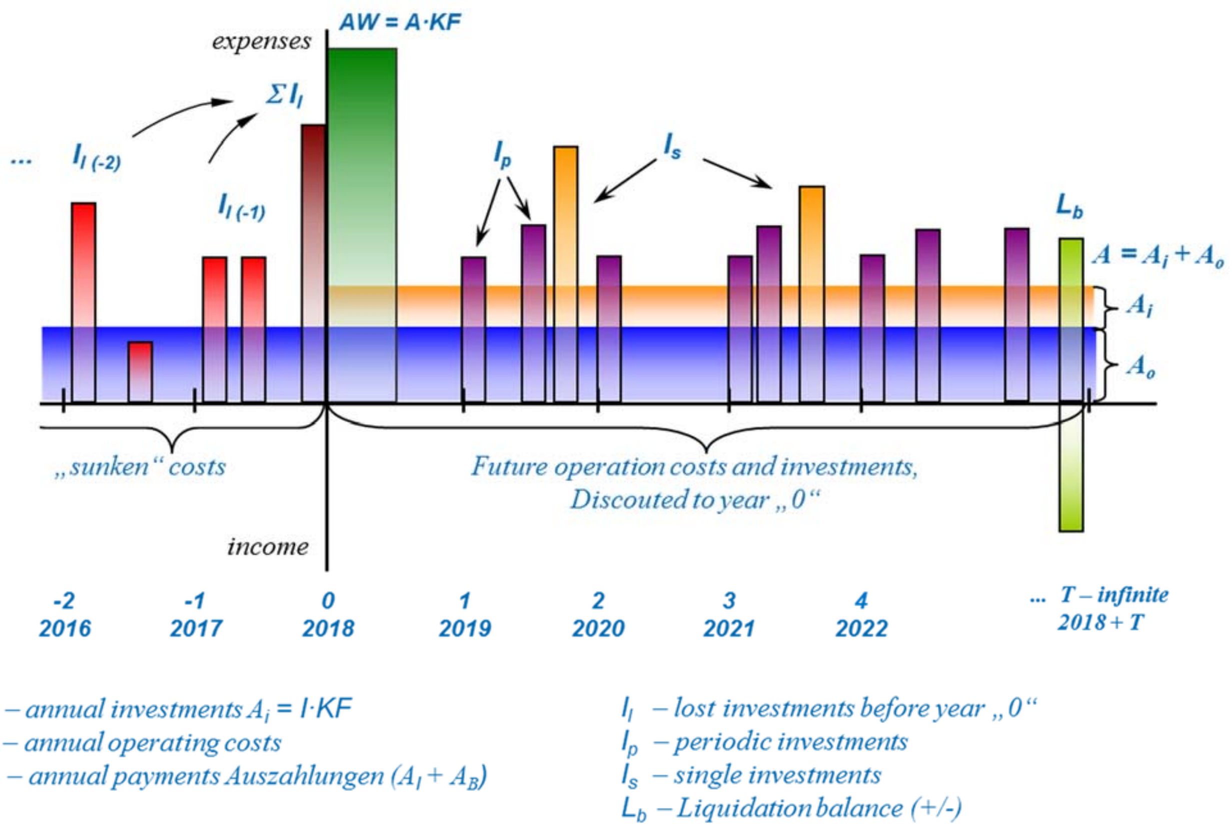

Figure 1 Valuation strategy

Prerequisites for calculating the expense parameter AW on the basis of equation (2) are therefore:

- The calculation of the payment/expense annuity $A_{t(0)}$. This includes the preliminary calculation of the cash-layout for the operating costs and other cyclic and non-cyclic payments that may become necessary as well as their calculation as representative expense annuity over the period *T*.
- The calculation of the capitalization factor *KF*. This requires decisions to be taken over the period *T*, decisions as to the rhythm of the cyclic investments (renewal cycle) and the determination of the imputed interest rate *q*.

If the object to be evaluated is subject to price increases for the consumption of production factors (such as prices and labor rates) to and specific technological and commercial risks, it is recommended to calculate a modified interest rate q, which will then have to be taken into account, and the expected inflation rate as well. Assuming that there is a continuous and steady development over the period T (with the same percentage), the imputed basic interest rate (the real rate of interest) will have to be modified as follows:

$$q = q_R * \frac{q_{Infl.}}{q_V} - \frac{p_R}{100} \tag{3}$$

where q = imputed interest rate now modified; qR = original imputed real interest rate; qInfl. = inflation factor; qV = summarized object-related modification factor of the valuation criteria (prices) for the expense factors, such as for labor, energy etc.; pR = discounted interest rate in % p.a. to take specific technological and commercial risks into account.

The calculation of the expense parameter AW on the basis of equation (2) with the given capitalization factor KF and an expense annuity At(0) that remains constant over the period T is recommended, when payments for the objects remain unchanged over the period T and when the expense parameter AW does not change, either. In the case of any deviating conditions, such as changing expense curves and liquidation balances, the calculation regulations will have to be modified further. Should the expense curve fluctuate, the calculation will have to be made on the basis of irregular amounts being paid over the period T according to equation (1). In practice, it may be typical that the trend of expenditure is decreasing which can be mathematically described by a digression of the changing amounts. The expense parameter AW will have to be interpreted as a negative revenue item.

As a result of the sensitivity analyses carried out and depending on the model input, the following conclusions are generally valid and can be drawn with regard to the sensitivity of the target parameter "capitalized expense parameter" (AW) (Drebenstedt, 2006).

- AW responds rather sensitively to changes in the modified interest rate q and shows an exponential growth with a declining interest (rate). AW's sensitivity is therefore felt more strongly in areas with a high interest rate than in areas with a lower interest rate. This, in turn, makes it necessary to define q thoroughly, i.e. the influencing factors must be taken into account in this respect. For the mine closure activities with long term character and risks a reasonable funding is necessary. The basic of the calculative real interest rate therefore can be only long term and safe investments. Interst rates from such inverstments are comparable low, in Germany in the rage from 2.5%/a to 3.5%/a.
- The decisions on the structure of these parameters, including the capture of detailed data for individual cost items, will be pushed in the background, while the decisions on the rate of the inflation-adjusted basic interest (q) and on the interest rate for risks involved (pR) will be given much more priority, although the cause/effect relationship between price increases (qV) and inflation (qInfl.) as well as the adjustment between the effects of this relationship on q will have to be given due consideration.
- The influence of T on the amounts involved in AW is considerable over a 20 to 30-year period (T), but will decline when T is in excess of 30 years. This fact points to the necessity that T for the objects with a limited duration must be determined very carefully.
- The safe knowledge of the amounts involved in the expense parameter and of the expense curve in the case of projects with a long (T longer than 30 years) and an infinite duration as well as the required knowledge of possible liquidation consequences is less important and fades in the background. The influence of long-term jobs tackling so-called permanent mining damage on AW is almost irrelevant under the aspect of a commercial valuation when T = 50 years. The one-off payment in the case of a constant expense annuity over the period T = ∞ and a modified interest rate q = 1.05 amounts to only 9.55 percentage points above the amount which would have been due if T was 50.
- The expense curve over the period T (either constant or declining) is of decisive influence especially on objects with a limited duration. This explains the demand to determine the expense curve for these projects over the period T very carefully, apart from the demand to also limit this period T to a reasonable duration.
- Irrespective of the project duration T, the statements about the expense volume and the development of the expense curve for a period of up to 20 - 30 years are of the essence.
- In general, AW shows a higher sensitivity in areas with a lower interest rate, also when T, LT and the expense curve change. Consequently, the claims for funding of these parameters will be higher at a lower interest rate than at a high interest level.
- Should AW be used as a criterion for determining the commercial advantages of (different) options, any variations in the interest level may change the advantageousness of the option hitherto preferred. A higher interest rate favors options and makes them more advantageous, where most of the required expenses become due in the far-away future. In other words: a low interest rate

promotes behavioral alternatives requiring a less intensive aftercare, but requiring higher investments.

4 CASE STUDY

In previous publications were demonstrated a case study of everlasting water level regulation in a mine lake and the decision making in choose alternatives between pumping or build a free outflow (Drebenstedt 2006).

Here is presented a case study of a cost calculation for a time limited soil and water treatment project to answer the question of the needed financial amount to transfer the project to a third party for operation. The situation is shown in figure 2.

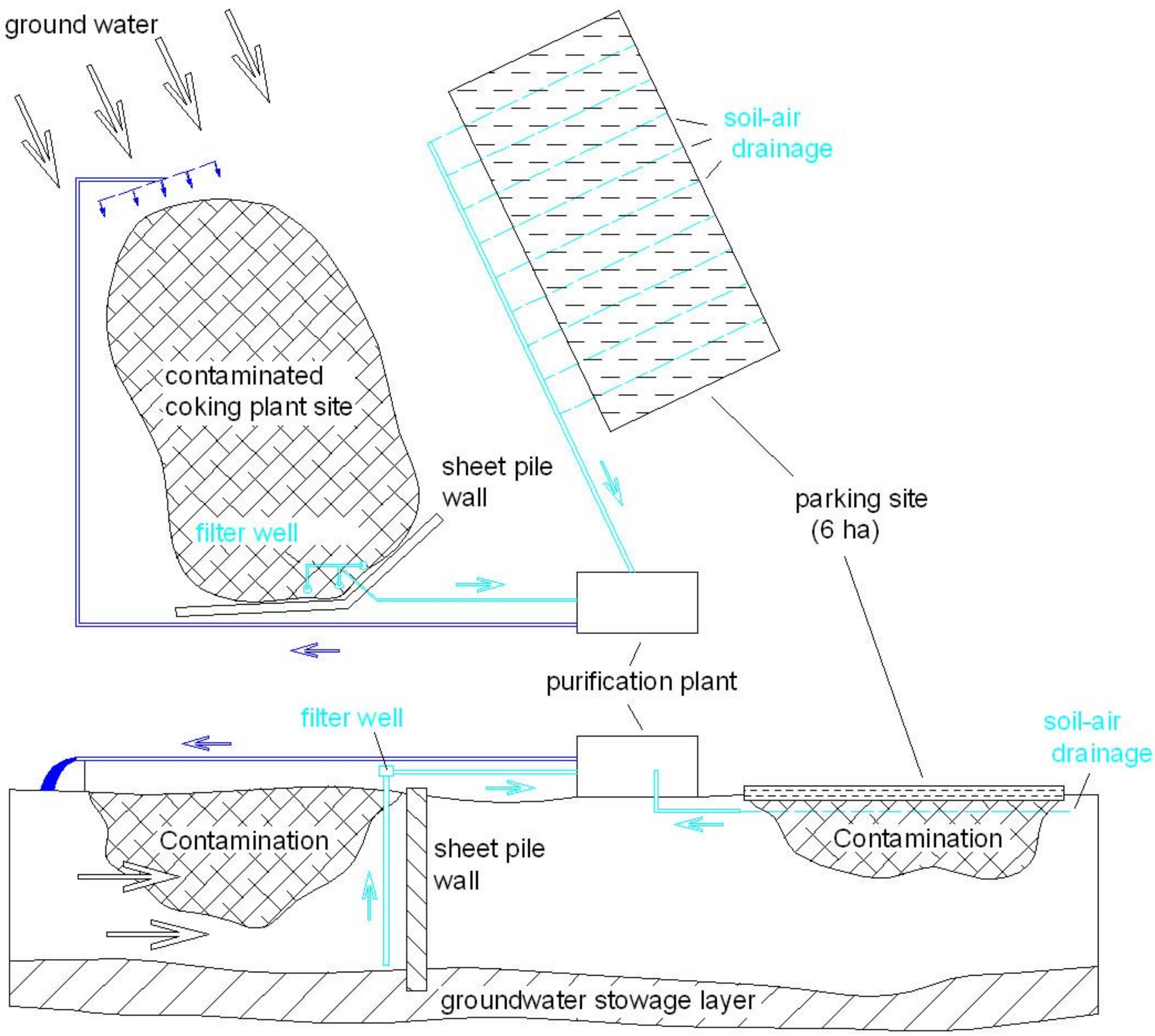

Figure 2 top view (above) and cross section (below) of the treatment unit

4.1 The Problem

The long-term operation of a coking plant led to contamination of the underground. Alternative to a change of the soil and external treatment was decided to decontaminate the underground in situ by a treatment plant. The treatment unit consists of three elements: a six hectare surface sealed soil air drainage, a funnel & gate system to catch and pump out the groundwater flowing through the contaminated side up to a depth of 10m (below is a non-permeable layer), and the treatment plan for the air and water.

In the situation of evaluation the treatment plant was two years in operation. After an operation period of 10 years, the plant is planned to shift to another place for 15 years. The monitoring system is not included in the calculation of expenses.

4.2 Basic data for calculation

The still realized investments for the existing treatment unit with an amount of approx. 1 Mio € are not more considered in the calculation for the future expenses. For the new plant the investment is 0.75 Mio €. Because the operation time is 15 years, a replacement investment is not necessary. Table 1 shows the operation costs.

Table 1 Operating costs for the treatment plant (from real project)

Type of operating costs	Amount per year,
Personal costs	92,000
Energy costs	17,600
Material costs (Chemicals)	40,200
subcontructor:	
- maintenance	32,700
- engineering services	40,200
Others	15,100
Overall	**237,800**

The main component of the operation costs are the costs for staff (40%).

When the treatment activities finished, the treatment plant must be eliminated. The costst for elimination are calculated with 191,000 €. There is no income from elimination. Because of some uncertainties of operation time, the interest rate for risk pR is applied with 0.5%.

4.3 Results

Under consideration of the interest rate for risk, the modified interest rate q (equation 3) used in the finance-mathematical calculation will be 3%. Assumed constant operating costs over the years. The yearly operation costs are calculated with 238,000€ (table 1), and the overall expense parameter (equation 1) with 4.8 Mio €. The share of operation costs is 86%; 14% results from the new investment in the year x+8. The capitalisation factor is 17.4.

5 CONCLUSION

A major feature of mine closure activities is their long-term character and the special risk. This applies particulary to remediation in the field of water management, such as to objects for to objects for the collection, treatment and disposal of contaminated seepage water from mining slopes, dumpsites and disused industrial facilities, as well as to objects for controlling and limiting the rising ground water levels in old mining locations affected in this respect. Alternative technological and commercial options to solve the problems as well as specific technological and commercial risks are typical of these long-term objects, and they often seem to require an infinite duration to complete them.

In the current practice of mine closure, the general problem of the commercial valuation of long-term remediation objects is embedded mainly in two fields of the decision-taking process: First of all, as a prerequisite for determining the most suitable option of technological and commercial behavioral alternatives. Secondly, the progress made with the remediation creates the prerequisite for transferring the object into the responsibility of a third party. The problem is to make an inter-temporal comparison of the expenditure involved, depending on the time when these amounts become due. The problem can only be solved by applying financial and mathematical valuation models. The approach is to establish the cumulative cash value of all financially assessed expenses required for the valuation projects over a limited or unlimited time horizon and in accordance with the required safety and remediation standards. These "mathematically calculated financial investment costs", referred as the expense parameter (AW), act as criteria when the commercial advantages of alternative options are compared and when a one-off payment is made to the future owner after the financial responsibility has been transferred.

The paper introduces typical reasons for a valuation, the valuation model and the conclusions for the model drawn from a sensitivity analysis. Problems arising when the model is applied are highlighted in a case study.

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Establishing Legal Regulations on Mine Closure

L Baasan *SESMIM Consultant, Mongolia*

S Galsan *SESMIM Consultant, Mongolia*

MB Dagva *QMC LLC, Mongolia*

Abstract

As for Mongolia, its mining sector accounted for 16.6% of the GDP in 2016, whereas it is forecasted it will reach 29% in 2040.[1] Therefore, apart from supporting the mining sector and ensuring its sustainable development, we are facing a the dilemma of preserving the natural resources for the present and future economic growth as well as social well-being.

International good practice requires that mining licenses shall be granted according to these principles: if closure plan has been developed and approved by the authorities, if resources that are economically viable are used, if all the risks of extraction of resources have been assessed, and if financial assurance of the risks have been made before granting permission to use mineral resources. However, in Mongolia's legislation, mining licenses are directly granted without requiring the Feasibility Study (FS), the financial assurance, contrary to the international norms, leading to the possibility of the government bearing the risks of the license holders.

Abandoned or orphaned mines not only raise many difficulties for the authorities, local residents and mining companies but also harm the reputation of the entire industry. This act is also occurring in Mongolia, so although the mining sector is a major part of the economy, the negative impacts such as environmental impacts, depletion of water resources in mining areas, lack of proper closure and lack of reclamation have been on the rise, leading to the general population developing negative views and ultimately reducing the reputation of the mining industry. Mongolia consists of 21 aimags (provinces) from which 15 aimags have an area of 566 parcels in 56 sums (counties) making up 3984.46 hectares of abandoned and disturbed land from mining activities. Reclamation of degraded and abandoned lands cost at least 25 million tugrug per hectare and for full rehabilitation 80-100 billion are required. Currently there are 10.5 billion tugrugs allocated in the special fund for financial assurance that equals to 10 percent of the overall budget requirements. In total, 3984.46 hectares of land has been destroyed due to mining. The government is required to pay at least 25.0 million tugrugs for the full rehabilitation of 1 hectare area of the abandoned land, a total of 80-100 billion tugrugs.[2]

Mine closure has been discussed in Mongolia over the past 20 years but there are still no direct regulations. Regulations related to mine closure which should have been approved according to the laws of Mongolia are not in effect. The regulation for mine closure in Mongolia is comparable to the international level of mine closure in the 1960'.

71 questions regarding "Examining the Mine Closure Legislation" and Administration Management for the Asia-Pacific Economic Cooperation Forum was drafted by APEC in May 2017 on "Criteria for Legal Closure of Mine Closure". The answer was "yes" to 7 out of 71. In other words, the regulatory closure of Mongolia's mines is 10 percent.[3]

Therefore, Mongolian government policies must take effective, progressive measures regarding: reducing the impact of mining on the economy as well as the negative approach to mining; further development of the mining sector; mining exploration; preventing the creation of abandoned and orphaned mines; and not increasing the number of areas not rehabilitated, any further.

Keywords: *mine closure regulations Mongolia*

1 Introduction

The main purpose of this research is to establish a legal environment for mine closure in Mongolia through assessing the government regulations and operations involved in the closureactivities. In Mongolia relations concerning the mineral resources are regulated byLaw on Subsoil; radioactive minerals and nuclear energy are regulated by Law on Nuclear Energy;petroleum and unconventional oil are regulated by Law on Petroleum; minerals other than the water, petroleum, natural gas, radioactiveand common minerals are regulated by Law on Minerals;artisanal mining related issues are regulated according to the common minerals law, the government adopted regulations and the Common Minerals Lawrespectively. Therefore depending on the classification of the minerals, relations concerningthe minerals are regulated by many different laws, so it is worth noting that mine closure and land reclamation regulations are to some extent exist in the above mentioned laws. Considering that the scope of this research is limited to the mine closure issues regulated by the Law on Minerals only,there is a need for further study other laws and policies in order to improve the mine closure regulations.

The research has been done in 2 stages. The 1st stage involved comparing the laws and regulations of Mongolia with those ofinternational best practices and make suggestion for improvements. In the scope of initial research, reflection of the mine closure basic elements such as closure plan, financial assurance, public participation, social impact assessment and monitoring issues in the laws and regulations of Mongolia were studied.

At an international level, the mine closure plan, a separate document is usually approved along with the requirements of community involvement and the demand of monitoring expenses by financial means of bonds, monies before issuing any licenses. Whereas in Mongolia, a license is issued for 20 years which is a long term, without requiring the mine closure plan and financial assurance at all. This is not on par with the international norms and standards. As a consequence Mongolia is facing day by day increase of abandoned mines, environmental pollution, general public resistance and local community conflicts. According to the Mineral Law of Mongolia, EIA is approved based upon the feasibility study after issuing the license only which becomes the cause for all negative consequences.

EIA is being adequately done in Mongolia, but the socio-economic impact assessments and the mine closure stakeholders engagements are not reflected as a legal requirements yet. Current regulations ensure stakeholders engagement during the EIA report processing stage only, a procedure subsequent to the issuance of the license which makes it less significant.

According to the order #A-04 “Transaction control of the Environment protection and rehabilitation fund” which was approved by the Minister of Environment on January 6, 2014, the project implementer/license holder is required to allocate 50 percent of the next year’s progressive rehabilitation expenses into state budget’s fund. Thus there will be no funds sufficient for mine closure. Monies allocated in the above mentioned fund total 10.5 billion tugrugs, which only equal 10 percent of the required amount of money for the disturbed, abandoned mine closures.

Also the public involvement matter is not reflected into the mine closure activities, as such the public involvement is only formally done during the EIA approval process, and it can be observed on many circumstances that companies don’t conclude community development agreements, and even they do sign community development agreements companies fail to fulfill their obligations. Again, the purpose of the community development agreements doesn’t guarantee the post closure land use and there is lack of regulations for the local developments in the post closure land use.

At the exploration licensing stage the Ministry of Environment, General Authority of State Inspection receive notification, but they aren’t involved in the license issuing decisions. At this stage MRPAM’s participation is screening the applications and transfering information to other government organisations only. As you can see, there is no mutual dependence between the Ministry of Mining and Heavy Industries, General Authority of State Inspection and the Ministry of Environment and Tourism.

The regulation reflected in the law on mine closure plan doesn't comply to the international norms and standards, contents in the mine closure plan and the government control are not defined, and there are many gaps in the regulation. Even though issues related to the mine closure plan are governed by the Ministry of Environment and Tourism and Mineral Resources and Petroleum Authority of Mongolia issued regulations respectively, those regulations don't handle situations completely and are isolated. Therefore there is a strong need for combined solution to the issues and regulations in accordance to the international standards.

The next stage of this research aimed to improve the mine closure legal environment, and to study as how the government organisation prepare and implement the mine closure plan and corresponding documents in order to comply to the international standards so that we could determine the next steps and support professional capacity building.

The laws of Mongolia doesn't require a separate document, namely the mine closure plan. That's why we chose 87 feasability studies and 13 EIAs of 87 license holders which were documents comparable to the mine closure plan and examined them any indication on mine closure matters. Out of 87 feasibility studies, 10 FS didn't mention mine closure at all, and 77 FS provided little awareness about the mine closure. 38 FS didn't provide calculation of mine closure expenses and merely 49 FS provided sums of mine closure expenses in tugrugs. But from these 49 FS, 11 FS didn't mention about what mine closure costs cover. Mine closure costs vary from 3000 to 500000 USD. For the mine closure costs only 3 of the 49 FS has calculated only the costs of moving equipment and demolition buildings and another 3 FS has calculated the costs of management and mine closure plan development. They are both 6 percent of all the FS that calculated costs. 2 FS had reflected costs to implement project programme, risk funding, support for local community employment, which makes up 5% out of 38 FS which included cost estimates, and 18 FS reflected monitoring costs which makes up 47% out of total 49 FS respectively. Compared to the international checklists documents being used in Mongolia reflected mine closure issues 27.7 percent in EIA and 21.1 percent in FS.[4]

This shows that content and quality of EIA and FS need to be improved. Also legalisation of approved requirement and clarification of content of mine closure plan before the mining license issuing will be important to make mine closure activity clear and understandable, calculate financial assurance accurately and undertake monitoring.

2 Methodology

We have studied and made a summary on the suggestions and researches of international and Mongolian researchers. We used the following methodology in this study, including:

"The duplication of legislation, gap, elimination of contradictions and methods of improving their harmonization" approved by the MoJHA minister by order #84.

"Methods of assessment of law implimentation", the 6th attachment in the 59th Government resolution in 2016.

The Checklist was developed by the Mining Task Force of APEC, in a program coordinated by National Resources Canada, with development carried out by Golder Associates. The Checklist particularly advises government policies with respect to mine closure and how these policies should be implemented and sustained (including administration and governance).[5]

3 Conclusion

Legal regulations for mine closure don't comply with international standards, their content is unclear, and they lack control of government bodies, contain conflicts among laws, and are insufficient. Although some elements of mine closure issues are reflected in the laws and regulations, there are separate arrangements, so there is need for an integrated set of regulations, equal to international standards. In addition, the regulations contradict to legislations, which necessitate the need to change mine closure regulations reflected in laws.

In addition, there are a lack of coordination and understanding between the agencies responsible for monitoring. A legal framework for enforcing the law at the local level exists, but the monitoring system is divided into different agencies. Central and administrative organizations make decisions, approvals and authorizations based upon the materials and GASI reports produced by the aimag and soum environmental departments. But activities of these units with limited facility, budget, human capacity, and insufficient knowledge are not effective. Most of the government agency functions are regulations on the receipt and delivery of reports, notifications and deliverables. In other words, regulatory mechanisms as how to process those documents, and further procedure are not defined in the laws and regulations. After the mine closure, organizations or officers responsible for monitoring functions are unavailable.

There are no requirements for social impact assessment in any closure plan and the law doesn’t require any public discussions about closure plans. Even though public participation is adequately defined in the EIA law and relevant regulations, it only exists during the ESIA process, which becomes a less meaningful activity after the mining license has been granted.

The current legal regulation for financial assurance is poorly enforced, funding for closure is insufficient, and monitoring mechanism is absent. As for the financial assurance of mine closure, it is possible to calculate the reclamation costs. However, there is no regulation on how to calculate social impact costs and closure management costs.

There are 2 types of mining companies operational in Mongolia. The first type is the companies which developed a mine closure plan own their own and undertake operations according to the investors’ requirements and in compliance to the international standards. While there is insufficient legal regulation on mine closure, large legal entities such as Oyu Tolgoi and South Gobi Sands have developed international standard compliant closure plans and organized public consultations, which would indicate that legislative reforms are lagging behind. In addition, international financial institutions and the Mongolian Bankers Association have developed principles for Sustainable Financing in Mongolia and are providing funds according to these principles, so laws need to be revised immediately.

The second type of companies operates according to the laws and regulations of Mongolia which have very low requirements in regard to the mine closure legislation. Since it is not compulsory to develop mine closure plan and allocate financial assurance, those companies aren’t obliged to implement them. On the contrary, companies which consider raising money on the international capital market or selling its share on the stock exchange face higher requirements that create unfair competition. If the legal environment of mine closure in Mongolia is not revised soon, there will be rising tendency of negative effects, such as the government needing to take responsibility of the rehabilitation of increasing number of abandoned and orphaned mines nationwide, and furthermore increase of public resistance. Depending on this, global reputable companies might lose interest to be competitive to the 2nd type of players and to invest in Mongolia; consequently there is a threat of emerging many smaller companies which don’t follow rules and laws.

Mongolia is a country which has erosive soil with increased desertification, dry and cool weather, and raise traditional livestock. On the other hand, it is a developing country with lots of natural resources so the mining sector is considered a key industry. It has become a big challenge to retain traditional livestock and agriculture, to resolve ecological issues such as pasture scarcity that leads to people’s protests, with the implicit needs of mining development issues.

In order to grant an exploration license, companies have to receive approval from the local authority and residents. But for the past 3 years reputation of the mining industry has fallen due to the lack of rehabilitation and mine closure, 90 percent of all votes have been negative. During the past 2 years, the Petition committee received complaints concerning mining operations which are 50 percent of overall complaints. Among the citizens of Mongolia mining sector has a bad reputation and people tend to protest more often. 2015 report of the Extractive Industries Transparency Initiative of Mongolia suggests that 544 billion tugrugs has been paid to state budget as a mining royalty. Out of this amount merely 3.6 percent or 20 billion tugrug goes to the municipal development funds of 21 aimags.[6] In other words mining industry does not bring benefit to the local economic growth so that local communities are against it. It means Mongolia is more likely to repeat the same mistake of the 1990s international mining sector that caused conflicts among parties and the associated financial crisis.

Inherently the mining operation creates harmful impact to the environment, society and the human health, therefore it is necessary to make the following amendments to the laws and regulations in accordance to the international best practices: (i) the ESIA and mine closure plan should be undertaken in advance to the approval of the mining license; (ii) financial assurance should be reflected carefully in the mine closure plan; (iii) financial assurance should be allocated in special fund before the approval of the mining license. If we don't create best mechanism for the mine closure it will not succeed even if we improve the state monitoring system. The international practices show that if we don't change current laws and regulations of mine closure it will be increased the number of abandoned mines, the Government might spend a huge amount of money for the rehabilitation and closure of those abandoned mines.

Therefore the best way to prevent the above mentioned consequences is to establish a proper mine closure regulations. It is of high significance to the sustainable development of the mining sector to earn support of local community and contribute to the Mongolian economic growth and development.

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What Comes After Mining? How Regulatory Frameworks Can Enable Creativity

J Heyes *BHP, Australia*

D Murphy *Jacobs, Australia*

S Foster *Golder Associates, USA*

S White *BHP, Australia*

Abstract

The global mining industry has a poor reputation for effectively completing site closures. This reputation impacts the licence to operate that is crucial for new and expanding operations necessary for the health of the resources industry. As Erskine et al (2015) note, "The evidence that is available in the public sphere indicates that there are very few mines in Australia that have been successfully rehabilitated". This challenge is global and not unique to Australia; the number of mine sites awaiting reclamation far outnumbers the successfully closed sites.

A contributing factor to this challenge is that regulatory closure frameworks and mining company approaches to closure are interdependent and potentially conflicting. For example a company with a strong outcome- focused approach is not going to do well in an overly prescriptive framework. Similarly a company with a loose approach to closure will find a non-prescriptive framework very challenging.

Where regulatory requirements and processes are in place for closure, they generally default to the land use types that pre-dated mining activity; typically native vegetation or some form of agricultural or livestock grazing activity. Regulatory processes to promote and ultimately optimise post mining (or post-industrial) outcomes through alternate land use options are rare, but are important analogues to consider.

The fact that we see excellent examples of mine closure in various quarters of the world, some actually arriving at relinquishment and beneficial re-use, argues that successful closure is achievable under the right regulatory environment.

The mining community and regulators alike are ready and anxious for a change in relinquishment approaches and sustainable re-use of properties/infrastructure, as it is currently neither straightforward nor well understood in most mining regions of the world. There is ample opportunity for the mining industry, communities and regulators to collaborate in this rapidly evolving and often heated debate.

In this paper, we examine aspects of current legislation that limit the achievement of truly sustainable post mining land uses and offer potential approaches that may resolve the current impasse.

Keywords: *legislation, sustainable post mining land use*

1 Introduction

Mining methods, philosophies and efficiencies have evolved enormously in the last decade as the industry has wrestled with the turbulence of the Global Financial Crisis, the commodity super-cycle, and the collapse (and slow rebound) of prices for nearly all extracted resources. As financial markets have evolved, so have mining companies and their stakeholders, including host communities and regulators. Entwined with this evolution, there is a growing concern regarding the number of mines facing closure due to changed market conditions, resource depletion, and growing pressure from environmental issues (Jeyareatnam, 2017).

Accordingly, mine closure is now among the highest profile agenda items for mining companies and their stakeholders (Ernst & Young, 2016; Campbell, et.al. 2017).

There is growing concern regarding the ability of both mining companies and governments to manage closure to benefit, or at the very least, not negatively impact future generations (Roche and Judd, 2016). This is in complete alignment with the Brundtland Report definition of Sustainable Development (Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.)

Blackrock CEO, Laurence Fink (2018), in his recent letter to the S&P 500 CEOs echoed this sentiment stating that "Society is demanding that companies, both public and private, serve a social purpose. To prosper over time, every company must not only deliver financial performance, but also show how it makes a positive contribution to society." This broader overlay of social contribution adds further complexity to considering and preparing for mine closure and post-closure options.

Inevitably governments across the globe are responding with ever-tightening regulation on mine permitting and consequently on closure requirements. A recent example of this is the new requirement in Chilean regulations discussed by Sanzana et al. 2015, where additional regulations for waste characterisation have been introduced; and in Australia, where all mining states have been through a period of reform over the last decade, including guidelines for closure plans (Western Australia), and amendments to financial assurance requirements (Queensland). Globally, the International Standards association is developing a standard on mine closure (Unger, 2017) and ICMM is updating its Mine Closure Toolkit and developing a Social Closure Guidance. This evolution of the closure paradigm presents mining companies with considerable challenges, including closure cost inflation, increasing scope complexity, regulatory uncertainty (i.e. relinquishment), community demands, and reputational exposure.

Current regulatory frameworks for the closure of mines focus largely on the protection of environmental values and minimisation of liabilities that may fall to governments and host communities. Generally, post mining land use defaults to the pre-mining land use. Notwithstanding, there are many published 'disaster stories' of the mining industry and regulators that fail to manage closure (Sheldon and Strongman, 2002; Mudd, 2013). Conversely, there are a growing number of examples of post mining development for alternative land use across the globe, including Australia, USA (Mborah et.la., 2016; Solar Fields at KGHM Carlotta Mine and USEPA Elizabeth Copper Mine Superfund Site (Brightfields Development, 2018), Vietnam (Boemme et.al., 2014), Indonesia (Kodir et.al., 2017), and Teck's Sullivan Mine in British Columbia, Canada (Teck, 2018). Whilst the ability and benefits of planning and designing for post mining land use as part of mining operations has been espoused since the 1960s (Wang et.al., 2013), relatively few such success stories have been driven by, or involved, the mining operator (Butler and Bentel,2011). There is a growth in desire among the mining community to change this trajectory.

Murphy and Heyes (2016) recently challenged the status quo, with the suggestion that there are a number of changes that mining companies could make to their closure planning activities which could help to open up the value of what historically has been considered 'closed' sites. They specifically highlighted the opportunity to 'repurpose' mine sites for alternative land uses that could be aligned with regional development strategies and which presented long term inter-generational benefits to host communities. Challenges to alternative and sequential land use proposals included limitations within legislative statutes under which mines are approved and regulated, as well as the need to engage with future potential investors. They suggested that current regulatory frameworks greatly stifle the degree to which innovation can be deployed within closure strategies and to which alternative land users can be engaged to develop future sustainable business ventures or projects without incurring the cost of long term closure liabilities.

In the following sections of this paper, we explore the challenges associated with regulatory limitations and propose solutions for miners and regulators to address these constraints. Whilst this is a global challenge this paper is focussed on representative examples from the USA and Australia for illustration purposes.

2 How does legislation limit innovation in post-mining land use?

Innovation in post-mining land-use planning has been and will continue to be influenced, both positively and negatively, by a multitude of interrelated factors, none of which can be considered in isolation of others. Key factors are those associated with the regulatory frameworks at play and regulator hands-on experience, the alternative post-mining land uses under consideration, the mind-set and experience of the operating mining company at the time of closure, and the varied points of view of communities within which they operate.

In most jurisdictions, if not all, mining legislation is established to facilitate resource development for the economic benefit of the community. Such benefit is generated through taxes and royalties as well as economic benefits through direct employment. In the 2013/2014 financial year, Australian mining generated $25 Billion (AUD) in taxes and royalties (Frydenberg, 2015). Generally, mining legislation facilitates development of mineral resources through the grant of specific tenure, licences and permits, based on development proposals submitted by mining companies. Regulation of specific activities (e.g. processing, tailings disposal, water extraction) is often facilitated under separate environmental protection and resource management statutes. An added complication is that mining statutes regulate for individual mines, despite the many examples of mines that operated by different companies that share a spatial boundary and catchment scale receptors.

With a strong focus on mine development, post closure land use objectives are more often than not locked in by permits and approval processes, usually under the pressure of approvals timeframes to meet fluid market conditions. Accordingly, and not surprisingly, land use objectives typically default to the pre-mining land use. A key failure of this process however is that non-mining land uses are regulated under separate legislation. Agencies responsible for the regulation of alternative land use and regional plans are therefore seldom consulted or engaged within the early stage permit and approvals process by either regulators or mining companies. As a result, conditions and completion criteria placed on mining operations are generally focused on protection of environmental values and stability of final landforms to limit liability when the site is relinquished back to the land owner or host government. Examples of mine closure plans where completion criteria address productive land and infrastructure capability are rare, if non-existent (Smyth and Deardon, 1998; Murphy and Heyes, 2016) outside of the US coal mine provinces.

Not only are regulators who are responsible for alternative land uses absent at the planning stage, but potential future investors and land users are seldom engaged within the mine closure planning process (Harvey, 2016; Murphy and Heyes, 2016). As such, there is seldom robust evaluation of post closure land use options against land use capability or regional planning objectives. The requirement for regulatory permits and approvals for alternative, and non-pre-mining, land use is generally ignored or beyond the scope and capacity of the planners at the outset of mining. Such approvals can be as onerous as the mining project approvals themselves and carry similar conditions and completion criteria granted under relevant legislation. Furthermore, any proposal for development of an alternative land use would require the proponent to undertake approvals in parallel with mining operations.

The timeframes associated with closure are lengthy and subject to many shifts in societal expectations and political flux. Post closure land uses that are locked in early in a mine life, without a clear process to change, run the risk of failing to account for generational change; defined as 40 years (Australian Government Treasury, 2015)). With mine lives of anywhere from 10 to 50 years (2 to 3 or more generations), it is only natural to expect socio-economic change over this timeframe and, therefore, different expectations in what a successful transition from mining to post-mining should look like. Political flux results in legislation being subject to the influence of incumbent governments. Whilst the intent of mining legislation is generally perpetual, associated regulatory statutes and guidelines can be changed, amended and repealed within and between the lives of single governments which can exist for as little as 3 years in some jurisdictions. Mine closure guidelines issued by government agencies, despite their name, are often mandated under relevant regulations and updated on a regulator basis which force mining companies to play continual catch up with requirements. Such requirements can often be prescriptive and follow the environmental protection and landform stability focus of preceding approvals.

With the current legislative focus on environmental protection, it comes as no surprise that conditions and completion criteria placed on mining operations can prohibit innovative or novel post mining land uses. Land use plans are typically based on land (and ecosystem) capability. Whilst use of productive completion criteria is rare within closure planning, such criteria have been developed to identify and protect specific land uses (Murphy and Heyes, 2016). Although the majority of land capability criteria and guidance material has been developed for the assessment of natural or non-mining degraded land, it should be possible to utilise such information to establish potential productivity and capability criteria for mined land. For example, within Queensland's Bowen Basin the creation of strategic cropping land (SCL) from post-mining landforms could be included within a prioritised list of potential land use that aligns with strategic plans for the region. Such aspirations are no more difficult or challenging than the rehabilitation of disturbed land to pre-mining conditions (Murphy and Heyes, 2016).

Similar to mining, non-mining land uses are market driven; sustainable success is more likely where there is broad-scale development of multiple projects supported by local/regional infrastructure. Such infrastructure might include roads, port, rail, water, power, and natural gas services. Unlike mining, where cash flow and margins can allow private development of the needed infrastructure, governments may need to actively encourage development of specific industries and other activities through the installation, maintenance or upgrade of infrastructure, provision of tax incentives, etc. Accordingly, the development of post-mining uses will have a higher likelihood of long term success where there is alignment of multiple mine closure projects, as well as significant investment by government. Given the focus of regulation on single mines and limited engagement between mining companies, it is not surprising that the pre-mining land use becomes the default for the majority of mine closure plans.

Post-mining land use which differs from the pre-mining land use would require a proponent to approve the land use and development under separate legislation. Given that mining is a temporary land use, mining companies expect to be able to relinquish or divest mining assets once mining is completed, allowing them to move-on to new projects. Mining companies are generally not in the business of development or management of alternative or non-mining land uses and typically are not well organised internally to address the business aspects (profit and loss, risk, community interaction) associated with non-core business interests. Whilst current social license to operate philosophies encourage corporate responsibility, there is limited financial incentive for mining companies to drive approval for an alternative land use and extend their responsibility beyond relinquishment, which they may view as more of a long term host-government responsibility. An added complication is that there is no clear, robust method for a mining company to value (in real financial terms) the social license benefits of mining land that can been repurposed to an alternate use.

3 How can these limitations be addressed to bridge the legislative gap?

There are a number of trends and case studies that have emerged that highlight institutional and systemic changes that are shifting the paradigm of mine closure and post-closure land use. These trends and case studies are generally localised, however they directly or indirectly address the constraints across industry, government and communities related to bridging the gaps in legislation, the adoption of a regional perspective, the incorporation of land capability within completion criteria, and the engagement of future investors and land users.

The separation of legislation for the development of mining and non-mining land uses, including the requirement for counter-current approvals for closure and alternative land use development, presents a significant hurdle to the drive for better mine closure outcomes. It would not be realistic however to expect that all land uses are regulated under a single statute. A glimpse into how the gap between mining and non-mining land use might be bridged is however is provided by US Environmental Protection Agency (USEPA).

Through the Small Business Liability Relief and Brownfields Revitalization (the "Brownfields Law") the EPA has promoted the transformation of brownfields sites, including mines and smelters/refineries, into new centres of commerce and industry where job creation through clean-up and reuse has reinvigorated some communities in mining states. The Brownfields Law defines brownfields as industrialised sites which have been either abandoned or have been relinquished back to the relevant State. Under the Law, innovative partnerships can be formed among US Federal, State, and local governments and private-sector stakeholders, including developers and lenders, to clean up and redevelop brownfields sites for future beneficial or economic use. Seed funds are provided to projects which can include training communities for higher-wage jobs. This process has had a positive impact on local economies and communities adjacent to these sites.

The Town of Silverton, Colorado is a good example of EPA's Brownfields funding for a mining community (US EPA, 2009). Silverton had a thriving mining economy from 1876 to 1991; nearly 400 jobs were lost when the mines closed. In recent years, the area has seen an increase in tourism with its mining history and the scenic narrow gauge railroad that serves as its anchor. According to EPA, many of the houses of former miners have been sold as vacation, seasonal, and second homes, that has resulted in a lack of affordable housing in the county. The majority of the area's workforce spends 50% or more of their income on housing costs.

In an effort to provide affordable and energy efficient housing, San Juan County and its partners developed the Anvil Mountain Neighbourhood, including single and multi-family affordable housing units that incorporate sustainability features, historical preservation, trails and open space amenities. The town developed the project on the former Martha Rose/Walsh Smelter site, as the proximity to town and the local terrain made it an ideal spot for the growth in housing demand. (US EPA, 2010)

EPA lessons-learned at Brownfield projects that may be considered in the context of mining sites include (US EPA, 2015)

- Meaningful and ongoing community involvement is essential
- Formation and maintenance of strong and supportive partnerships are key
- Identify and focus on realistic and feasible outcomes and prioritize projects
- Develop strategies for plan implementation throughout the process and maximize
- Resources through targeted project area investments and leveraging

Also in the USA, in 2016, the bipartisan Reclaim Act was introduced to the House of Representatives to amend the Surface Mining Control and Reclamation Act and address the wind down of the US coal industry. The legislation releases $1 billion from the Abandoned Mine Lands (AML) Fund to assist communities that have traditionally relied on the coal industry for employment or have recently experienced significant coal job losses. Under the plan, US$200 million will be distributed to participating States annually for five years, that will empower those states to work with local communities to identify and fund economic development projects at AML sites.

In South West Virginia Appalachian Voices, a community based group, and its partners has developed a program of innovative mine reclamation projects focused on cultivating sustainable economic opportunities for the region for which it is proposed to seek funds under the Reclaim Act (Appalachian Voices, 2016).

Whilst the Brownfields Law and the Reclaim Act demonstrate that opportunity exists to bridge the gap to novel and innovative land use it does not directly link the transition process to mining statutes. Furthermore, mining companies are notably absent from the partnerships formed to execute the redevelopment projects.

In Western Australia, comprehensive engagement in the recent past has shifted governments view of what was needed to alleviate legislative constraints on alternate land use. Opportunities for future development of irrigated agriculture within the Western Australian Rangelands are being supported by the Western Australia Governments Water for Food Program and funded by investment through Royalties for Regions. The Rangelands, which are recognised by the State Government for their unique value and potential to contribute to the future social, economic and ecological sustainability of the State, encompasses both the Pilbara and Goldfields-Esperance Regions. A significant constraint on the realisation of the State's ability to harness this potential has been the restriction on land use and specifically repurposed land use created by the Land Administration Act 1997. Through the Act, the management of the Rangelands is primarily focused on the establishment and administration of pastoral land. The Act does not currently readily facilitate the repurposed tenure for broader land uses. In response to this constraint the Western Australian Government proposed the Land Administration Amendment Bill 2016 which would have streamlined the development of land uses other than pastoralism. The Bill was eventually dismissed under political pressure from the Pastoralists and Graziers Association who felt that they would lose control of the Pastoral Lands Board.

4 Adopting a regional approach to delivering positive outcomes

Sticking with the Australian context, in 2014 and 2015 the Victorian Government conducted two independent inquiries into the cause and effects of a fire at the Hazelwood Coal Mine, which specifically examined public health impacts and rehabilitation options for the three coal mines in the Latrobe Valley. Recommendations from the later inquiry included improvements to planning and preparation for the closure of the mines to address interdependencies between closure strategies across the three mines, as well as significant knowledge gaps associated with cumulative impacts and constraints of the existing strategies. In response to these recommendations the Victorian Government has committed to the development of the Latrobe Valley Regional Rehabilitation Strategy (LVRRS) by June 2020. The purpose of the LVRRS includes:

- Undertaking investigations to address knowledge gaps relating to mine rehabilitation at both a regional and mine specific level
- Work with the community and the mine operators to understand the findings of these investigations
- Guide regional level land use planning for mine operations, rehabilitation, mine closure and post closure taking account of the inter-connectivity between the three mines

The outcomes of the LVRRS will provide certainty for mine operators regarding the objectives for mine closure and specifically the final landforms across the three mines. Such uncertainty has historically hampered future land-use planning for the Latrobe Valley. It is expected that the LVRRS will enable optimisation of land use associated with post-mining landforms for the benefit of the Latrobe Valley community. The Victoria Government has committed $12.6 Million (Aus) to development of the LVRRS which includes the appointment of the Latrobe Valley Mine Rehabilitation Commissioner and a community based advisory committee.

The LVRRS is a strong example of a government lead regional approach to mine rehabilitation in consultant with mine operators and the community. Legislative reform in the US, that has released funds accumulated from mining industry fees, has also enabled community lead programs for regional approaches to mine site repurposing for long term and broader community benefit.

5 Pathways forward - what can be done to accelerate change?

Further to the Brownfields Law and Reclaim Act, there are other examples of innovative community led mine repurposing solutions driven from necessity and demand and generally based around a single site (Butler and Bentel, 2011; Harvey, 2016, Murphy and Heyes, 2016). There are also examples of the emergence of developer led repurposing projects, however details of the projects regarding how they have been facilitated through legislation are not publicly available. A recent interesting example is the purchase of the Kidston Gold Mine in Queensland by Genex (from Barrick) in 2014 to develop the Kidston Solar and Pumped Hydro Project. Genex received its first revenue from the project in December 2017. It is not clear at this stage, however, what the conditions and obligations are for Genex with respect to residual or latent liabilities, or what conditions and obligations have been retained, if any, by Barrick. Nonetheless, the Queensland Government, who has given the project a ‘prescribed project’ status, is to be commended for the facilitation of the project. In time it is hoped that the project will become a case study for successful repurposing of a mine site. The Kidston Project clearly demonstrates that the pathway to successful relinquishment through repurposing requires a “pull through” from a future development or investor with support from the relevant government and local community.

From the assessment of existing constraints and examples of where constraints are being overcome, it is clear that collaborative regional approaches that embrace and align with objectives for future development provide a largely untapped opportunity for successful mine closure and creative post-mining land use. Whilst mine closure is not specifically addressed some mining companies have started to adopt regional approaches to environmental impact assessment. The recent example of the BHP Strategic Environmental Assessment (SEA) developed for its Pilbara iron ore mines is notable for this approach. Closure considerations within this approval are addressed from a cumulative impact perspective only. Whilst the SEA draws on externally available data from other mining companies, the approach is limited to assessment of BHP sites and does not consider closure within a regional land use context.

Extension of the SEA process to assess the cumulative opportunities associated with multiple mine sites is demonstrated by Kivenen (2017) who examined landscape characteristics and post-mining land use for 51 mines across Finland. Kivenen undertook a retrospective assessment to identify the characteristics of mine sites that enabled repurposing; in a similar way, a forward looking assessment of opportunities is certainly possible. Methodologies for such assessments have emerged (e.g. Palogos et.al., 2017; Wang, 2017), which focus on the economic and social value with the mining assets including available natural resources (e.g. water, land) and infrastructure (e.g. rail, power distribution), as well as potential residual and latent impacts, against long term regional development strategies.

Key to the success of such assessments is the collation of 'big data' such as governments and mining industry are already collaboratively undertaking to seek improvement in issues such as minerals processing (e.g. CSRIO, 2016). Whilst data capture and storage present challenges to the establishment of big data, a number of land use planning platforms have emerged which harness social, economic and environmental information. Commercialised access to big data is becoming more prevalent for traditional planning activities (e.g. ALCES). Mining companies, however, remain reluctant to share data regarding mine sites which may be considered competitively sensitive or used against the company in any way. Some governments are starting to explore how this issue can be addressed to achieve more environmental, social, and economically efficient cumulative impact assessment of new projects. It does not seem a long stretch to extend this consideration to data which will assist regional assessment of mine closure opportunities.

Enabled by Big Data it would be relatively simple to run analyses looking at the potential to develop new regional land uses based around regional development objectives. Who would lead and facilitate such analysis however is a pressing challenge. As discussed within this paper no single stakeholder is fully incentivised or motivated to step up to the plate on the issue of mine site repurposing. The reality is that it is a collective responsibility, requires leadership from all stakeholders to achieve a win-win-win outcomes. Regional development organisations already play a role in the facilitation of planning and development within the regional context and are therefore potentially a common point of reference for all stakeholders. Success however will be dependent on the establishment of stakeholder reference groups with all stakeholders needing to take a seat at the table. This must include future investors, developers and land users. Regardless, such partnerships must align with regional development strategies with repurposing aimed at long term target land uses and industries to achieve diversification and growth within regions.

An example of where this approach is being tested is the Sunshine for Mines program undertaken by The Rocky Mountain Institute (2017). A team of experts conducts a multifaceted site analysis to assess the complete renewable energy potential for each legacy mine site within a portfolio. The analysis consisted of the evaluation of environmental, permitting, and regulatory considerations; energy production; net present value; and innovative alternatives designed to maximize value for the mine owner.

Aa a key player in any collaborative approach government must facilitate clear pathways to improved mine closure outcomes through the development of frameworks, including legislation reform, that enable transition to alterative land uses following mining. This must include establishment of regional development strategies, consideration of bridging legislation including the legal and commercial transfer of liabilities, and may involve investment by host governments to ensure start-up business ventures and activities are sustainable. The investigation and adoption of productive land use criteria and engagement of relevant regulatory agencies within mine project approval processes will also greatly improve the opportunity for improved outcomes.

Inclusion of recognised and respected community leaders (especially indigenous people) as key partners is critical for any dialogue and negotiations between mining companies and governments. Realistic goals must be set to ensure post-mining growth and sustainability of the local communities is not compromised. Consideration of early in kind and/or financial support for sustainable projects from the mining company and local/regional/national governments, many years in advance of closure, will enable the community to be sustainable by the time closure is imminent. Given the opportunity and encouragement, entrepreneurial individuals will make the most of any situation. Creation of derivative businesses in the wake of mining will take advantage of land, infrastructure, utilities and the natural environment to generate profit. Innovation as part of closure planning does not necessarily mean "technology-driven" pursuits. Innovation can come in the form of social/economic models for microfinancing, small business start-up support, re-education, reuse/refurbishment of idled infrastructure, or other forms of government-community collaboration and investment.

Ultimately, as mining companies move away from their former host communities, governments must be prepared to lead the way to enable and encourage sustainable livelihoods. Social investment among mining companies remains a confusing challenge to most…..how much, when, where, how? ICMM is working on the development of guidance on Social Investment for member companies that will begin to shed light and help answer some of these questions. However, this will likely remain a challenge across industry for many years to come.

6 Conclusion

Current legislation around the world generally does not enable or promote innovative thinking around post-mining land use. We as an industry and as regulators and interested parties need regional collaborative and government-led mine closure strategies focused on the maximisation of mine site repurposing opportunities for the benefit of future generations and under-pinned by legislation that encourages and facilitates and bridges the transition between sequential land uses. We need to approach the challenge through regional initiatives that can address the concerns and opportunities for a stand-alone single mine or a host of close-knit mining operations. Host governments must take the lead in shepherding a collaborative approach with mining companies and communities, enabling this change. Such an initiative will be met with resounding support from the mining industry, its host communities and investors alike as it delivers truly sustainable mine closure outcomes.

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Coal Policy in the Czech Republic: Key Organizational Actors and their Coalitions

K Svobodova *Czech University of Life Sciences Prague, Czech Republic*

P Ocelik *Czech University of Life Sciences Prague & Masaryk University, Czech Republic*

M Hendrychová *Czech University of Life Sciences Prague, Czech Republic*

L Lehotský *Czech University of Life Sciences Prague & Masaryk University, Czech Republic*

Abstract

Coal and lignite mining is a declining industry that faces uncertain future worldwide. However, coal is a cheap source of energy and provides energy security in many countries. Coal production of the Czech Republic has been declining since 1990s, however the country is heavily dependent on coal. Furthermore, Czech communist history has heavily influenced the entire national mining sector. On the other hand, there is increasing external pressure, such as the European Union's energy policies, that force the involved policy actors to struggle over future organization of the coal domain. To disentangle this puzzled situation, we examined policy networks in lignite sector of the Czech Republic and applied an Advocacy Coalition Framework. Interactions of organizational actors within the lignite policy and their potential coalitions were investigated. Data were collected via questionnaires completed by the organizational actors and analysed using exploratory social network techniques. The results showed two main competing and ideologically distant coalitions: Industry Coalition (IC) and Environmental Coalition (EC). While the IC is a dominant coalition with higher political influence and direct access to decision-making, the EC is a minor coalition that relies more on relational capacity of its core. The dominant IC has huge vested interests that go against transition. Our study determines expected mode of the lignite policy change in the Czech Republic - layering, i.e. new policies formulated without elimination of the old ones.

Keywords: *contested transition, lignite, policy network analysis, political influence, political cooperation, information exchange*

1 Introduction

Coal has been recognized as a reliable and cheap source of energy from the very beginnings of the industrial revolution and soon became a backbone of traditional energy industries (Schobert 1987). It was the fastest-growing primary energy source in the world in the past two decades. During the same time period, total anthropogenic greenhouse gas emissions were the highest in human history (Energdata 2017; Watts et al. 2017). Coal mining is now considered to be one of the major anthropogenic drivers of greenhouse gases emissions (IIPC 2014). A growing global movement is challenging the coal industry's expansion and promoting real solutions to electricity needs. Building on existing international efforts to mitigate the consequences of climate change, the Paris Agreement within the United Nations Framework Convention on Climate Change (UNFCCC) sets in place a durable and dynamic framework for all countries to take climate action (United Nations 2015). The Paris Agreement deals with greenhouse gas emissions mitigation, adaptation, and finance starting in the year 2020. As of June 2018, 197 UNFCCC members have signed the agreement, and 178 have become party to it (United Nations 2018). Moreover, the European Union (EU) assumes a phase-out of the coal production in 25 to 50 years and requires the member state governments to engage this plan in their energy policies (European Commission 2017). However, especially for Eastern European countries, the real challenge is to balance the importance of climate change targets with the immediate economic and social needs of the population, which would be more easily met through fossil fuels (Jones 2018). These processes generate pressures spilling to the EU member states where involved policy actors and their coalitions compete in uncertain environments over definition of specific transition pathways (Geels and Schot 2007).

Against this background, our research study focuses on one of the key issues of the European energy policy - the future of the coal phase-out. We approach the issue using Advocacy Coalition Framework that enables to better understand the complex institutional contexts within a coal policy domain. The advocacy coalitions have been defined by Weible et al. (2016) as cohesive groups of actors that share policy core beliefs. The aim of the study is to identify these actors and to describe their core beliefs and mutual relationships creating an environment of policy networks in the coal mining domain in the Czech Republic.

2 Case description

The Czech Republic represents a post-communist country with a significant coal mining history. Since the beginning of the 19th century, there has been extensively coal mining, and it is still an important part of the national economy (Vlcek and Jirusek, 2015). Coal located within the Czech boundaries was the key driver for the country's industrial revolution and helped to develop not only the country, but also the rest of the Austrian-Hungarian Empire. During the socialist era, coal was the key source of domestic energy production with its production peak in the late-1980s (ca 130 Mt). This level of production has dropped significantly over recent decades, mainly due to the environmental and social impacts of coal mining (Frantál, 2016). Nowadays, the Czech Republic is self-sufficient only in the mining of lignite and bituminous coal. However, the available reserves available are limited both in quantity and with respect to the temporal horizon (Sivek et al., 2017).

Under the Paris Agreement signed by the Czech Republic in 2017, the Czech government suggests that the country can meet new ambitious climate targets (IEA 2017). However, the current national energy policy remains highly dependent on conventional resources (Energostat 2018) and the country has been regularly ranked among the largest world net exporters of electricity in the European Union with about 17 TWh generated by an equivalent of 15 Mt of burnt coal (Frantál 2016). The lignite annual production in the Czech Republic is 40 Mt that accounts for 46% of total primary energy supply (Energdata 2017). Furthermore, besides the exploitable lignite reserves of around 800 Mt, there are another 900 Mt of reserves behind the territorial ecological limits established by the first post-communist government (Vlček and Černoch 2013; see Figure 1).

Figure 1 The lignite mine Bilina. The area framed by the red lines indicate reserves behind the territorial ecological limits.

Possible changes to these limits have significantly influenced a public debate and political disputes over the future national energy policy (Sivek et al., 2017). The question of the limits has even become one of the major issues of the forming environmental movement that started to rely on advocacy, lobbying, and expert knowledge (Fagan 2004). In this way, the Czech Republic stands before the strategic decisions of how transform the carbon intensive energy industry and how quickly. Considering that national energy security is particularly tied to the extraction of lignite used in the production of electricity and in the heating industry (Sivek et al., 2017), any related policy changes demand support of political elites as well as advocacy groups (Dermont et al. 2017). Considering this puzzling environment, the study has been designed to explore the Czech lignite mining domain.

3 Methods

3.1 Methodological framework

Methodological framework used in the study is Advocacy Coalition Framework (ACF). ACF is a useful approach to identify coalitions of actors actively involved in discussing, framing, or lobby for and against the design of different steering systems (Dermont et. al 2017). Using ACF we assume that policy issues are contested by diverse organizational actors and their coalitions that advocate different perspectives on different political problems (Weible et al. 2016; Ingold 2011). Advocacy coalitions are further recognized as groups of actors that share policy core beliefs and engage in a nontrivial degree of coordinated activity (Weible et al., 2009). The policy core beliefs are normative assumptions about how the subsystem ought to be organized (Sabatier and Weible 2007). The interactions among the actors are often informal and are driven by an exchange of information that relates to substantive policy issues and political efficacy (Cairney et al. 2015).

3.2 Study design

Within the ACF methodological framework, the quantitative research on organizational network in lignite mining policy in the Czech Republic has been conducted. In the preparation phase of the study, the research team identified key actors (i.e. organizations that are important in the mining policy of the Czech Republic) based on literature review and preliminary research. The institutions were identified within pre-selected five stakeholder groups: research organizations, political parties (region, state), governmental organizations & state agencies (region, state), non-governmental organizations, and industry. The positional and decisional approaches to define network borders were applied (Fischer and Sciarini 2016). Further, we asked 14 experts from pre-selected organizational groups. The expert survey was conducted with the aim to validate the list of key organizations in the Czech lignite mining policy based on the experts' knowledge and actual situation in the sector. A total of 83 policy actors involved in the Czech lignite mining domain were identified. The anonymous online questionnaire was sent to representatives of the listed organizations, always to one person per organization. The questionnaire consisted of three sections measuring belief systems, interactions of the policy actors and context information. The first part included measures of policy core beliefs using the attitudinal statements and a four-point Likert scale (strongly disagree – disagree – agree - strongly agree). The second part contained the list of organizations where respondents identified the political cooperation, expert information exchange and political influence of the listed organizations. The last part focused on context information and the organizational involvement in a mine life cycle. The pre-testing of the survey included respondents debriefing and a pilot study (24 responses received). The online questionnaire survey was conducted from June to November 2017. The total response rate was 82%. In regard to particular groups of organizations, the response rate was following: 100% response rate of governmental organizations, 89% political parties, 89% environmental non-governmental organizations, 88% research organizations, 43% professional association and trade unions, 65% industry.

In data analyses, confirmatory factor analysis was applied to validate the Likert scales that capture economic, environmental, policy, and process-oriented dimensions of the policy core beliefs. We calculated the sum of all items for each dimension and rescaled the scores from 0 to 1 to maximize clarity of the interpretation and readability (see Gronow and Ylä-Antilla 2017). The political influence network was used for the construction of the reputational power measure. It simply expresses relative frequency of the political influence indications for each policy actor by others. This corresponds to indegree centrality of the policy actor in the political influence matrix. The measure ranges between 0 and 1 after normalization (Gronow and Ylä-Antilla 2017). The resulting networks consist of directed binary ties. To identify coalitions between actors in the policy domain, we used combination of two exploratory techniques such as, faction analysis applied to the political cooperation network, and cluster analysis applied to policy core beliefs. We used standard descriptive statistics to describe the coalitions' attributes in terms of the policy core beliefs as well as their relational characteristics. The coalitions were identified as intersections of the results of faction analysis applied to political cooperation network and K-means cluster analysis of the policy core beliefs.

We used R 3.3.1 (Team R Core 2013), UCINET (Borgatti et al. 2002), igraph (Csardi and Nepusz 2006), sna (Butts 2008) for data processing, data analyses, and results visualization. The data were collected through the SurveyMonkey platform (www.surveymonkey.com).

4 Results

Based on data analyses, we identified two relationally cohesive and belief-homogenous groups of policy actors: Industry Coalition (IC) and Environmental Coalition (EC), and one residual group. Both Coalitions were heterogeneous, ideologically distant and relationally cohesive. It demonstrates a presence of polarization within the Czech lignite policy network.

As shown in Table 1, the Industry Coalition consists of 16 actors and is dominated by the industry sector represented by six private companies, a professional association, and a trade union. There are also two political parties at the state level (one ruling and one opposition) and three political parties at the region level (two of them ruling). The IC further contains two state agencies, where one is the Ministry of Industry and Trade, and a regional agency. The Environmental Coalition consists of 17 actors: 8 environmental non-governmental organizations (ENGOs) and 6 research organizations. The remaining members are a political party from the state level that has not been represented in the Chamber of Deputies, the Ministry of Agriculture and another state agency.

Table 1 Key organizations identified in IC and EC coalitions within lignite domain in the Czech Republic

Industry Coalition (IC)	Environmental Coalition (EC)
3 political parties (region) 2 political party (central) 2 NGOs 2 state agencies (region) 1 state agencies (region) 6 industry private companies	8 ENGOs 2 state agencies (central) 1 political party (central) 6 research organizations

The matrix blocked by coalition memberships shown in Table 2 presents high within-group densities for both coalitions, 0.267 (IC) and 0.265 (EC) that are about three times of the overall average (0.090). However, the within-group density of the Residual Group (RG) (0.058) is not statistically different from overall network density (0.090).

The degree centralization differs significantly as shown in Figure 2. The Industry Coalition is highly centralized (0.533) around the most active actors such as, a state-owned company (coalition outdegree (co) = 10), a ruling regional party (co = 10), and a trade union (co = 9), as well as around the most popular actor - the Ministry of Trade and Industry (co = 11). On the other side, the degree centralization[1] of the Environmental

[1] Degree centralization indicates a variation in the node degrees divided by maximum degree score. Higher degree centralization indicates larger difference between the maximum degrees and all nodes' degrees and vice versa.

Coalition is significantly lower (0.338). While the IC is centralized around the above mentioned actors and is clustered at the state and regional level (see Table 1), the EC is formed around 5 ENGOs that are the core members of this coalition.

Table 2 The group densities as a result of the block model analysis[2]. The statistical significant assessment in in bold.

	1	2	3
1	**0.267**	0.055	**0.145**
2	0.074	**0.265**	0.064
3	0.063	0.025	0.058

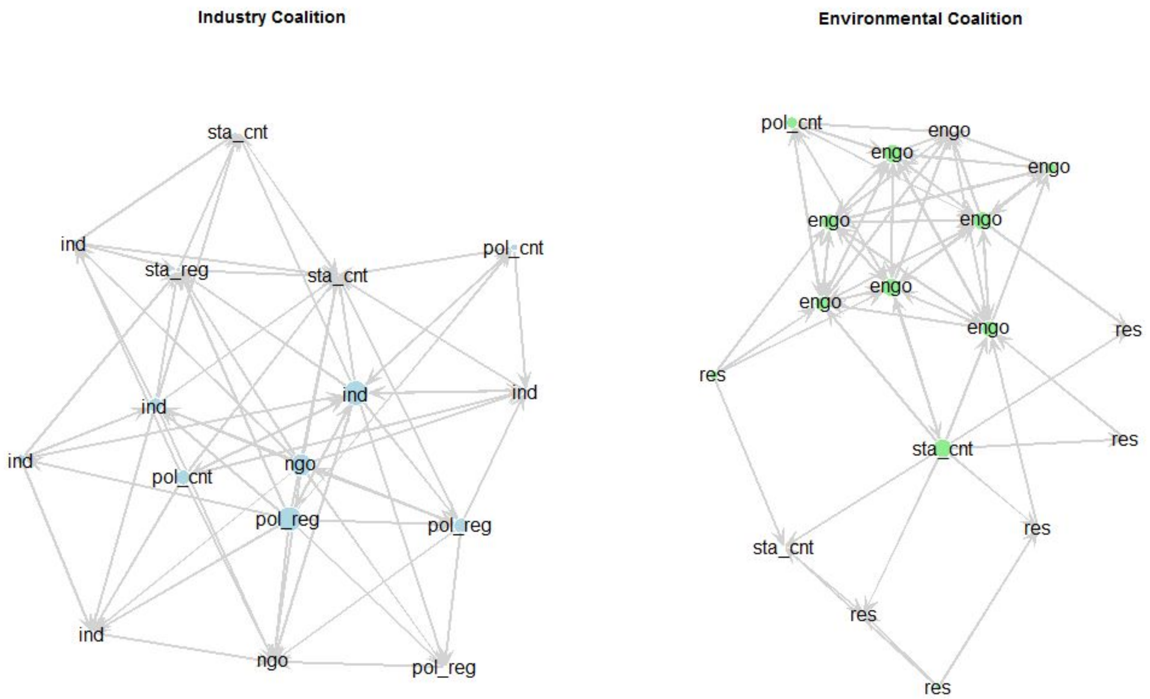

Figure 2 Shema of coalitions of actors actively involved in discussing, framing, or lobbying in the lignite mining domain in the Czech Republic[3]. The node size represents coalition outdegree centrality.

Attributes of the coalitions that have been analysed and presented in Table 3 are: reputational power (RP)[4], policy core beliefs (divided into four dimensions: policy, economic, environmental, and process), density of the within-group interactions, and the core-periphery structure[5] (% core). At the network level, there is only a moderate fit with the core-periphery structure (0.405) that corresponds with the presence of two coalitions. The core consists of 23 organizations, 10 belong to the IC and 6 to the EC. In terms of RP, the IC has about 2.5 times higher score (0.471) than the EC (0.185). The differences are statistically significant and

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[2] The statistical significance assessment (p) is based on the Quadratic Assignment Procedure (Krackhardt 1985) which used 5000 trials of the random matrix permutations and estimated standard errors based on resulting simulated sampling distribution. The model fit (Adj. R2) is given by a ratio of the variance in the pairwise presence or absence of ties explained by the differences among the blocks (Hanneman and Riddle 2005). The 68*68 matrix contains 4556 cells (obs) excluding the diagonal (68).

[3] sta_cnt = state agency (central), sta_reg = state agency (regional), pol_cnt = political party (national parliament), pol_reg = political party (regional assembly), res = research organization, engo = environmental non-governmental organization, ngo = non-governmental organization, ind = industry

[4] The basic explanation of reputational power is that actors belonging to a political system have the most accurate view of how power is allocated among actors. Reputational power of an actor = the sum (or the mean) of power attributions granted to this actor (see Fischer and Sciarini 2015).

[5] The core-periphery model assumes that network is partitioned into two groups, a dense core and a sparse, loosely connected periphery. The fit function is the correlation between the permuted data matrix and an ideal structure matrix consisting of one in the core block interaction and zeros in the peripheral block interactions (Borgatti et al. 2002).

could indicate that although the EC is well-connected to the decision-making actors, the impact of its interactions is limited.

Table 3 Attributes of the coalitions[6] (means and standard deviations are in parentheses).

	RP	Policy core beliefs dimensions				Density	% core
		econ	enviro	policy	process		
IC	0.471[a] (0.227)	0.267[a] (0.154)	0.378[a] (0.177)	0.244[a] (0.158)	0.350[a] (0.176)	0.267	44
EC	0.185[b] (0.180)	0.785[b] (0.160)	0.903[b] (0.146)	0.792[b] (0.151)	0.766[b] (0.167)	0.265	26
RG	0.221[b] (0.210)	0.476[c] (0.292)	0.571[c] (0.231)	0.423[c] (0.267)	0.504[a] (0.284)	0.058	30
Total	0.271 (0.233)	0.511 (0.301)	0.481 (0.281)	0.485 (0.299)	0.540 (0.275)	0.090	100

Summarizing our findings, the Industry Coalition possesses more resources, both in terms of reputational power and a direct access to the decision-making through the ruling political parties and the Ministry of Industry and Trade. On the other hand, the Environmental Coalition is more homogeneous in terms of involved actors and disposes with markedly lower resources. The relational position of the coalitions in the network is similar, however the IC extends more ties to the Residual Group than the EC, especially to the decision-making and administrative bodies. In sum, our study demonstrated that the Industry Coalition is a dominant coalition with superior resources and political authority, whereas the Environmental Coalition is a minor coalition that mainly relies on relational capacity of its core.

5 Conclusion

Our study examined that the Czech lignite domain is clustered into two coalitions with opposing policy core beliefs that include different organizational actors. While the Industry Coalition as dominant in the lignite policy domain considers coal as an integral part of the future energy mix and supports breaching the mining limits, the Environmental Coalition promotes a rapid decline from coal mining while challenging the current situation in the lignite sector. We suggest that, in terms of future development, the situation in the Czech lignite sector will continue to be affected by the *devil shift* (i.e., actors perceive opponents to be stronger and more *evil* than they actually are). Distrust between both coalitions will be further deepened which will block any internally driven major policy change. We argue that the Czech coal phase-out does not unfold through incremental adjustments that would result from policy learning or negotiated agreement. It is rather driven by external developments that follow established institutional and policy framework in the Czech Republic.

Acknowledgement

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[6] One-way ANOVA tests for reputational power and PCB economy dimension significant at $p < 0.05$. One-way ANOVA tests for remaining three PCB dimensions significant at $p < 0.001$. Fisher's Least Significant Difference test was used to determine pairwise differences between the three groups for each dimension. The groups with a different superscript letter are significantly different at $p < 0.05$ with Bonferroni correction.

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2. Planning, modelling and monitoring

Comparisons between Numerical Model and Field Results of Instrumented Experiments of Cover Systems for Gold Mine Tailings

RF Azevedo *Federal University of Viçosa*

G Silva *Geoestável Consultants and Projects*

N Amorim *Geoestável Consultants and Projects*

A Nepomuceno *Kinross Brazil Mining*

A Matos Kinross Brazil Mining

LC Ventura *Geoestável Consultants and Projects*

L Cunha *Kinross Brazil Mining*

G Vargas *Kinross Brazil Mining*

Abstract

Santo Antonio TSF (tailings storage facility) is located at Paracatu city, Minas Gerais state, Brazil. It belongs to Kinross Brazil Mining, embraces 927 ha and stores 472x106 m^3 of tailings. The embankment is 5 kilometers long and 100 meters high. The TSF, the largest in the country, finish its operation in the beginning of 2016 (Matos et al., 2016). Geoestável Consultants and Projects Company was contracted by Kinross Brazil Mining to design the final soil cover system for the tailings at Santo Antonio TSF.

A pilot-scale soil cover experiment was design to subsidize the final design of the soil cover. One type of soil cover system has a store and release (S&R) layer constructed with a non-compacted silty soil to have sufficiently high void ratio and permeability coefficient. The second type has the same store and release layer overlying a hydraulic barrier layer formed by the same silty soil, although well compacted to ensure sufficiently low void ratio and permeability coefficient. For both soil cover types, two test cells were built. One is a lysimeter and includes on the bottom, at 1.5m deep, a drainage layer upon a geomembrane to allow percolation measurements. The other is an infiltration cell without geosynthetic layer and studies the interaction between the soil cover and the tailings. Therefore the experiment has four test cells of around 100 m^2 each, the instrumentation in each test cells includes nests of moisture (water content reflectometer) and suction (heat dissipation metric) sensors, and oxygen meters to evaluate sulfide oxidation, as well as special flow meters to measure runoff and infiltration. A previous paper Matos et al. (2016) described the construction of the field experiment and the four test cells, as well as first instrumentation results.

This paper shows field measurements from May, 12th, 2016 till January 31th, 2018, obtained at the four cells. Although there is monitoring data of runoff, suction and oxygen concentration, in this article, we present only the moisture data and comparisons with the numerical model.

A finite element numerical model of the infiltration problem considering the climate data and all the physical processes that occur at the ground drive by the sun energy (evaporation, transpiration, runoff, etc) was made.

The paper presents comparisons between field and numerical results. Main conclusions are that the numerical model was able to capture important aspects of the field results and can be used to design the final cover thickness.

Keywords: *gold mine tailings, numerical modelling, experimental instruments*

1 Introduction

To prevent soil and groundwater contamination by acid rock drainage, tailings storage facility (TSF) with tailings presenting sulfide minerals must be closed with cover systems that minimize water and oxygen infiltration.

There are many different types of cover systems made with water, soil, geosynthetic products and combinations of these options.

However, any solution has to be economical and technically viable. Many factors interfere in this decision like climate, the size of the reservoir to be closed, the availability of soil borrow areas and the type of soils in this areas, cost of geosynthetic products, amount of acceptable infiltration, etc.

2 Methodology

Initially, a basic decision was made with respect of what cover type should be used. In this regard, given the size of the reservoir (very large), the cost of geosynthetics products in Brazil (yet expensive) and the local soil availability (sufficient silt soil, very little clay soil), a soil cover system was adopted to close 540 ha. The rest would be covered with a lake.

After that basic decision, the methodology used consists of the following steps. The first one, based on the available soil information in the surroundings of the reservoir, to perform laboratory tests with these soils. Second, to construct and monitor different types of soil cover with the selected soils to verify which one performed better. The third step was to use a robust soil infiltration model to analyze the field tests with the best performances. Following, to perform an optimization process of the soil parameters used in the model to minimize the differences between field and numerical results. Finally, to use the optimized numerical model to calculate the thickness of soil cover layers in order to attain the allowable infiltration rate and avoid acid drainage.

3 Data

3.1 Field Experiment

Figure 1 presents the field experiment constructed at the Santo Antonio dam reservoir.

Figure 1 General view of the experiment and the four tests.

Four tests were made with two pairs of different types of soil covers: the first pair has three soil layers; and the second one only two soil layers. In each pair, one test had on the bottom a drainage layer and a geomembrane layer to collect infiltration, therefore was a lysimeter, and the other one did not have this membrane and could not measure infiltration (Figure 2).

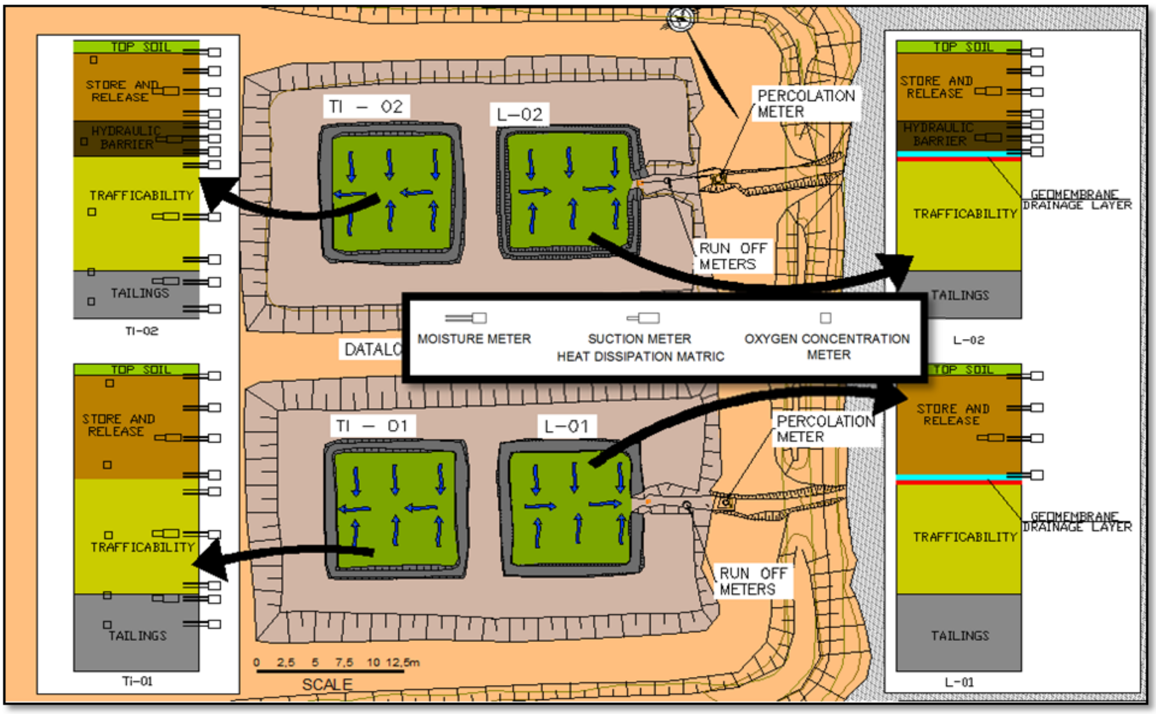

Figure 2 Schematic view of the experiment, the four tests and the respective instrumentation

3.2 Climate

Figure 3 shows climate data, precipitation and evaporation, from beginning of 2016 to beginning of 2018. The experiments were built in December 2015, but the monitoring with instruments began in May 2016.

The total precipitation and evaporation in the monitoring period were 1552 mm and 4040 mm respectively. The accumulated total for the period is below the historical average.

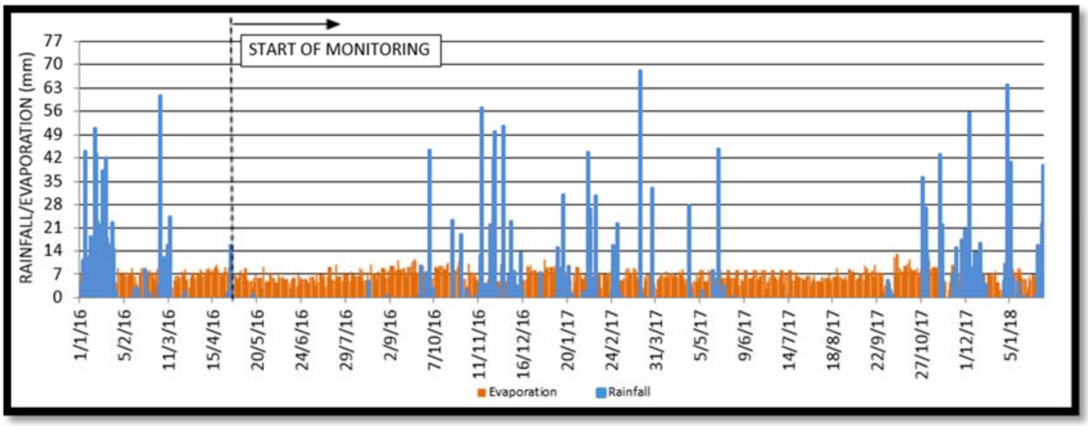

Figure 3 Precipitation and evaporation distribution in the analyzed period

3.3 Laboratory test results of the soil used in the layers

The Figure 4 show the main physical characteristics obtained in the laboratory for the soils that composing the soil covers, respectively S&R and hydraulic barrier.

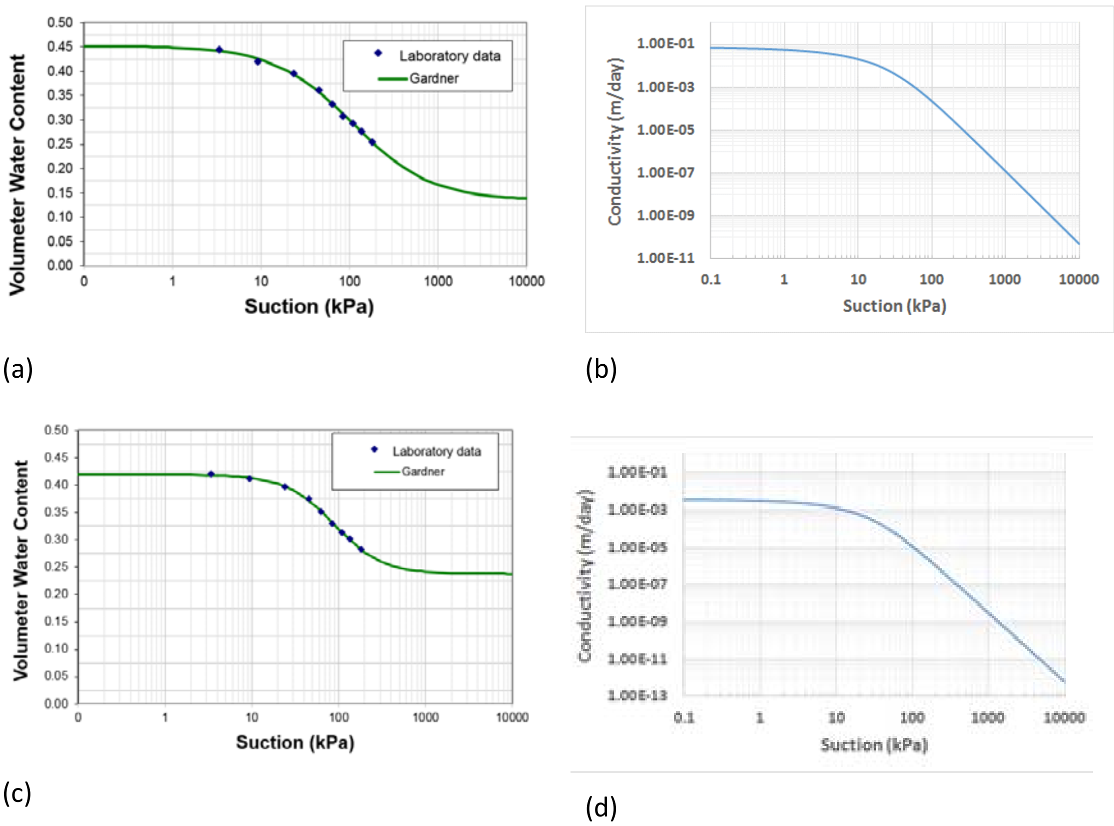

Figure 4 **Hydraulics properties of soils are respectively: (a, c) water content of S&R and hydraulic barrier; (b,d) hydraulic conductivity of S&R and hydraulic barrier**

4 Results

Figure 5 present saturation profiles for the lysimeter and infiltration tests number one and Figure 6 present the same for the number two.

The field results presented in Figures 5 and 6 allows for the following discussion. First, water content values in the lysimeter tests were greater than the one in the infiltration test due to the presence of the drainage layers.

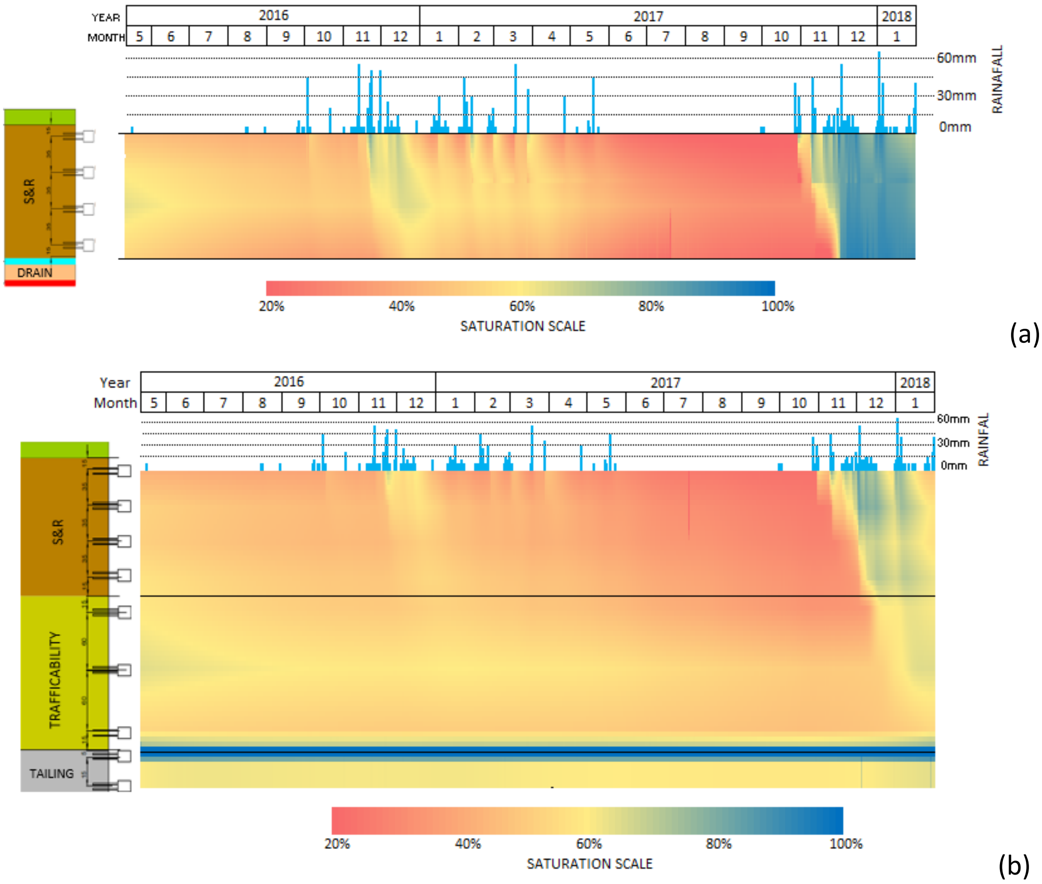

Figure 5 Saturation - monitored period (a) lysimeter 01 (b) infiltration test 01

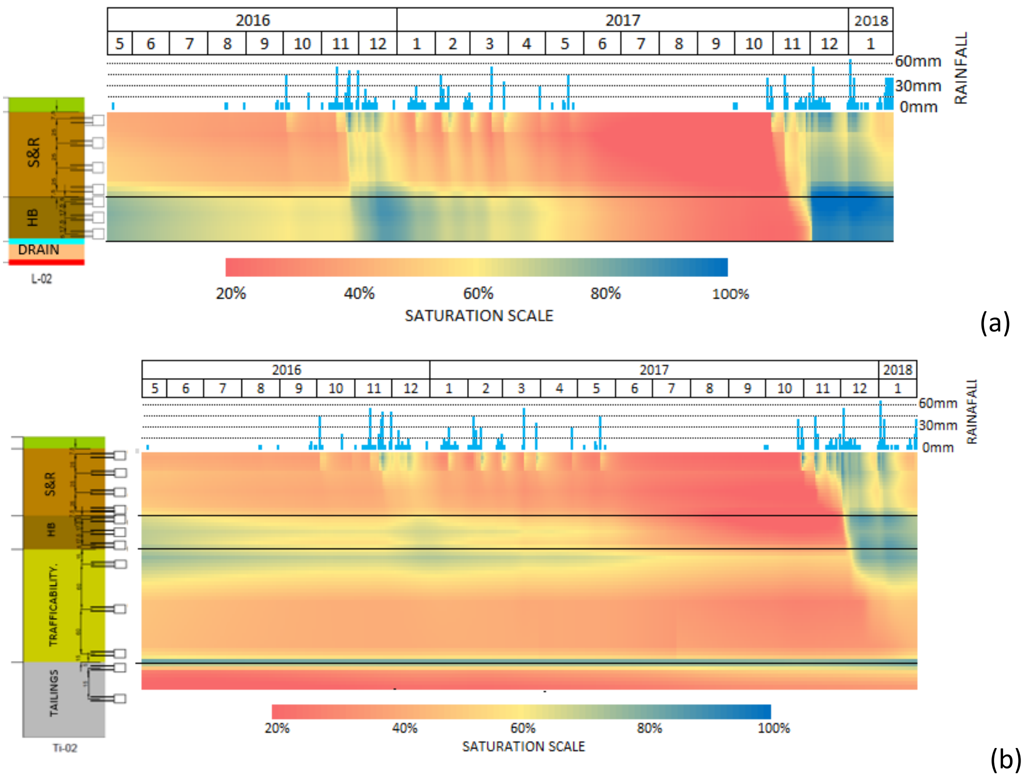

Figure 6 Saturation - monitored period (a) lysimeter 02 and (b) infiltration test 02

The field results presented in Figures 5 and 6 allows for the following discussion. First, water content values in the lysimeter tests were greater than the one in the infiltration test due to the presence of the drainage layers. The goal of constructing a draining layer on lysimeters was to collect and measure the flow. As it was expected that it would interfere in the results, the infiltration cells were constructed using the same solutions to evaluate the free flowing between the cover and the tailings, without drainage or geomembrane layers.

The second discussion is that the water content in infiltration test 01 was smaller than in the infiltration test 02.

The volume of water that passed through the cover layer (1.5m) of the infiltration test 01 was calculated from the variation of the moisture in the experiment resulting in a total of $0.009m^3/m^2$ or the equivalent of 9mm of rainfall. This result can be considered positive, since the accumulation of precipitation for the same period was 1552 mm, approximately only 0.6% of all rainfall.

Figure 7 shows the flow along the monitored period, where positive values mean flow in the direction of gravity, i.e. from the cover to the trafficability. The negative values represent the upflow or the flow from the bottom to the cover. During the monitored period it is possible to notice oscillations between positive and negative flows and only at the end of 2016 and 2017 there was a significant increase in the flow of the cover to the layer below it. The sum of the negative values also resulted in $0.009m^3/m^2$. Although there was a fairly low total pass through (0.5% of total rainfall), when analyzing the whole monitored period the amount of upflow was equivalent of the flow that went through the coverage, this shows that the cover was quite efficient.

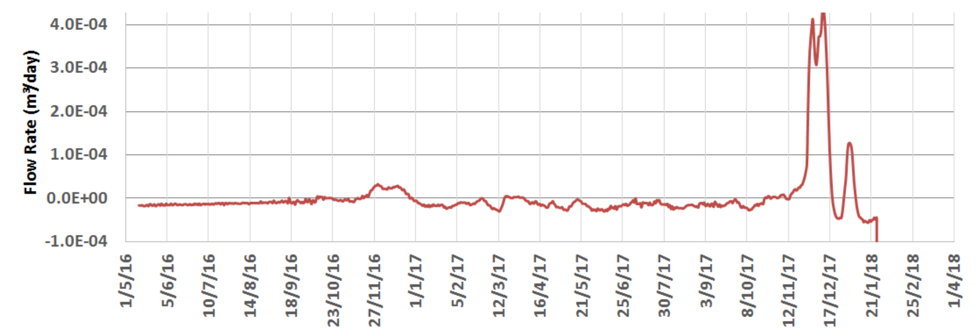

Figure 7 Flow rate at the surface between S&R and trafficability layers

Therefore, the solution tested in the infiltration test 01, clearly showed the best results, and in the following items only results of infiltration test 01 will be presented and, when possible, compared with the numerical results.

Numerical Comparisons

Results of volumetric water content in all sensors installed in infiltration test Ti-01 are presented in Figure 8. As it was expected, sensors that are closer to the ground surface experimented larger water content variations than the other ones.

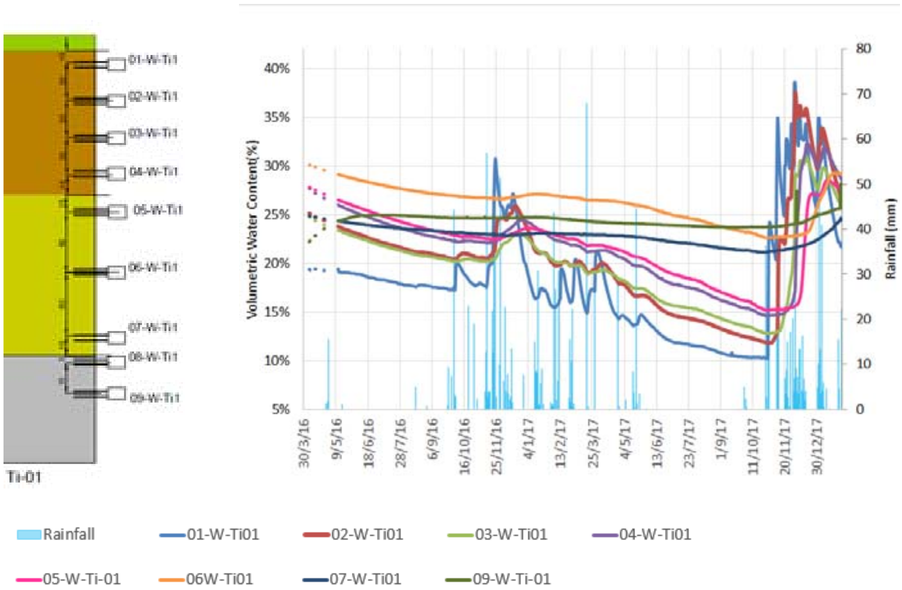

Figure 8 Volumetric water content during the period of analysis in all sensors installed on infiltration test Ti-01

The first results of the numerical model output data were not very close comparing to field data. Thus, it was necessary to calibrate the numerical model. Climate data were obtained from the Kinross weather station, vegetation data were estimated and soil property data were obtained in the laboratory. The reproduction of the field conditions in the laboratory can be considered difficult given the soil etherity and the variability of its characteristics. To calibrate the numerical model in order to approximate the model results to the field data, the retention and permeability curve data obtained by laboratory were modified in order to obtain results similar to the real data measured.

Figure 9 and 10 show comparisons between field and calibrated numerical results for sensors WRC 02-W-Ti01 and 03-W-Ti01, respectively. It can clearly be seen that the agreement is very good, therefore allowing the numerical result to be used for the final design of the soil cover.

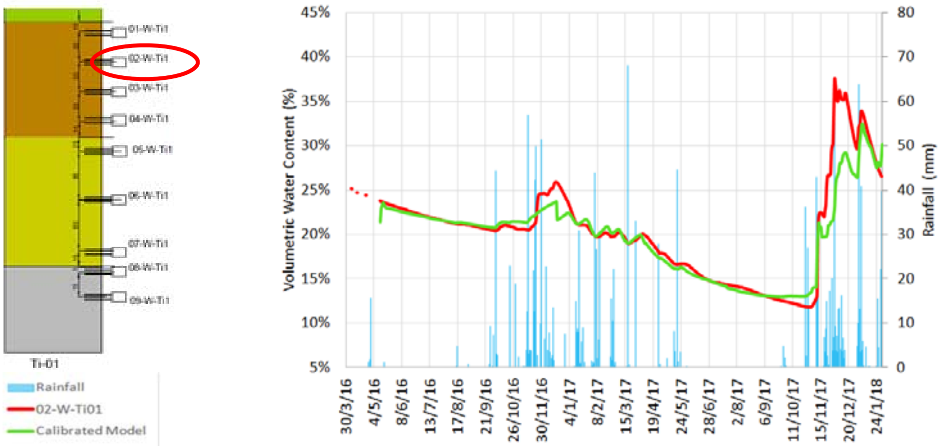

Figure 9 Comparisons between field and numerical results for sensor WCR 02-W-Ti01 of infiltration test Ti-01

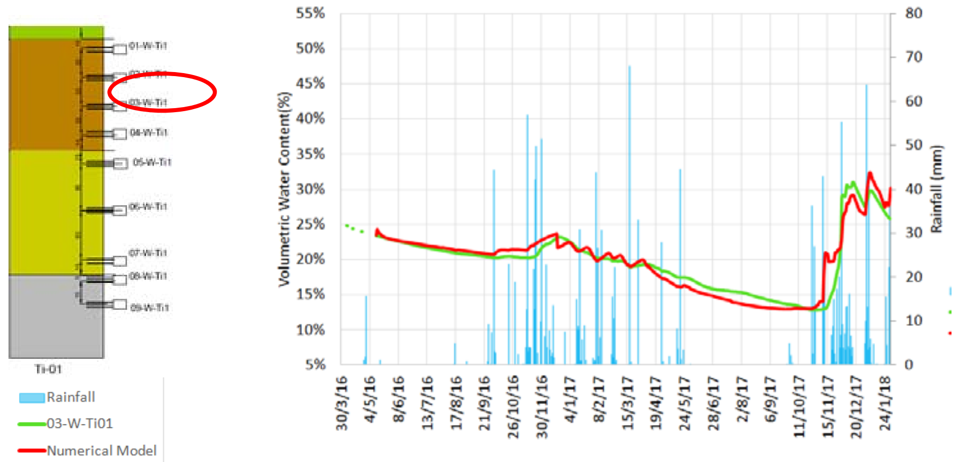

Figure 10 Comparisons between field and numerical water content results for sensor WCR 03-W-Ti01 of infiltration test Ti-01

The annual average for the city of Paracatu is 1387mm per year. As the monitored period accumulated values below this average, to evaluate the efficiency of the soil cover, the year with the highest accumulation of rainfall among the existing historical series was adopted. The meteorological data of the year of 1983 were adopted as input data in the calibrated model totaling 2606 mm of rainfall in a year. The result was a total flow passing equivalent to 19,8mm of rain when the cover layer is 2,0 m of thickness.

5 Conclusion

A field experiment was constructed to help the design of a soil cover for a closed TSF in Paracatu, Minas Gerais state, Brazil. The paper discussed briefly the experiment, presented the instrumentation results obtained from May, 12th, 2016 to January 31th, 2018 and comparisons between field and numerical water content results.

The main conclusions are:

- The field experiment has been very helpful to the cover design. It allowed the conclusion that a hydraulic barrier is not feasible with the available material and the store and release solution (Ti01) presented better results
- Comparisons between field and numerical water content was very good but required an optimization of the soil parameters first obtained with laboratory tests;
- The calibration of the numerical model allowed the simulation of critical rainfall conditions, making possible to evaluate the cover efficiency for more severe climate conditions, as already observed in the past. The result, even for severe conditions, was considered positive and it was possible to validate the proposed layer thicknesses for the soil cover solution.

Rethinking Closure Planning: A Case Study of BHP Nickel West

C Bagnall *BHP, Australia*

Abstract

Mine closure is complex, with challenges and risks that are distinct within mine planning. Closure objectives, scope, stakeholders, risks, opportunities and costs can be miscalculated. It is also difficult to predict future Government policy, feasible land-uses and performance criteria, changes in climate and other factors that influence closure success. This can be done only to realise late in closure planning, or execution, that we got it wrong. If this happens, the impacts can be adverse for the mining company, environment, stakeholders and wider industry.

At BHP Nickel West, one of the world's largest nickel concentrate producers (with mining and downstream operations located in Western Australia and a planned operational life beyond the next two decades), these common experiences within the mining industry have been recognised contributing to a rethink in closure planning.

Combined with an appetite to review more closely closure risks, costs and liabilities to strengthen business planning, this recognition has led to a fundamental shift over the last three years in Nickel West's approach to closure. This change was most evident in the implementation of a major studies and options evaluation program as part of an Identification Phase Study (IPS). The scale of the IPS was rare for a closure study in Australia. The approach set out to tackle the root causes that undermine the progress and quality of closure outcomes, and address them within a comprehensive risk-based, 'first-principles' review of the existing closure plans.

Three years on, and the results from the studies program have been significant. For a modest investment, the mitigation in design of closure risks and the substantiation of closure costs have been materially improved. In addition, there is strengthened alignment with regulatory authorities on what constitutes acceptable outcomes. Importantly, there is also improved clarity on where to invest during continued operations to benefit closure.

This paper will explain the merits of the Nickel West approach, from its early framing to the delivery of results and its value to continued operations. Specifically, those elements that were different from conventional planning will be covered. Key lessons learned from the IPS will be shared. Ultimately, it will be argued that you do not need to wait until closure or near closure to implement a studies program of this kind, and that it makes good business sense to do this early in operations when your abilities to respond and maximise the gains are greatest.

Keywords: *BHP, nickel mine, Identification Phase Study (IPS)*

1 Introduction

Mining companies face the significant and complex challenge of ensuring their progressive planning and financial provisioning for closure is sufficiently robust to prevent material miscalculations from eventuating at closure.

This is made difficult by many factors, not the least of which is the significant time, and often decades, until closure. Technical knowledge, Government policy and stakeholder expectations can materially alter or evolve within the space of only a few years having major consequences on closure risks and costs if under-estimated or unchecked.

In Western Australia, the lack of successful mine closure examples (to the point where relinquishment of the mining tenure and any residual liabilities has been successfully achieved by the mining company) has also greatly diminished the ability for companies to reliably predict, plan, invest and replicate success in mine closure.

For these reasons, for some companies, a malaise or apathy in organisational cultures towards closure can develop. Closure planning can be seen as too complex, distant and/or uncertain to warrant investment beyond the minimum required to meet any compliance obligations. The net effect from this is that closure can become secondary in business planning and decision-making, exacerbating latent risks and the potential for missed opportunities.

The upside from an alternate approach that adopts a deeper analysis and active operational response to closure risks is compelling. The benefits are not just to avoid getting it materially wrong at closure where significant, late adjustments to funding provisions can negatively affect stakeholder confidence and business performance. The benefits are also to capitalise on the available 'win-win' opportunities that can arise from a targeted campaign of progressive reductions in closure risks during mining operations. In addition to the closure benefits, such actions taken pre-closure can greatly improve the operational management of health, safety, environmental, community and reputational risks and enhance the regard by regulatory authorities and other key stakeholders of company performance to help support/underpin successful Asset growth approvals.

At BHP, there is a mature cycle of annual review and update of site closure plans and the related cost estimates undertaken by Assets, or business units, such as Nickel West. BHP has in place rigorous standards for the development of plans and cost estimates to ensure a consistent approach is maintained across its global operations.

In 2015, Nickel West made a decision to go beyond these internal requirements and rethink its approach to closure planning. This involved the implementation of a large-scale closure studies program within a new framework. The initial trigger for this decision was a developing scenario where the entire Asset may close within five years should market conditions, operational efficiencies and growth prospects not materially improve. However, within only one year of commencing an Identification Phase Study (IPS) the likelihood of closure eventuating within five years had greatly diminished. This change had resulted from an urgent and committed response by the entire Nickel West workforce over that year that materially extended the previous Life of Asset date.

Importantly, this rapid improvement in the future prospects for Nickel West did not reduce the importance of the closure studies program underway. Instead, both Nickel West and BHP recognised the momentum and emerging value from the studies and elected to continue to maintain the program to plan until the completion of the IPS.

This was a key decision point in the completion of the IPS program and provides the basis for the main argument in this paper - which is that ultimately implementing a studies program of this kind makes good business sense and particularly when done early enough in operations to maximise the potential gains to the triple bottom line.

Three years on, the results from the program have been significant, exceeding many of the original expectations. Nickel West has strengthened site closure plans from advanced risk evaluation, engineering, benchmarking and stakeholder acceptance testing. These plans factor and are resilient to a range of mining, environmental and land-use conditions that may prevail over time, including changes to climate. They also propose an improved and more credible path to the relinquishment of mining tenements and residual closure liabilities.

In addition, from the active engagement of key operations and functions personnel during the completion of the studies, the Nickel West workforce is now, and more than any time in its past, well equipped to readily identify and mitigate closure risks and seize 'win-win' closure/operations opportunity benefits in their daily work.

2 The Asset

Nickel West is a fully integrated nickel business with mining and processing operations in Western Australia. Operations commenced in 1967. With its head office in Perth, the workforce totals over 2,000 employees and contractors. Current Nickel West operations comprise:

1. Mt Keith Mine, a large open-cut nickel mine, 430 km north of the regional city of Kalgoorlie;
2. Cliffs Mine, a small underground nickel mine, 425 km north of Kalgoorlie;
3. Leinster Mine, a large open-cut and underground nickel mine, 370 km north of Kalgoorlie;
4. Leinster town (a town owned and operated by Nickel West), 370 km north of Kalgoorlie;
5. Kalgoorlie Nickel Smelter, 15 km south of Kalgoorlie;
6. Kambalda Nickel Concentrator, 60 km south of Kalgoorlie;
7. Kwinana Nickel Refinery, 40 km south of the State capital city of Perth; and
8. Other activities including mineral exploration and non-operating (legacy) sites associated with former activities.

The locations of the main operating sites are shown in **Figure 1**.

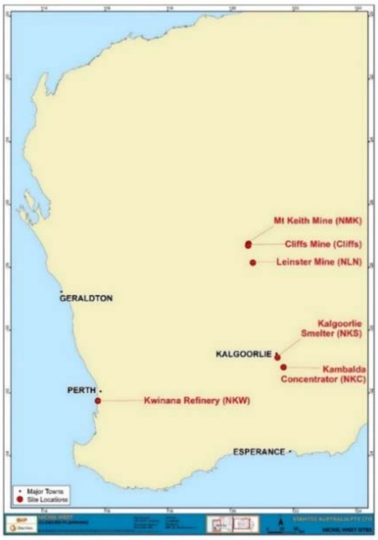

Figure 1 Nickel West Operating Sites

This portfolio of sites, with a history dating back five decades, provides a complex and diverse scope for closure. The range in affected stakeholders and regulations across the different mining and processing sites provides added challenges, particularly given the consistent Asset-level approach to closure that was being sought. As the largest nickel producer in Australia and an important employer and contributor to the State economy, these inherent Asset features provide additional interests, complexity and scrutiny in Nickel West's closure planning.

3 Methodology - A new approach

Where do you start when challenged with a new business requirement to review the existing closure strategy for an entire Asset to ensure its preparedness for a potential near-term closure scenario? This was the question put to the newly assembled Nickel West closure planning team in mid-2015. The initial response was to recognise that the existing closure planning processes, whilst disciplined, could be strengthened if assessed within BHP's major project framework. The logical and impartial sequence of work in developing a major project could anchor the studies program minimising the potential for drift, misses and wastage whilst strengthening the credibility of output with internal audiences unfamiliar with closure planning. The investment size also exceeded US$250M, requiring that BHP's major project framework be applied.

For these reasons, the planning for transition from the existing theoretical and compliance-based closure planning framework to an IPS began in earnest. Critical at this time was ensuring a clear definition and agreement with internal stakeholders of the project scope. What was out of scope was equally important to what was in scope. This required due consideration, particularly because many needing to authorise the IPS work plan were not necessarily familiar with the scope of a closure project increasing the potential for misunderstanding. After some review, the project scope was decided upon as being the optimal technical solution to close the entire Asset. This assumed the decision and timing to close Nickel West was made and therefore not in doubt. On this basis, the scope did not extend to broader strategic reviews of the Asset future and therefore excluded the evaluation of growth, divestment, cessation/suspension or closure deferral options. These valuation reviews were facilitated by Nickel West/BHP separately during the completion of the IPS.

BHP has standards for the development and execution of major projects that were considered from the outset of IPS development. These standards prescribe project framing, governance and reporting obligations and requirements for internal peer review of key project deliverables. Whilst these standards informed the initial development of the project, it was important when reviewing their application to carefully consider their relevance and coverage against the nominated project scope. Often these standards are designed for conventional mining and related infrastructure proposals with limited, if any, consideration for the anomalous qualities of a closure project. This was important to recognise to avoid waste from ‘compliance for compliance sake’ against standard requirements. Examples of differences for closure projects include catering for the extended period post execution until project closeout is realised, factoring of greater inherent uncertainties, typically earlier stakeholder acceptance/approval agreements required and the different metrics used to measure financial performance (e.g. total undiscounted capital cost instead of net present value or return on investment).

When defining the investment opportunity, additional to the usual commitments for a closure project to deliver outcomes that satisfy legal obligations and stakeholder expectations, the relinquishment of tenure and residual company liabilities at closure was identified as a fundamental project objective. The project team believed that relinquishment defined in this way (i.e. as a responsible ‘walk away’ solution) was the ultimate closure end-point. It assumed that the core business of mining was not to accrue and manage closed sites in perpetuity, but instead to close sites post-mining in a timely and responsible manner for the future use and benefit of others. It proposed that relinquishment should be the starting point in evaluating closure alternatives with the pursuit of other options such as in-perpetuity management only where relinquishment proved unviable.

By prioritising relinquishment in this way, the project team committed to examining what was necessary to achieve relinquishment and why it had been rarely achieved in Western Australia. It also meant challenging some inherent biases within the project team, and more broadly, that believed relinquishment was just too difficult or unlikely to ever be realised but without having undertaken any serious evaluation of it, or having resigned it prematurely as being uncompetitive on a cost-basis compared with an ‘in-perpetuity management’ scenario.

The inclusion of relinquishment as a specific project objective made a clear statement about the parity of all objectives and subsequently had a profound impact on project framing, scope, risks, costs, decision-making, internal reviews and stakeholder engagement. A relinquishment objective clearly challenged the mindset of many leading to deeper analyses. Critically, it redefined what closure success looks like, and what is required to achieve it.

An experienced project team was assembled comprising local and global expertise in mine closure to execute the IPS program. In addition, advantage was made of the diverse closure and major project experience within BHP. The nearly 3-year duration of the IPS was scrutinised at the project outset because some, on the surface, saw it as being too long, and particularly when compared to the average IPS duration for other major projects in BHP. These perceptions did not last long once the scope and key deliverables of the IPS program were explained and understood. This is an important observation, as there can be a tendency to under-estimate the complexities of a closure project and the time needed to effectively complete the work required in an IPS study.

Table1 IPS main stages

No	Phase
1	Update the Knowledge Base
2	Identify & Evaluate Options & Select the Preferred Closure Alternatives
3	Finalise Preliminary Engineering & Class 4 Cost Estimate for Selected Alternatives
4	Update Site Closure Plans & Obtain Key Internal & External (Regulatory) Approvals
5	Update Asset Closure Financial Provision (and Closure Valuation) per Revised Plans

These stages were concluded in June 2018. In February 2018, Nickel West and BHP made the decision to not progress to the next phase of project development. Beyond the IPS, the Selection Phase Study (SPS) and Definition Phase Study (DPS) complete the development (design) phases of a major project after which it is executed. The decision to not proceed to SPS was made due to the expected closure date extending from within five years at the start of IPS to beyond 20 years (as determined from the FY2018 Life of Asset plan update). As submitted in this paper, there is potentially significant value in completing an IPS level of study as part of Asset/site closure planning well prior to the closure date. However, pursuing the remaining SPS and DPS development phases when there remains significant time before closure is not considered to hold the same value. This is because the level of required scope and cost definition and stakeholder engagement necessary in SPS and DPS generally requires more certainty of the closure timing to minimise the potential for rework and waste.

4 Methodology - Lessons Learned

Some of the key features, and lessons learned, from the IPS are described below.

4.1 Experience and diversity matters, assemble a capable team

Like all major projects, the success of the IPS was directly attributable to effective planning/execution by a capable team. For the complex scope, an experienced team with diversity and strength in all key closure disciplines was required. A project team was assembled that comprised a small owner's team and a large part-time technical consultant base. The Project Manager was a BHP employee - a key learning from other large closure projects - who reported directly to the Nickel West Asset President ensuring the project had a high profile and priority within BHP.

The owner's team implemented an innovative tender process to select the principal studies consultant. As part of the tender design, Nickel West recognised that no lone consultant could deliver the entire technical scope required. As a result, Nickel West challenged the consultant industry by encouraging collaboration between traditional competitors to ensure the diversity, capability and availability of the key personnel necessary. After a three-month tender process, Nickel West selected Stantec Australia (formerly MWH) as its principal consultant for the IPS. Stantec was engaged on a schedule of rates contract with a cap on costs for each phase of work.

The tender scope and evaluation criteria (and awarded contract) placed importance on the principal studies consultant being able to routinely flex, and with minimal fuss (i.e. minimal costs and delays), to meet the dynamic phases of the scope. This was a lesson learned from other closure projects where contractual frameworks were adopted that did not adequately recognise and cater for the unique uncertainties and exploration required for closure projects, and particularly during the preliminary development phase of the IPS. As part of its successful bid, Stantec engaged more than 25 sub-consultants over the contract term. Along with Stantec, these consultants brought additional niche local and global experience to the project team in the following:

- Mine Rehabilitation
- Landform Engineering
- Contaminated Sites
- Geotechnical
- Tailings Engineering
- Materials Characterisation
- Surface Water Hydrology
- Pit Lakes
- Revegetation
- Erosion Modelling
- Climate Modelling
- Demolition
- Pastoralism
- Socio-Economic
- Groundwater (Hydrogeology)
- Cultural Heritage
- Regulatory Approvals
- Opportunity Framing
- Multi-Criteria Analysis
- Risk Management
- Cost Estimate Development/ Modelling

Whilst technical diversity was a key attribute of the project team, diversity was also sought in the character and experience of the team. This helped to enhance workshop evaluations, often creating a contest of ideas strengthening outcomes. Former Government officials with experience in State closure policy development, independent Site Auditors appointed by Government to advise as experts on contaminated sites matters and those who were involved in preparing previous closure plans prior to the IPS and/or those who had strong views on the merit of past closure designs were often invited to participate in key workshops to test and evaluate thinking. Having such a large team of normally competing companies working alongside each other on a project team, and in many instances collaborating for the first time, carried obvious risks in organisation, culture and consistency in quality. These risks were managed by establishing a clear and compelling vision and performance expectations (and seeking alignment) at the outset and building and maintaining a positive, supportive and inclusive culture. The rare opportunity to work on a project of this kind also helped to galvanise the team.

4.2 Start with 'do nothing', as part of a risk-based approach

A key challenge for any project team is minimising the bias and rush towards a particular action or outcome from a pre-determined idea of what constitutes the underlying risk/s (to be managed) and, as a consequence, the right solution/s. Doing this can have a profoundly adverse effect on a closure project, where site-specific solutions are often required in response to a complex matrix of risks, local conditions and/or stakeholder preferences.

To address these issues, and taking a 'first principles' approach to risk evaluation, the project team chose to qualify and evaluate risk from the starting point of "what would happen if nothing was done at closure?". This sounds obvious but the experience of the project team was that this was rarely done. In a practical sense, this meant asking: *"if no rehabilitation or other remedial work was done at closure, what would happen?"* It sought to challenge any bias and assumptions by asking: *"does anything need to be done, or are we simply assuming something is required?" and "are we then jumping to the conclusion of what we think the solution should be without first qualifying the risks that require remedy?".* By first qualifying the inherent risk from a 'do nothing' scenario, the basis for any action/s and what form this action/s should take was able to be objectively determined.

This approach led to important discoveries about the key underlying risks associated with site closure domains. A good example of this was the assessment of inherent risks associated with the Tailings Storage Facility (TSF) at the Mt Keith Mine, which has the largest TSF of all of the Nickel West mines. The IPS knowledge update concluded that if Nickel West 'did nothing' at closure, then the tailings dust and surface drainage were the predominant risk issues potentially requiring remedy. This was a key finding because pre-IPS the mitigation of potential tailings seepage and the establishment of vegetation on rehabilitated areas were assumed to be the main closure issues.

This change in understanding of the primary risks led to profound changes in the TSF rehabilitation design. These changes included a 50% thinner waste rock cover system (of maximum 0.5 metre thickness) to predominantly manage dust and a new 'water retention' landform design (in lieu of a 'water shedding' previously) to effectively manage surface water run-off within evaporative cells on the 1,900 hectare (ha) final landform.

Predicted changes in climate and over a maximum practical design life of 300 years were also factored, which only increased the inherent risks, strengthening support for the new, alternate IPS design. Higher intensity storm events within an overall drying climate exacerbating erosion and revegetation risks respectively are effectively managed by the new landform design that increases surface water retention in the naturally high evaporative conditions. From a cost perspective, the new TSF rehabilitation design was also 25% less expensive than the previous design.

This example illustrates the material value that can be unlocked from an accurate qualification of inherent risks early in closure planning, and particularly for the key closure domains. In this case, the revised rehabilitation design was superior in its risk control, engineering, constructability, costs and acceptability to stakeholders in contrast with the former design that was ultimately fatally flawed, as concluded during the IPS.

4.3 Challenge the status quo, if there is a better way

To avoid slavishly following pre-existing closure designs for 'compliance sake' and potentially leading to flawed or sub-optimal closure outcomes, pre-IPS designs were never automatically assumed the best alternatives to maintain/adopt or having to be complied with instead relying on the knowledge base and risk-based analyses to determine this.

This approach challenged some on the project team who viewed many pre-existing commitments, particularly those derived from statutory approvals, as fundamentally or substantially non-negotiable. However, this bias towards a particular outcome was inconsistent with the IPS approach that sought to let data derived from 'first principles' assessments build knowledge and inform decision-making relating to the commitments that are made. This is particularly important when you consider most, if not all, statutory approval commitments can be amended (where superior merit can be demonstrated in application to the regulatory authorities) and that most aged obligations were based upon limited rehabilitation experience and understanding of risks at that time.

An example of this was in relation to the preferred post-mining land uses. Whilst the historical statutory commitments were varied, achieving a cattle grazing (pastoral) land-use equivalent to pre-mining on rehabilitated TSFs and waste rock landforms was the general expectation of most regulatory authorities before the IPS. However, in examining what may be feasible land-uses over time, and within an already marginal pastoral landscape (that will only become drier and more challenged over time from predicted changes in climate), the project team evaluated a range of different land-use alternatives. These alternatives included the option to graze cattle but equally to exclude cattle from rehabilitation areas to promote increased biodiversity. From a focus on the economic and environmental sustainability of nominated land-uses, cattle grazing was ultimately deemed sub-optimal and therefore undesirable for the majority of mine rehabilitation areas. This new position was supported by pastoral stakeholders and this open and unconstrained approach to solutions led to the alternative commitment to implementing a range of pastoral improvement initiatives on surrounding pastoral lands whilst producing biodiversity land-use benefits on mine rehabilitation areas. This combination of initiatives was designed to achieve a sustainable 10-fold increase in local cattle stocking rates above what would have been achieved by the pre-IPS commitments whilst also improving biodiversity and conservation. The selection of an alternate land-use to pastoral was subsequently approved by regulatory authorities.

As departures from historical statutory obligations were identified, these differences were discussed with key regulatory authorities. As part of this, the project team attempted to understand the intent of an obligation rather than just its 'literal meaning' to evaluate risk and develop an effective response to authorities. In doing so, the project team endeavoured to clearly understand and respect the basis for the original obligation, recognising the onus was on it to demonstrate a compelling case for any change. This approach ensured key differences were tested early for stakeholder acceptance with effective actions subsequently taken to remedy any issues.

4.4 Focus on materiality, the things that matter most

In undertaking a major closure study of complex detail, it can be easy to expend limited project resources on scope elements that are intriguing but which lack materiality. An important success factor of the IPS was the continual review of merit and subsequent pursuit of deeper analyses only where there was material risk or reward. From the project outset, materiality framed the identification of study priorities. Materiality was determined from an evaluation of risks and assumptions that if misdiagnosed could have significant adverse impacts on closure costs and/or outcomes. This approach identified and elevated the importance of key issues including early and effective stakeholder engagement, relinquishment planning, constructability of landform designs and contingency/risk allowance development in the cost estimate.

In relation to risk allowance, the project team recognised the importance of having a distinct event risk allocation that catered for the residual uncertainty in the cost estimate. This allowance was deemed material by the project team in developing a robust cost estimate, particularly due to the inherent and unique complexities of a closure project. This risk allowance was in addition to the 25% contingency on direct costs. Including a risk allowance, based on defensible criteria, in the closure cost estimate was found rare from benchmarking. The risk allowance covered specific events that had the potential to materially undermine or exacerbate closure risks and costs if not effectively managed in closure planning and/or execution. These risk events were categorised in primarily one of two groups; the first category was during the planning phase where "closure designs are flawed and/or ultimately not accepted by key stakeholders"; and the second category was post-execution where the "completed rehabilitation and other activities do not achieve closure performance criteria and/or relinquishment is materially delayed beyond expectations or ultimately not achieved". From an event risk register (that included over 50 risks in total), many risks were combined ('rolled up') to ensure their collective materiality was not lost when an assessment of each individual risk alone failed to pass criteria. This was in response to a key observation from industry benchmarking that found individual risks can be defined in such a way that they rarely, if ever, trigger materiality on their own but when some are considered in combination - which were tested by the project team for likelihood, and from this deemed to be plausible scenarios - the risks cause materiality. The event risk allowance added approximately 10% to the final closure cost estimate and, equally as important, has materially informed the future closure priorities in operations.Independent peer reviews were co-ordinated for landform engineering, cost estimation and contaminated sites assessments that had high technical and/or stakeholder risks and/or which represented material components of the cost estimate (e.g. contingency). These reviews, conducted by subject matter experts, provided additional quality assurance to minimise the potential for gaps, bias or errors that could materially affect results.

4.5 Lead change to unlock new value

Fundamental to the IPS, the project team sought to lead change on key issues that had the potential to either materially limit opportunities or undermine closure success. Whilst there were many instances of this, some already discussed in this paper, the project team committing to unprecedented measures to chart a more reliable and credible path to relinquishment offers some of the best demonstration of leadership on chronic industry challenges.

Of these measures, the proposal to create a new independent auditor assurance scheme was arguably the most significant commitment made by the project team. Further discussion of this is provided below. From targeted relinquishment workshops, the project team identified that assurance processes adopted by proponents and regulatory authorities to progressively assess and verify compliance against performance (success) criteria in closure plans had serious shortcomings. These issues were contributing, along with often having inappropriate performance criteria in the first place, to variable (unpredictable) and stalled closure assessments. In response, the project team contemplated a range of options to address this key issue. From this, Nickel West committed in its site closure plans to further assessing the feasibility of appointing an independent Mine Closure Auditor (MCA) to review the adequacy and integrity of progressive closure activities, results and reporting. This idea for an MCA was born from project team experiences in the execution of large, complex closure projects in other jurisdictions and effectively working with Government-accredited auditors for contaminated sites assessments.

The purpose of the MCA would be akin to the role of an independent Contaminated Sites Auditor (CSA) in Australia which is valued by Government and industry alike. CSAs are suitably qualified and experienced experts accredited with State Governments to independently advise them on the efficacy and completeness of industry contaminated sites assessments. This assurance program provides the basis for the regulatory authorities to more capably and readily assess proponent applications and reach timely approval decisions. The CSA advice is non-binding to the regulatory authorities but is often adopted by authorities making it a reliable process that progressively reduces uncertainty. Funded by proponents, the CSA scheme maximises process certainty and minimises process delays. This process, in part, recognises that both the capacity and capability of authorities to regulate in a timely manner the many, complex disciplines of contaminated sites assessments can be challenging, which helped trigger the original need for a different approach. Mine closure planning and delivery has similar complexities and constraints that Nickel West considers a scheme equivalent to the CSA model could help to achieve a breakthrough in establishing a more credible and reliable path to relinquishment. It also adopts a process already developed, accepted and proven as effective by the State Government, therefore reducing some initial trepidation otherwise in piloting something completely new or untested.

Recognising that it is unrealistic for an individual to have the expertise to assess all closure disciplines relevant to site or Asset, the MCA would need to be sufficiently proficient in the main disciplines but like the CSA be able to draw from a suitably qualified team of technical and other specialists to audit the range of relevant issues. In the absence of there not yet being a regulatory scheme of this kind for closure in Australia, Nickel West has committed to working with the key mining regulators to explore the potential for such a scheme to work in Western Australia (with the potential for wider application to other jurisdictions, if proven effective, over time). The mining regulator has approved the site closure plan, recognising the potential merit of the MCA process (subject to further development). Similar to the CSA model, the MCA scheme to work must not just add complexity, time and expense to existing processes but instead reliably provide a more simple, credible, predictable, timely and achievable path to closure and (where sought) relinquishment of tenure and residual liabilities.

5 Results

The IPS has delivered lasting, material benefits to closure planning at Nickel West. For a modest investment of USD$10M, there have been substantial changes to the site closure plans, with revised designs that are superior in their scientific basis, engineering, constructability, risk control, sustainability and stakeholder acceptance compared to their predecessors. At the same time, through the reset and optimisation of closure designs and by achieving material reductions in the potential ranges of costs associated with the key closure domains, the Nickel West total closure cost estimate has been materially reduced, positively affecting business value.

Critically, this rethink of closure planning has challenged traditional planning approaches by BHP and regulators, promoting new conversations and debate about what closure success looks like and how it is best measured. In addition, it has questioned what constitutes a robust, durable closure cost estimate that sufficiently caters for risk and uncertainty and is resilient to factors that can undermine it and cause material errors.

The strategic engagement with key stakeholders has also been beneficial, building a new level of trust and credibility with regulatory authorities in Nickel West’s management of closure matters. This has provided a strong foundation for continued engagement on key issues, including relinquishment planning and closure performance criteria.

These strengthened relationships with key stakeholders have also enhanced (and in some cases restored) the broader environmental and social operating licences of Nickel West. The positive feedback received from regulatory authorities and community has extended the IPS benefits beyond closure planning to the wider operations.

The IPS has also created a new model for closure assessments within BHP that can be easily replicated, at low cost, in business planning at other company Assets around the world. There have also been key learnings, some described in this paper, useful to informing the continual review and improvement of BHP closure planning as well as financial accounting and major project standards to ensure the needs of closure studies are adequately covered.

Lastly, and arguably most importantly, the IPS has built a new, strengthened platform and momentum at Nickel West to optimise operational activities to further reduce closure risks, costs and liabilities in to the future. With an expected operational life of more than two decades, this time affords opportunities to modify existing practices early enough in operations to significantly lessen the resulting impacts otherwise realised at closure. At the same time, many of these changes could be expected to improve risk control during the remaining operations. For this reason, the earlier that studies of this kind are completed, and not left to the final years of mining, the more informed and effective decisions can be made, and with the least cost and impost to the Asset, regarding those operational activities that best mitigate the potential for adverse closure outcomes.

6 Conclusion

In the space of only a few years, and for a limited investment, the IPS has fundamentally reset closure planning at Nickel West. It has challenged the status quo to build a more clear, credible, resilient and feasible path to closure.

The IPS has prioritised relinquishment and in doing so asked questions of the Asset, BHP, wider mining industry and regulatory authorities that are new and may ultimately contribute to a breakthrough in this important area.

The IPS has shifted closure assessment from being broad, theoretical and compliance-based to being strategic, practical and risk-based. It has enabled the ready identification of operational priorities which have a superior cost-benefit for implementation over the coming years to fully leverage the value generated from the IPS studies. Through the structured and regular pro-active engagement with regulatory authorities, where their role is valued and considered essential to progressive planning and risk mitigation, the project team has built trust and credibility to successfully challenge existing obligations where there are compelling reasons for change.

Perhaps most significant is the observation most relevant to other Assets or sites within BHP and the wider mining industry, that an IPS-equivalent closure studies program has merit to implement at any time, and ideally well prior to the expected closure date to maximise the potential gains to the business triple bottom line.

In the case of Nickel West, the trigger to transition closure planning to BHP’s major project framework was a new, earlier expected closure date within five years being decided upon. It took this relatively sudden event to put in motion what has been described in this paper. Without it, the reality is an IPS would not have been contemplated. When these circumstances dramatically altered and the Life of Asset date was materially extended, it took a new decision by Nickel West (and BHP) to continue to stay the course to fully realise the value emerging from the IPS. And herein lies the key takeaway from the IPS and this paper - that to implement a major studies program of this kind should not take an event like Nickel West had initially required. With the benefit of hindsight, the potential value that can be generated is sufficient alone for implementing a studies program of this kind, and the earlier the better in operations when your abilities to maximise the gains are greatest.

Mine Geo-Environment Risk Management Based on Multiple Criteria Decision Making

B Chai *China University of Geosciences, Wuhan, China*

Z Tang *China University of Geosciences, Wuhan, China*

Y Li *China University of Geosciences, Wuhan, China*

A Zhou *China University of Geosciences, Wuhan, China*

Z Luo *China University of Geosciences, Wuhan, China*

Abstract

Mine Geo-environment risk decision making is a consultation process to meet multiple objects from multi-stakeholder. In order to control mine risk in the mine life cycles, the decision making was employed to approach three objects which were meeting acceptable risk, getting the most benefit from restoration engineering and making reasonable plan for mine closure. Then, the Hierarchical Analysis was applied to multiple criteria decision making in risk management of mine Geo-environment. Lastly, the consultation process was used to determine the engineering proposal that control the Geo-environment risk of a limestone mine in Fengshan town, Southwest China. The process considered some information from multi-stakeholder including of design organization, government and local people. It indicates that the optimal engineering proposal has four parts, i.e. P1 with cutting slope, clearing up unstable rock and anchoring; P2 with drainage, rockfall platform and monitoring; P3 with smoothing slope surface, carving and vegetation; P4 with risk education. It is not only a guidance to rebuilt environment of the limestone mine, but also has positive affect to develop mine closure.

Keywords: *mine Geo-environment, risk management, multiple criteria decision making, mine closure*

1 Introduction

Mine Geo-environment restoration is a scientific problem that involves multi-disciplinary, multi-objective and requires multi-stakeholder's participation (Huang et al. 2012; Amirshenava and Osanloo 2018). Comparing with general disaster risk management(Fell 1994), Mine Geo-environment risk management (MGRM) covers a wider range and needs a multiple criteria decision making (MCDM) of disaster mitigation, land reclamation, environment restoration and revegetation(Canbulat et al. 2013; Voulvoulis et al. 2013; Krzemien et al. 2016). The Whitehorse Mining Initiative (WMI) in Canada proposed that mine closure plan needs the multi-stakeholder consultation among mining companies, governments, trade unions, local residents and communities (Bowman and Baker 1998). Its aims are to promote sustainable development of society, economy and environment through linking policy and community, and to prosper mining industry. It is important for mine risk management to consider the multi-stakeholder's requirements and to realize the MCDM. The disaster risk management mainly consider death and economic losses. However, the MGRM mainly comes from land destruction, ecological damage and environmental pollution, which is more a reflection of social and environmental risk. The goal of the MGRM is to carry out comprehensive mitigation measure on the Geo-environment problems and to meet the requirements of social and economic development. The following questions should be answered in the decision making of MGRM:

- Is the risk of mine Geo-environment acceptable?
- How to make the risk at an acceptable level?
- How to maximize the benefit of mine risk control?

- Does the mine close plan is reasonable considering risk mitigation？

In this paper, we propose a MCDM to answer above questions and use it to determine the control engineering proposal of a limestone mine in Fengshan County, Southwest China.

2 Methodology: establish MCDM on MGRM

2.1 Objectives and approaches of MGRM

2.1.1 Meet acceptable risk

The mine Geo-environment problems can be divided into two categories, sudden Geo-hazards and gradual environment problems, according to their evolution speed. The minimum risk value is the optimal objective for the decision making of MGRM.

(i) Acceptable risk of sudden Geo-hazards

For sudden Geo-hazards, acceptable risk includes casualties and economic losses, which are often expressed by individual risk and social risk. The individual risk is the annual mortality rate or economic losses with the greatest impact on mine sudden geo-hazards. The individual risk must be lower than a certain value that could be determined according to the local socio-economic situation. Social risk is the annual fatalities or economic losses from all mine Geo-hazards. Acceptable level of social risk is usually determined by the F-N curve, namely the relationship between the number (N) of annual fatalities or economic losses caused by the geo-hazards and their cumulative frequency (F).

(ii) Acceptable risk of gradual environment problems

There are many indicators for the risk of gradual environment problems, including the population affected by environment problems, the public's dissatisfaction degree, the ecological fragility and lack of resilience. The risk values of gradual environment problems need to be normalized by using dimensionless parameter. Acceptable risk is also related to the local social economy.

(iii) Approaches to meet acceptable risk’s objective

For sudden Geo-hazard, it can be controlled at acceptable level by reducing its occurrence probability or reducing its consequences. The former mainly use some management engineering to reinforce hazards body or to decrease environmental input from rainfall, blasting and human activities. The latter reduce the hazard consequences by monitoring and early-warning, relocation, interception, buildings strengthening and disaster education, etc..

For gradual environment problems, its risk can be accepted by restoring mine environment or adjusting local socio-economic structure. The former is composed of the restoration engineering of land reclamation, terrain reengineering, ecological restoration and pollution control, etc. The latter reduce environment risk by changing the land use type, adjusting the economic development target, restricting population, long-term monitoring and environmental education, etc.

2.1.2 Get the maximun benefit of control engineering

Benefit maximization is the objective of the risk control engineering in MGRM. The benefits can be divided into economic, social and environmental benefits. The economic benefit is represented by the ratio of the reclaimed land’s value to control engineering cost. The social benefit is the improved living environment in the mine area and is expressed by the satisfaction of local residents. The environmental benefit is expressed by the restored rate of the environment problems of water, soil, air and ecological. The approaches to achieve this objective are to choose reasonable engineering measures and to optimize control engineering.

2.1.3 Make reasonable closure plan

Many mines have some existing plans such as land use plan, tourism plan and ecological plan. The objective making reasonable closure plan mainly is that the risk control engineering has positive effect on promoting the existing plans. The approaches to achieve this objective are the risk control project can coordinate the development of the mine and the surrounding social economy.

2.2 Establish MCDM

2.2.1 Framework of MCDM

The framework of MCDM is shown in Fig. 1.

(i) The objective system: The objective set and its structure indicate the goal of MGRM for the decision maker to make the mine closure plan. It is composed of three primary objectives and seven secondary objectives. (ii) Plan to achieve objective: The plan is designed by decision makers to achieve objective of MGRM. The plan is the approaches of MGRM that mainly depend on risk control engineering and their combination. Risk control engineering can be divided into four categories, and each containing some engineering measures. (iii) Decision criterion: optimal criterion (OC) and satisfaction criterion (SC) are the common criteria for decision. Satisfiability criteria applies to the object meeting acceptable risk and making reasonable mine closure plan, and the object getting the maximun benefit of control engineering can adopt the optimal criterion or the satisfaction criterion.

2.2.2 Solution of MCDM

There are many methods in solve the question of MCDM, and the common methods are the change multiple criteria decision into single criterion, rearrangement order and analytic hierarchy process. The analytic hierarchy process (AHP) is the most common method. It decomposes complex problems into layers and elements, and determines the weight through comparison and judgment between elements. The specific steps are shown in the following cases.

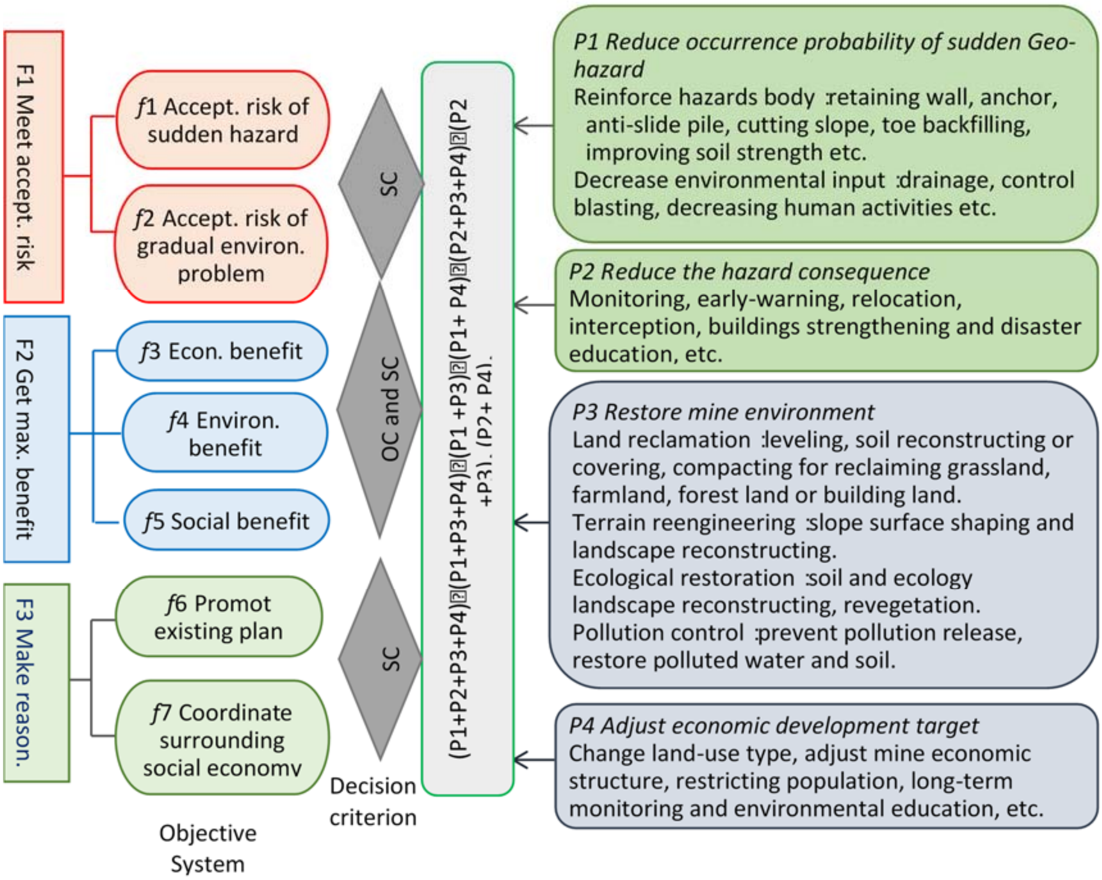

Figure 1 Framework of MCDM on MGRM

3 Background of study mine

The mine is a open limestone mine is belonged to a post mine in Fengshan county, Southwest China. The open face is 134m height and about 10,340 m^2. A rock avalanche occurred on Nov. 23, 2008, which resulted in six people killed, six people wounded, and 16 rooms buried. Also, the mine is located in urban areas, and the vegetation and landscape are seriously damaged, which impacts the urban living environment. The stone slag in the slope feet takes up about 5, 945 m^2 land.

The risk assessment of sudden rockfall indicates that the risk of three buildings in slope is one moderate risk (M) and two low risk (L) and is shown in Fig. 2(Chai et al. 2015).The gradual geo-environment problems are mainly reflected in the damage of vegetation and landscape, all of which are high risk level. The mine locals in the Leye-Fengshan International Geological Park in Guangxi, the requests for travel security and sight-viewing environment are extremely high.

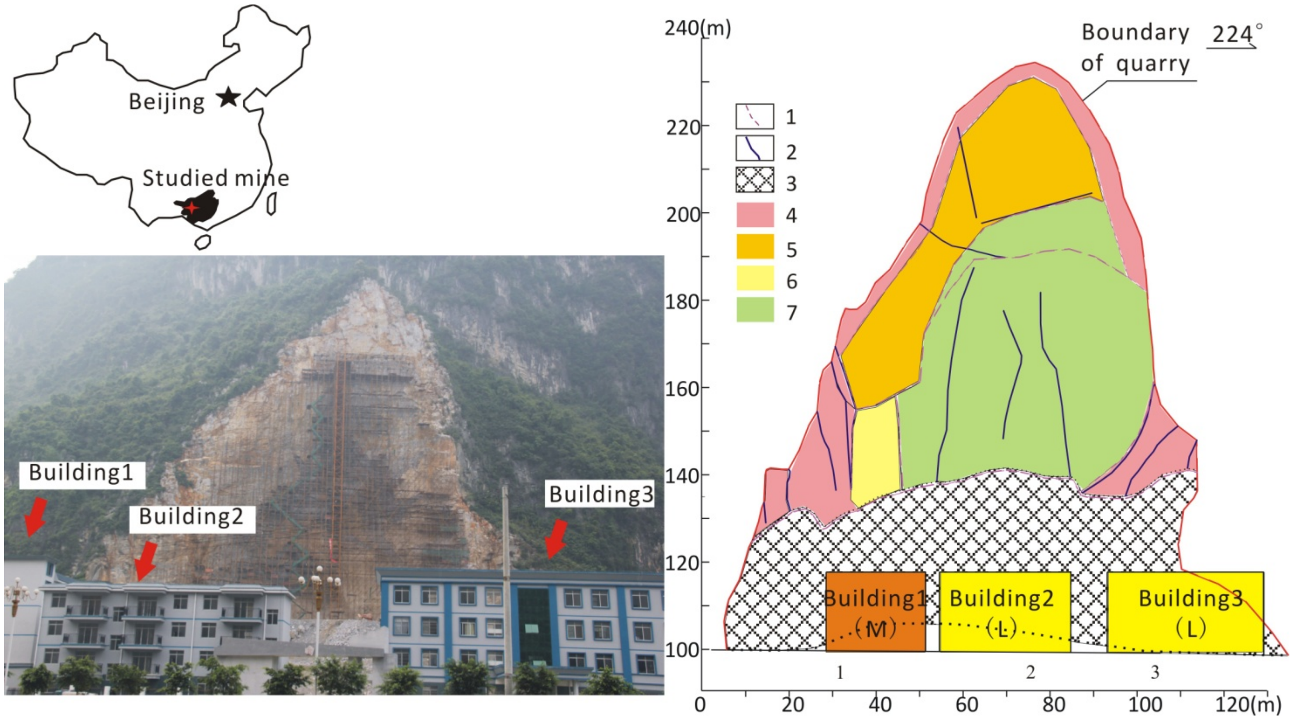

Figure 2 Risk zone of rockfall in the limestone mine: 1- boundary of zone, 2-large joint, 3-collapse deposit, rockfall probability, 4-high, 5-moderate, 6-low, 7-very low

4 Case: MCDM of risk control engineering

4.1 Constraint and plan of risk control engineering

The constraint of the mine risk control engineering are as follows:

(i) The control engineering is supported by national special funds and has cost limitation.

(ii) Local planning are building the limestone mine into a scenic spot of the International Geological Park.

(iii) The three buildings at front of the slope unable to be relocated.

(iv) Stone slag at slope toe unable to be relocated.

On the basis of the above restrictions, the proposed plan of geo-environment risk control engineering includes the following:

(i) Plan 1: P1 (cutting slope, cleaning unstable rock and anchoring)+ P2(drainage, rockfall platform and monitoring)+P3(slope surface shaping, rock carving and local revegetation)+ P4(risk education)

(ii) Plan 2: P1 (cutting slope, cleaning up unstable rock, anchoring, spraying concrete and borehole drainage)+ P2(drainage, monitoring)+P3(painting on slope surface)+ P4(risk education)

(iii) Plan 3: P1 (cutting slope, cleaning up unstable rock, anchorage and active SNS network)+P2(drainage and monitoring)+P3(slope surface shaping and whole revegetation)+ P4(risk education)

(iv) Plan 4: P1 (cleaning up unstable rock and anchorage) +P2(drainage, rockfall platform and monitoring) +P3(slope surface shaping and whole revegetation) +P4(risk education)

4.2 Solve MCDM of risk control engineering using AHP

(i) Establish hierarchical structure

The multistage hierarchical structure is divided into three layers, i.e. Objective, Criterion and Plan(Fig. 3).

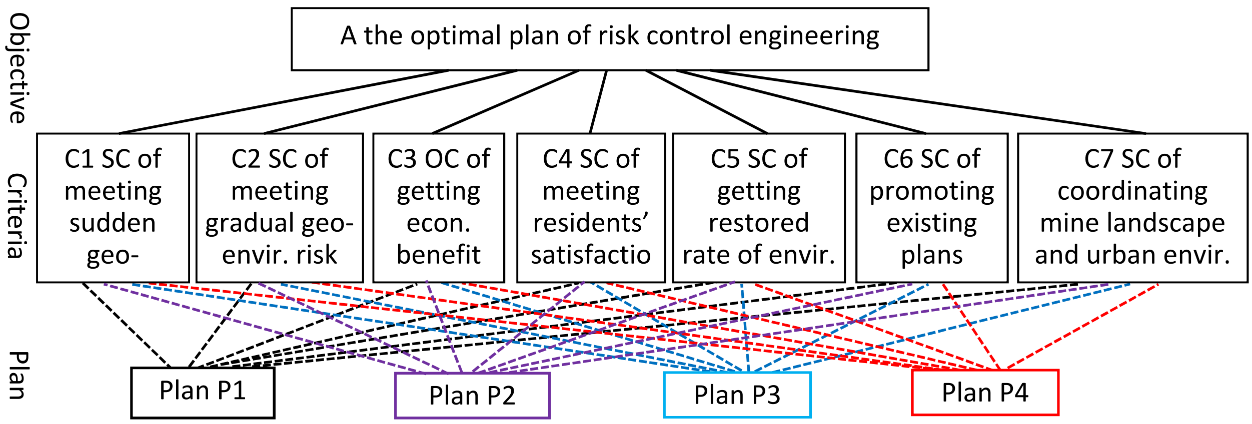

Figure 3 Hierarchical structure of determining the optimal plan of risk control engineering

(ii) Establish judgment matrix

The geo-environment risk control engineering involves multi-stakeholder of design organization, government department and local residents and so on. Before designing plan, design organization and government departments attended a meeting convened by the county government. The meeting introduced main geo-environment problems and existing plans in the mine. Also, a sampling survey was carried out to collect opinions of residents on the mine management. According to the meeting summary and the sampling result, the group simulates the multi-stakeholder and constructs the judgment matrix using the nine-scale method.

i) According to the opinions of the design organization, government department and local residents, it forms the judge matrix A/C (to compare the criteria importance for achieve objective), as shown in Table 1.

Table 1 A /C judge matrix

A	C1	C2	C3	C4	C5	C6	C7
C1	1	3	3	5	7	3	7
C2	1/3	1	1	3	5	1	5
C3	1/3	1	1	2	5	1	5
C4	1/5	1/3	1/5	1	3	1/2	2
C5	1/7	1/5	1/3	1/3	1	1/3	1
C6	1/3	1	1	2	3	1	3
C7	1/7	1/5	1/5	1/2	1	1/3	1

ii) The judgment matrix C1 / P (to compare the ability of plans for reducing risk of sudden geol-hazard) and C2 / P (to compare the ability of each plans for reducing risk of gradual geo-environment problems) are given by simulating design organization's opinion.

iii) The judgment matrix C3/P (to compare the role of plans for the economic benefit) is given by simulating the opinions of the land resources bureau and the tourism bureau.

iv) The judgment matrix C4/P (to compare the role of plans for meeting residents' satisfaction) is given by simulating the local resident's opinions.

v) The judgment matrix C5/P (to compare the role of plans for restoring mine environment) is given by simulating the design organization's opinion.

vi) The judgment matrix C6/P (to compare the role of plans for promoting existing plans) is formed by the opinions of the local government.

vii) The judgment matrix C7/P (to compare the role of plans for coordinating mine landscape and urban environment) is formed by the opinion of the land and resources bureau.

viii) Calculate weights, the maximum eigenvalue of judgment matrix and judge compatibility

iv) Calculation of comprehensive importance degree

The contribution of the n plans for objective is calculated by the hierarchical model using the product of the weight of C to A and the weight of P to C and is shown in Table 2. Therefore, the optimal plan for geo-environmental risk control engineering is the Plan1 that has the maximum contribution for the objective. The engineering design and (Fig. 4)

Table 2 Calculation sheet of importance degree

	C1	C2	C3	C4	C5	C6	C7	Contribution
	0.375	0.170	0.160	0.078	0.041	0.136	0.040	
P1	0.266	0.558	0.558	0.558	0.124	0.577	0.093	0.415
P2	0.558	0.057	0.263	0.071	0.058	0.261	0.048	0.306
P3	0.096	0.122	0.122	0.259	0.297	0.061	0.318	0.130
P4	0.080	0.057	0.057	0.112	0.520	0.101	0.541	0.114

5 Conclusion

Mine geo-environment risk decision need to consider multi-objective decision and multi-stakeholder's participation. The solving process of this decision needs to build a reasonable level of decision problem and collect the opinions of all stakeholder in the mine. To establish hierarchical structure is great important for the solving of MCDM. When the designer establish the plans, risk control engineering should consider comprehensive approaches with economic , administrative, legal and technical measures. In addition to the control engineering decision for post-mine management, it is also applicable to make closure plan of new mine and to modify control engineering of mine geo-environment for working mine.

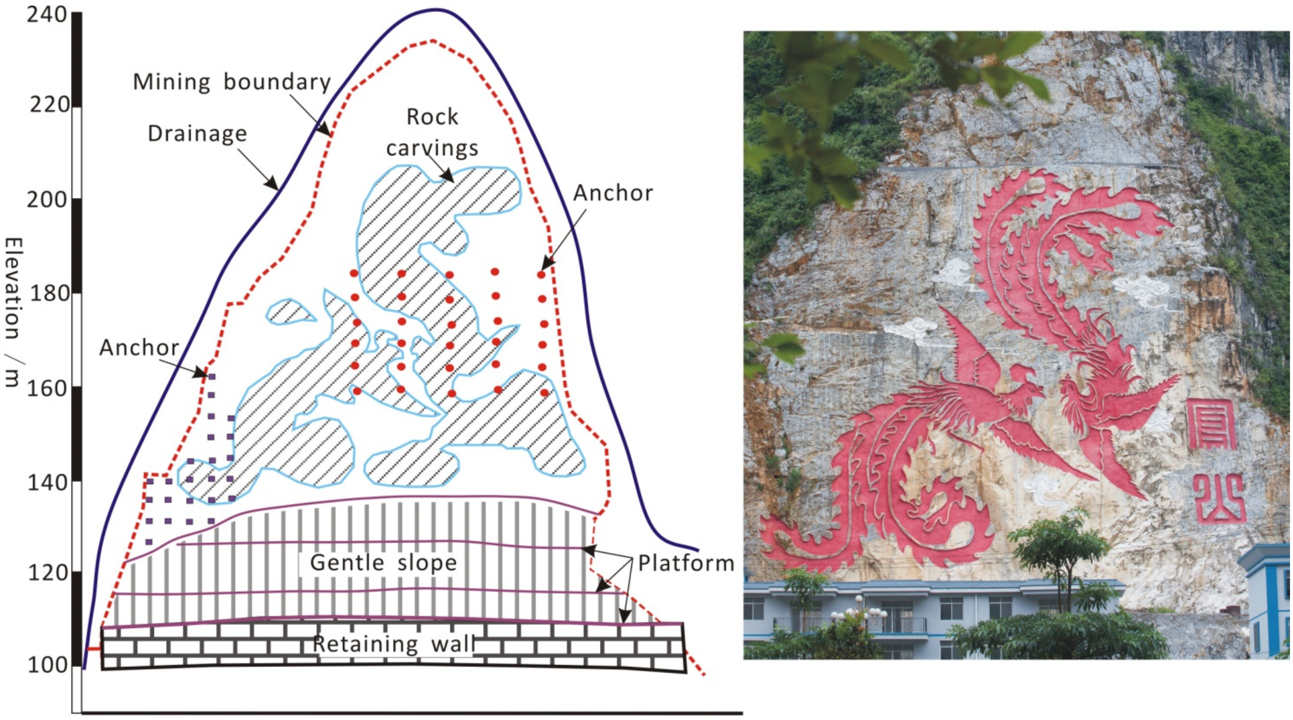

Figure 4 Design of the risk control engineering and its results in the limestone mine in Fengshan county

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Closure Planning on a Large-Scale – Approach to Optimising PFS Closure Designs for the Western and Central Development Areas at a site in Central Laos

JT Chapman *SRK Consulting (Australasia) Pty Ltd, Australia*

CM Linklater *SRK Consulting (Australasia) Pty Ltd, Australia*

D Hockley *SRK Consulting (Canada) Inc, Canada*

J Rowntree *MMG Limited, Australia*

D Noonan *MMG Limited, Australia*

Abstract

Closure plans for an extensive mine site located in central Laos are currently being developed. The mining area includes more than 40 pits, some of which have been backfilled, and 13 waste rock dumps.

In support of the development of the closure strategy, technical studies have been completed which included development of a site-wide water and load balance, assessment of the geotechnical stability of pit walls and dumps, and geochemical characterisation to understand the distribution of ongoing sources of solute production around the site. Specific issues associated with the site include proximity of local communities and accessibility of the site, stability of the pit high walls and exposure of acid forming rock on the high walls, positive water balances for the pit lakes and the large distance across which the site is spread.

Future water quality predictions were combined with the site-wide water balance to develop an integrated closure strategy for the site, identifying optimal closure measures to mitigate water quality impacts to downstream receptors (drinking water resources) and ensure public safety. Conceptual closure designs for WRDs and pits were developed incorporating both passive and active water management infrastructure. Two companion papers describe the development of the water balance and the water quality predictions. This paper presents the practical implications of the outcomes and the overall closure strategy that was developed for the site.

Keywords: *mine closure planning, integrated strategy, closure measures*

1 Introduction

The open cut gold and copper mining operation located in central Laos comprises several gold and copper open pits, with the gold operation currently in care and maintenance. Figure 1 shows the site layout, comprising open pits, waste rock dumps, and water management structures, and the proximity of human habitation to the site.

For the purposes of closure planning, the operations have been separated into three distinct areas, based on geographical location and operational status. The current assessment primarily deals with the Western and Central Development Areas which comprise a series of open pits and waste rock dumps for both copper and gold operations that fall primarily west of the main river that passes through the site. The other two areas comprise the tailing storage facilities (TSF) and a copper open pit operation that includes the process plant and other infrastructure.

Key closure challenges at the site included human habitation and farming lands located in close proximity to the mining operations, which increase the potential risks to human health and safety post closure. Other challenges at the site include i) the large number of pits and dumps to be managed, which drain to two separate major catchments (towards the west and the east respectively), with potential for localised impacts and more distant impacts, ii) the high rainfall environment, iii) the risks of acid mine drainage (AMD), iv) steep terrain that contributes to geotechnical risks, and v) physical stability of pit high walls and other landforms. Whilst water quality is currently being managed through active treatment, groundwater quality impacts have been detected downstream of the operations.

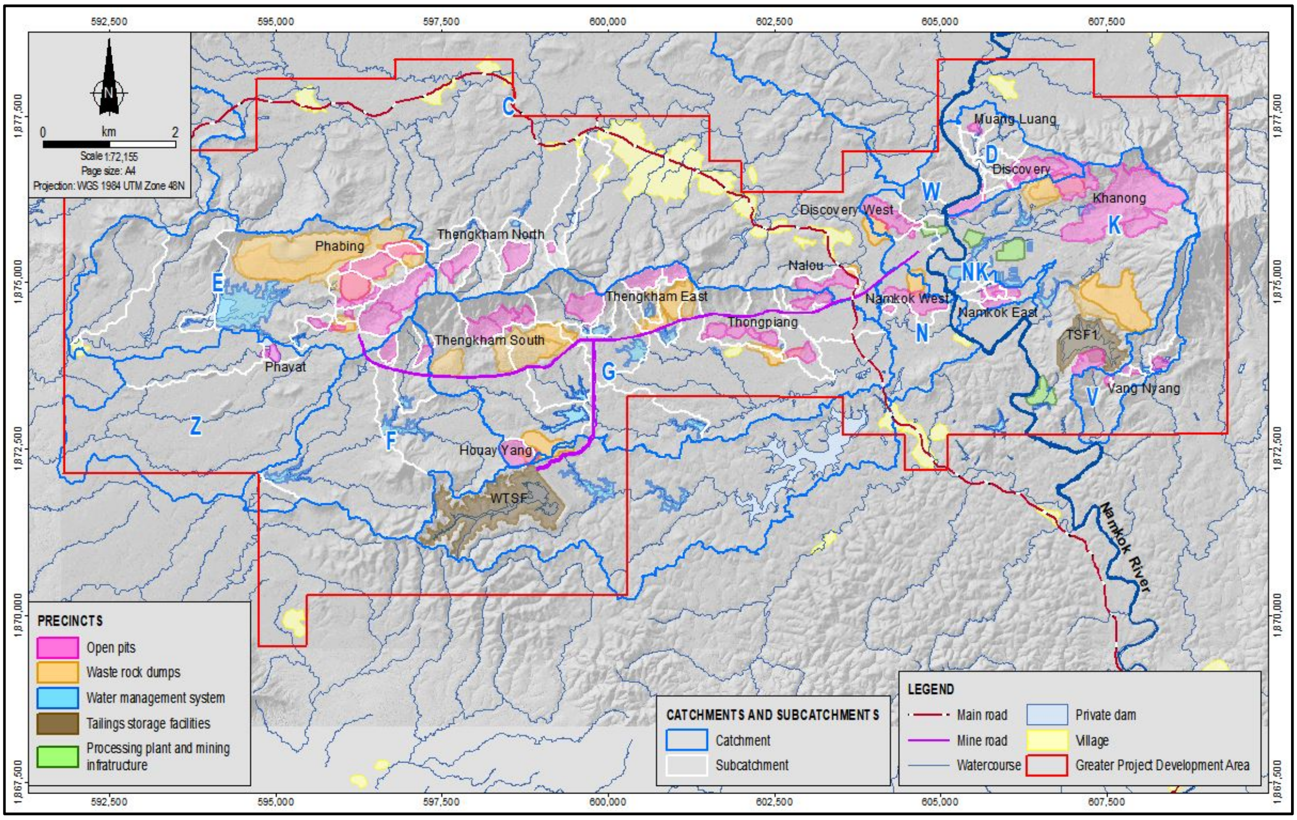

Figure 1 General layout and catchment delineation for the mine site showing primary receptors and proximity of human habitation.

2 Closure objectives

Closure objectives can be structured in a range of ways. Generally, high level objectives for the overall closure plan are set first, and then more detailed objectives are established for each area. The high-level objectives should address the major requirements, commitments and risks, and should be clear to designers and stakeholders. The objectives should also be cognisant of the completion criteria (i.e. can they be achieved within reason) and whether they will achieve an acceptable outcome to all stakeholders, be compliant with legal requirements and specific obligations.

More detailed closure objectives and completion criteria focus on specific closure measures that are generally more technical in nature, and, by necessity, they can only be fully defined after the closure designs have been developed. However, even at the pre-feasibility stage of closure planning, it is useful to define preliminary "completion criteria" to ensure that they can reasonably be achievable. These criteria that can be further developed as design details emerge. Two types of completion criteria are generally identified as follows:

1) Criteria related to construction (i.e. has construction been completed to specification, generally referred to as leading indicators).
2) Criteria related to outcomes (i.e. has the closure measure met the design performance criteria, generally referred to as lagging indicators).

Both are required to measure performance and evaluate closure. Construction-related criteria generally are defined in detailed engineering design and addressed through QA/QC procedures. Outcome-based completion criteria are developed as the closure design progresses, and through consultation with local regulators or stakeholders. Table 1 summarises some relevant closure objective and preliminary closure criteria for the site.

Specific criteria (e.g. for discharge water quality) were based on local regulatory requirements, or where these do not exist or are not considered sufficiently protective, were based on international standards.

3 Overall approach

An initial risk assessment was undertaken that identified the major risks and key areas that would need to be addressed by the closure strategy. As noted above, water quality impacts and geotechnical stability issues were identified as major risk areas. To address the water quality impacts, an integrated model of the surface and groundwater balances for the area, combined with estimation of solute loadings from potential contaminant sources, was developed. This integrated approach allowed identification of mine precincts that represented significant contaminant sources and enabled ranking of the sources based on overall impacts. Closure designs were then prioritised toward mitigation of contaminant release from the highest ranking sources, which allowed optimisation of the overall site closure strategy. The overall process for evaluating and developing the closure strategy is illustrated in Figure 2.

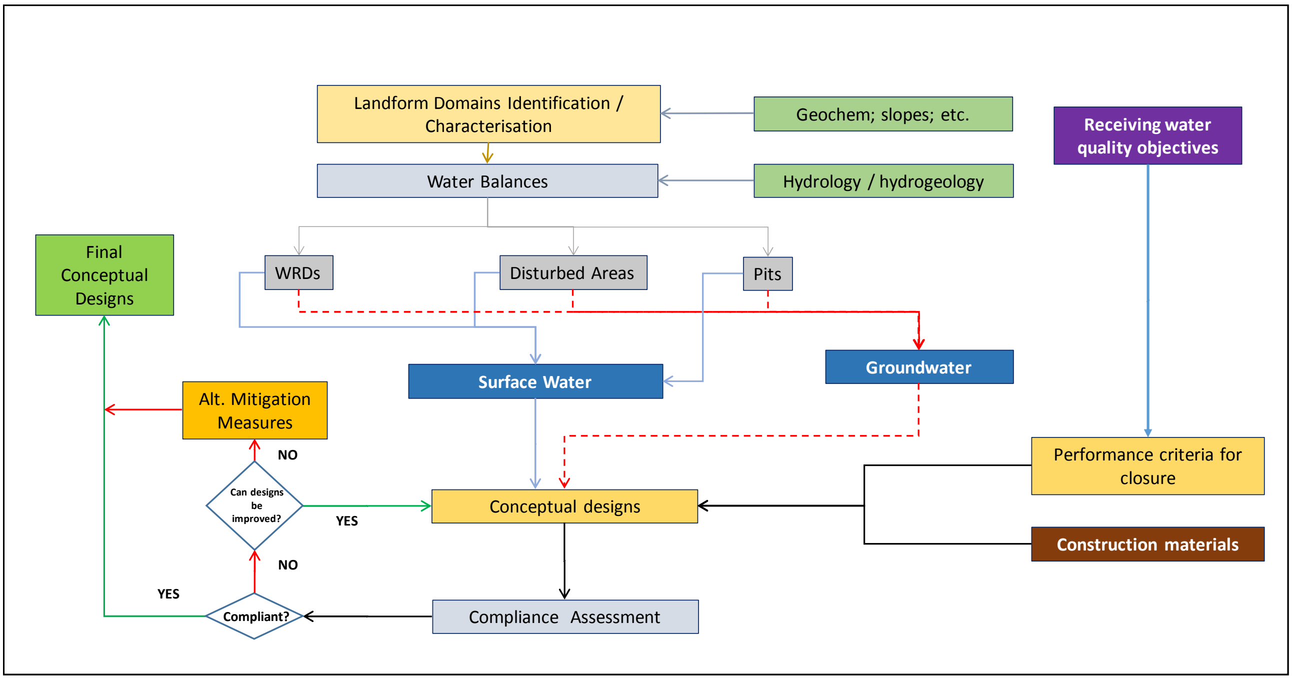

Figure 2. Overall approach for developing closure plan.

Table 1 **Closure objectives and preliminary completion criteria**

No	Closure Objective	Draft Completion Criteria
1	The site must be rendered safe to humans, domestic livestock and wildlife.	Final landforms constructed to design specifications.
		Identify hazards and Install appropriate signage on site access routes and pit locations. Community education.
2	The residual landforms are to be physically stable.	Stability analysis and inspection.
		Landforms are non-eroding.
3	The site must be rendered geochemically stable (i.e. non-polluting).	Surface water diversion drainage control measures are installed and meet design criteria.
		Surface water quality achieves the appropriate water quality criteria as determined at closure.
		Groundwater water quality achieves the appropriate water quality criteria as determined at closure.
		Water treatment meets discharge limits.
4	The closed site must be able to sustain an agreed post-mining land use.	Rehabilitated areas meet the agreed end land use, and these areas can be managed without significant external inputs and ongoing management.
		Species used for revegetation are capable of setting viable seed and recolonising disturbed areas.
		Vegetation is resilient and self-sustaining without additional inputs.
5	Project benefits contribute to sustainable economic and social development beyond mine life.	Meet the agreed end land use, which provide opportunities for local communities to maintain their sustainable livelihood.

In support of this approach, a number of supporting studies were completed. The key studies were as follows:

- Geotechnical assessment of pit slope and landform stability
- Geochemical assessment to examine the distribution of reactive materials and ongoing sources of solute production around the site, the subject of a companion paper (Linklater *et al.* 2018).
- Hydrological assessment with detailed delineation of water catchments within the project area, and the development of a closure water balance model, and the subject of another companion paper (Luinstra *et al.* 2018).

The outcomes of these studies were then used to identify and evaluate various closure and mitigation options, and to support the selection of specific closure measures for the development of the integrated closure strategy, as discussed below.

4 Evaluation and selection of closure options

Mine plans and designs included operational controls to both manage waste rock (with the intent to encapsulate acid generating waste rock) and water at the site, with the objective of meeting closure designs. These designs were implemented with varying degrees of success. Similarly, whilst the control measures for the placement of acid waste rock were identified, these were not always successfully implemented, as identified during site visits. Another complicating factor that became apparent was that due to variations to the mine plan, not all the pits were mined to completion which meant that some of the waste rock dumps were not constructed as per final designs. Furthermore, whilst low lying pits in some instances were backfilled, the sidehill pits generally resulted in the exposure of acid generating wall rocks, which, considering the steep terrain, were expected to be ongoing sources of contaminants in the longer term.

To develop the closure strategy, the mining areas were divided into key precincts based on the catchments and downstream receptors. Then, based on the constraints and observations identified above, key risks and concerns were identified. Based on these risks, potential closure options were identified and evaluated against the closure objectives and completion criteria. A spreadsheet-based collation of all these aspects was produced to allow comparison of different locations across the site, and filtering according to selected attributes.

4.1 Open pits

The options analysis for the final pits (based on Life of Mine plans) were completed based on the site water and load balance (Linklater et al. 2018; Luinstra et al. 2018) and the geotechnical evaluation linked to the understanding of the following criteria (where available):

- AMD runoff from pit walls, including poor quality pit lake discharges (to ground water and surface water);
- Stability and access, unstable walls;
- Unstable waste dumps within pit footprint, including AMD drainage from waste dumps or backfill;
- Backfill slumping; and,
- Proximity to sensitive sites / receptors.

For most precincts, do nothing was eliminated as an option since stability (highwalls) and water quality issues (AMD) were identified for most pits, with the exception of some of the low lying gold deposit pits and pits that have been backfilled.

As identified in the risk assessment and supported by the water quality predictions, AMD from the pit walls is a long term risk with significant consequences. Based on flow volumes and water quality observed and predicted), passive treatment options were eliminated as they would not be expected to be effective nor meet discharge water quality criteria. Active water treatment was therefore identified as a prerequisite to meet post closure objectives.

In all cases some measure is required to limit or prevent public access to pit high walls, where a risk of instability has been identified.

4.2 Waste rock dumps

The waste rock dumps, based on life of mine landforms shapes and construction to design specification (except for waste rock dumps already completed that are not to design specification) were evaluated based on an understanding of the following criteria:

- AMD potential based on NAF/PAF material distribution
- Physical stability of Slopes / Profiling
- Surrounding land use
- Drainage / upstream catchment
- Rehabilitation to date
- Erosion
- Constraint to Earthworks
- Proposed end Land Use

Stability analyses indicated that measures to address slope stability were not required for most landforms. Whilst the design criteria indicated that acid mine drainage would be limited for many of the waste rock dumps, some landforms that have not been constructed to specification would however require mitigation. For these dumps, a conceptual hybrid type barrier type cover was selected to reduce infiltration and control solute releases.

The high rainfall environment at the site indicated that erosion of the waste rock dumps is likely to be a significant risk to the long term stability of the landforms. In some cases, re-sloping would further reduce the risk of erosion and should be adopted where feasible. In some instances, cutting and filling (for re-sloping) of the NAF outer layer may compromise the thickness of the NAF layer (as per design) and so should only be considered where this was not a significant risk. Revegetation was selected for all locations where vegetation had been poorly established on the waste rock dumps.

Clean water diversions were also identified for most waste rock dumps to reduce run-on and overall risk of erosion by crest overtopping.

Fencing, as noted for the open pits, is not considered a feasible method to limit public access as fences are likely to be removed by the local population.

4.3 Sediment dams

The options considered for sediment structures included refurbishment or enhancement to support aquaculture and/or sources of freshwater supply. However, most of the sediment ponds rely on decant structures or spillways that are seated on the embankments or adjacent to the embankments, and as such will require active long term care and maintenance. In the event of failure most of the sediment ponds would represent a significant public safety risk and for this reason all structures not required for active water treatment and management would be breached and decommissioned.

4.4 Roads and infrastructure

Haul roads represent one of the largest sources of suspended solids release from the site; these roads also provide ready public access to the site, and since it is in the interest of public safety to discourage such access, all haul roads would be decommissioned and revegetated. Only service roads required to support active closure measures would remain.

5 Contingency strategies

As indicated by the water and load balance calculations, some areas may result in local water quality impacts. The following supplemental strategies would be considered:

- Alternate cover systems: Percolate and toe seepage from the waste rock dumps that may not have been constructed to design may be an ongoing source of solute that could cause exceedances of receiving water quality objectives. Should this prove to be the case, the effectiveness of the NAF cover will be assessed to determine net infiltration and oxygen ingress. The need for a revised cover system will be assessed, and if it is shown that an improved cover will mitigate these impacts, the revised cover will be constructed as a first contingency.
- Seepage interception: If the cover is shown to be unlikely to mitigate observed impacts, toe seepage and groundwater interception will be implemented as an alternate contingency. Interception wells will be established along the toe of the waste rock dump and contaminated water will be pumped and treated at the local water treatment facility.

Ongoing monitoring and assessment may also identify a requirement for additional contingency strategies, including strategies to mitigate groundwater sources. Mitigation measures that may apply could include the installation of interception wells for collection and treatment of flows, or, where groundwater is used for drinking water supply, sourcing drinking water from elsewhere.

6 Conclusions

Key to development of the mine closure strategy was the development of an integrated water and load balance to assess the potential impacts on the receiving environment, identify suitable closure measures and to assess their individual and combined effectiveness and ensure a cost-effective outcome acceptable for the site as a whole. As illustrated in Figure 2, development of the integrated closure strategy requires a number of key steps to be followed:

- Assess the ‘do nothing’ case to determine if objectives will be met
- Where objectives were not met, identify mitigation options
- Assess options to select the preferred approach in the context of the broader site strategy.

These steps require a number of site specific studies to first identify and quantify the potential risks that need to be addressed post closure, and then to evaluate and support the selection of the mitigation measures to reduce potential impacts to acceptable levels.

Another important step to facilitate the overall closure process is the development of measures that can be implemented during operations to integrate the closure strategy into the remaining operational life.

As indicated in the current assessment, the assessment of water quality impacts from the waste rock dumps and pit walls clearly identified the key sources that may lead to downstream impacts. This focussed the development of the closure strategy on identifying measures to reduce the most significant sources at site. Specifically, closure measures should seek to limit the volume of water contacting waste or pit walls, and allow contact water to be collected efficiently. Potential mitigation methods include:

- Improving covers on dumps that have not been constructed to design
- Installing diversions to minimise the contact of water with waste dumps or pit walls
- Constructing centralised active water treatment with sludge disposal in adjacent pit lakes.

The geotechnical conditions indicated potential instability in some pit walls and waste dumps. However, full stabilisation will be costly and, in some cases, create significant additional disturbance and safety risk. Therefore, it will be necessary to stabilise pit walls and waste dumps only where the instability represents a risk to people, and where the stabilisation can be accomplished without additional safety risk. Specifics vary from area to area, but in general this means:

- Stabilizing pit walls where failure could cause release of large volumes of contaminated water or directly impact areas used or traversed by people
- Stabilise waste dumps as part of closure re-sloping.

Safety is likely to be an issue in stabilisation of high pit walls, and will need to be assessed in a later stage of design. For this PFS-level planning, it has been assumed that safety concerns will not limit pit wall or waste dump stabilisation.

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An Algorithmic Approach to Optimising Modelling of Rehabilitation Surface Profiles

SA Dressler *Jones & Wagener, South Africa*

Abstract

Rehabilitation of a mine at the end of its economic life can be an expensive operation, predominantly since on most sites rehabilitation activities require large volumes of material to be moved to facilitate the desired post-mining land use. The final landform should be physically stable, requiring that surface slopes be sufficiently flat to reduce water-induced erosion to below acceptable levels. The final landform is also sometimes required to be free-draining to limit ponding, and so reduce the rate and quantity of water ingress through back-filled spoils which may contain polluting chemicals.

Unfortunately, development of a construction plan that will facilitate the achievement of the desired rehabilitated surface from the disturbed in-situ surface is often a difficult problem to solve optimally. In this paper, three algorithms are presented that were developed to allow for the design of the final rehabilitated landform as well as the determination of the optimal construction methodology. The first algorithm discussed employs a sand-pile approach to generate the landform with slopes within the pre-determined design range. In addition, it is possible to fix the boundaries of the design area and define different slopes for different areas or materials. The second algorithm solves the problem of determining the fill required to achieve a free-draining landform. Methods of ensuring drainage to either the region boundary or specific drainage points are presented. Possible applications of these algorithms for landform design are presented and discussed. For the third algorithm, the construction - using a bulldozer fleet, of a rehabilitated landform is presented as a linear programming problem and solved. Using the detailed solution from the last algorithm, a construction plan can be drawn up.

The observed effectiveness of using this methodology to inform construction, as well as the associated financial and time benefits for mine site rehabilitation, is discussed.

Keywords: *slope flattening, landform design, free-draining, material movement optimization*

1 Introduction

A large component of the costs of mining is inherent in the rehabilitation and closure of the mining operation. This cost varies across operations and is largely related to the specific mining method. For roll-over operations such as open pit coal mining, rehabilitation can be undertaken concurrently during the mining operation (Chamber of Mines, 2007), with a large portion of the final cost of rehabilitation incurred with infilling of the final pit from waste dumps.

Due to the large volume of material that needs to be moved during the rehabilitation operation, minimizing the volume as well as the distance material is moved is of paramount importance to the design criteria of a suitable rehabilitation plan (Johnson, Irvin, & Metcalf, 1997). An optimum rehabilitation design could ensure achievement of these requirements whilst also meeting agreed-on environmental rehabilitation requirements.

Rigorous mathematical optimization can be defined as a search procedure to locate the set of design variables which define a stationary point (a point with zero first derivative, being therefore a local maximum or minimum) of some objective function given certain constraints. In the case of optimization of the rehabilitation operation, the design variables are the description of the final rehabilitated surface. The objective function to be minimized is the cost of achieving the rehabilitated surface.

All optimization algorithms require sampling the objective function to determine function values and/or derivatives. The sample space to be sampled increases significantly with the number of design variables. Since the number of variables required to define a surface can be quite large, the optimization problem can be become too large for any reasonable optimization algorithm.

Cellular automata can be loosely defined as simple rules iterated many times (Wolfram, 1984). Complicated behaviour can be generated using this approach. In this author's experience this approach has proven to be useful for the design of rehabilitated landforms. Cellular automata can be used to determine optimal designs required without having to search out the entire design space (Qian, Zhao, & Hirata, 2001). Cellular automata can be naturally defined on a regular grid of points. The behaviour of a given point is then determined by the values of the surrounding points. Defining the pre-rehabilitation and rehabilitated surface as a regular grid of points allows the leveraging of cellular automata and simplifies the required computational process (the determination of neighbouring points is trivial).

This paper will discuss in greater detail the use of algorithms based on cellular automata adopted by the author to solve two core challenges in rehabilitation design. These challenges are: volume-balanced flattening of an existing topography to design slope requirements, and the determination of the minimum fill required to achieve a free-draining topography at a certain minimum slope. An optimal solution to the dozing operation by recasting it as a standard transport problem and experience in implementing on site is also discussed.

2 Optimization of Earthwork Volumes

In this author's experience the cost of hauling material is a large component of the costs of mining. It is also in general a large component of the rehabilitation and closure costs. The volume of material to be hauled is determined by the final designed landform. The final designed landform may need to comply to some or all the following design criteria (Walls & James, 2009):

1. The slopes must be flat enough such that water erosion does not lead to excessive loss of the capping material;
2. The landform should be free-draining. This means that there should be no low-lying points on the landform where water would pond. Standing water tends to wash the finer capping material into the courser backfill material. Groundwater recharge is also increase due to the increased infiltration rate, this additional groundwater may need to be treated later at great cost;
3. Knick-points on the topography should be avoided as these can lead to concentrated storm water flows and increased erosion; and
4. There should be a local volume balance between the design landform and the in-situ surface. It must be possible to construct the landform using the volume of material available at the site while minimizing the distance that material needs to be transported.

Minimizing the earthworks volumes therefore seeks to find the landform which meets all the above criteria.

2.1 Slope Flattening Design

In the case of unrehabilitated opencast spoils, or waste dumps, the material is usually at the angle of repose of the material. This slope is generally between 1:1 and 1:2. The required slopes for long-term capping stability regarding water erosion are a function of the capping material properties, rainfall and any erosion mitigation structures such as contour drains. The Chamber of Mines of South Africa provides guidelines for final landform slopes dependant on the proposed end land use (Chamber of Mines, 2007):

In most cases spoils or waste dumps will need to be shaped for rehabilitation. For simple topographies determining a volume-balanced surface meeting the design slope can be trivial; in general though the topographies are not simple and a different technique is required. The approach used to determine the design surface can be summarised as follows:

1. Describe the in-situ surface using a regular grid of points containing x and y coordinates as well as the elevation. The points are ordered using standard indicial notation which simplifies the computer code.
2. Each point is tagged with the design slope required at that point.
3. Compare the elevation of a point to its neighbours.
4. If a neighbouring point is below the present point then determine the slope to that point.
5. If the slope is steeper than the design slope then increase the neighbouring points elevation by a small amount and decrease the present points elevation by the same amount.
6. This procedure is repeated for all points until all points are within the required design slope or flatter.

The behaviour of this algorithm can be easily visualised as sand flowing down to a stable angle (Schmeier & Freyermuth, 2010). Some challenges are however immediately apparent when implementing the code as described above. A standard neighbourhood for a given point on a regular grid has eight members. If a point can only exchange material with these 8 points then constant slopes can only be defined in these directions. This leads to preferred slope directions and unnatural looking designs. This problem was overcome by increasing the size of the neighbourhood and including a volume preserving smoothing operation.

It is often necessary to shape a waste dump within a given footprint. Fixing the boundaries of the allowed landform is not trivial to implement using an algorithm as described above. Some success was however had by noting that it is possible to define roof and floor surfaces defined from the boundary. If the landform exists strictly between the roof and floor surface then the boundary has been fixed.

It may be required to shape a dump into a void where hard-rock is present that cannot be shaped. This can be accomplished by differentiating between points that contain material to be moved and points containing hard rock at the start of the algorithm. While the algorithm is running the extent of material moved is updated as the area spreads. This procedure is demonstrated in Figure 1. Here spoils have been modelled using a set of gaussian curves (the spoil placement location is known and the volume can be controlled by the weighting of the gaussian). Initially the modelled spoils are too high and steep but by applying the slope flattening algorithm they can be flattened into the surrounding pit and flow up against existing high walls as would be expected in practice.

2.2 Free-draining Design

A given surface is free-draining to its boundary with a minimum slope S if the following statement is true: All points on the surface can be connected to the boundary with at least one continuous line that is decreasing everywhere and nowhere flatter than the slope S.

An equivalent statement is (for a surface fully described by a regular grid): every point has at least one immediate neighbour that is below it with a slope equal to or exceeding slope S. It is apparent then that simple local rules can be used to check whether a surface is free-draining. The same simple rules can also be used to determine the minimal free-draining surface for any given surface. The code used to this was initially developed by Planchon & Darboux (2001) for cleaning Geographical Information System (GIS) Digital Terrain Models (DTM) before generating water flow paths.

The algorithm takes as input the surface requiring a free-draining design, the output is then the free-draining surface with a given minimum slope. The algorithm functions by generating a copy of the input surface which has the input surface elevations at the boundary and arbitrarily large elevations everywhere else. The second surface is then lowered onto the survey while repeatedly checking the previously stated requirements for a free-draining surface. Every point is repeatedly investigated to see whether its elevation can be dropped while maintaining the local requirements for a free-draining surface (and remaining above the surveyed elevation).

By inspection the generated surface will be the surface requiring the minimum volume of fill to be free-draining under the design criteria (Planchon & Darboux, 2001). The algorithm runs efficiently independent of the complexity of the surface and has proven very effective at solving a problem that is probably intractable without the use of a similar algorithm.

The free-draining algorithm as described above has been modified to suit specific requirements by the author:

1. It can solve for varying minimum slopes across the surface. This can be of use where flatter drainage slopes may be required further down the catchment for erosion control;
2. The discharge point can be specified. The standard algorithm will automatically find the optimal location for drainage on the boundary of the surface; and
3. Internal discharge points and elevations can be defined. This has proven useful for pan recreation projects.

Several drawbacks are however inherent in the algorithm at present. Due to the drainage of a point being fully determined by the points immediate neighbours preferred drainage directions are apparent. The primary drainage directions are therefore in one of eight directions. Additionally, the designed surface is not volume balanced, only the fill is given, no cut is modelled.

2.3 Design Example

A rehabilitation design is required for a coal mine. The coal adjacent to an existing void is to be extracted using a dragline. The design steps are shown in Figure 1. The dragline spoils are modelled using gaussian curves, the initial modelled spoils are too steep, the slope flattening algorithm is used to flatten them to the angle of repose of the spoil material. The free-draining surface with a minimum slope of 1 in 150 is then determined after the spoils have been flattened to a slope of 1 in 5. The final step is to flatten the remaining slopes in the pit to a final design slope of 1 in 7 and smooth the surface for final construction.

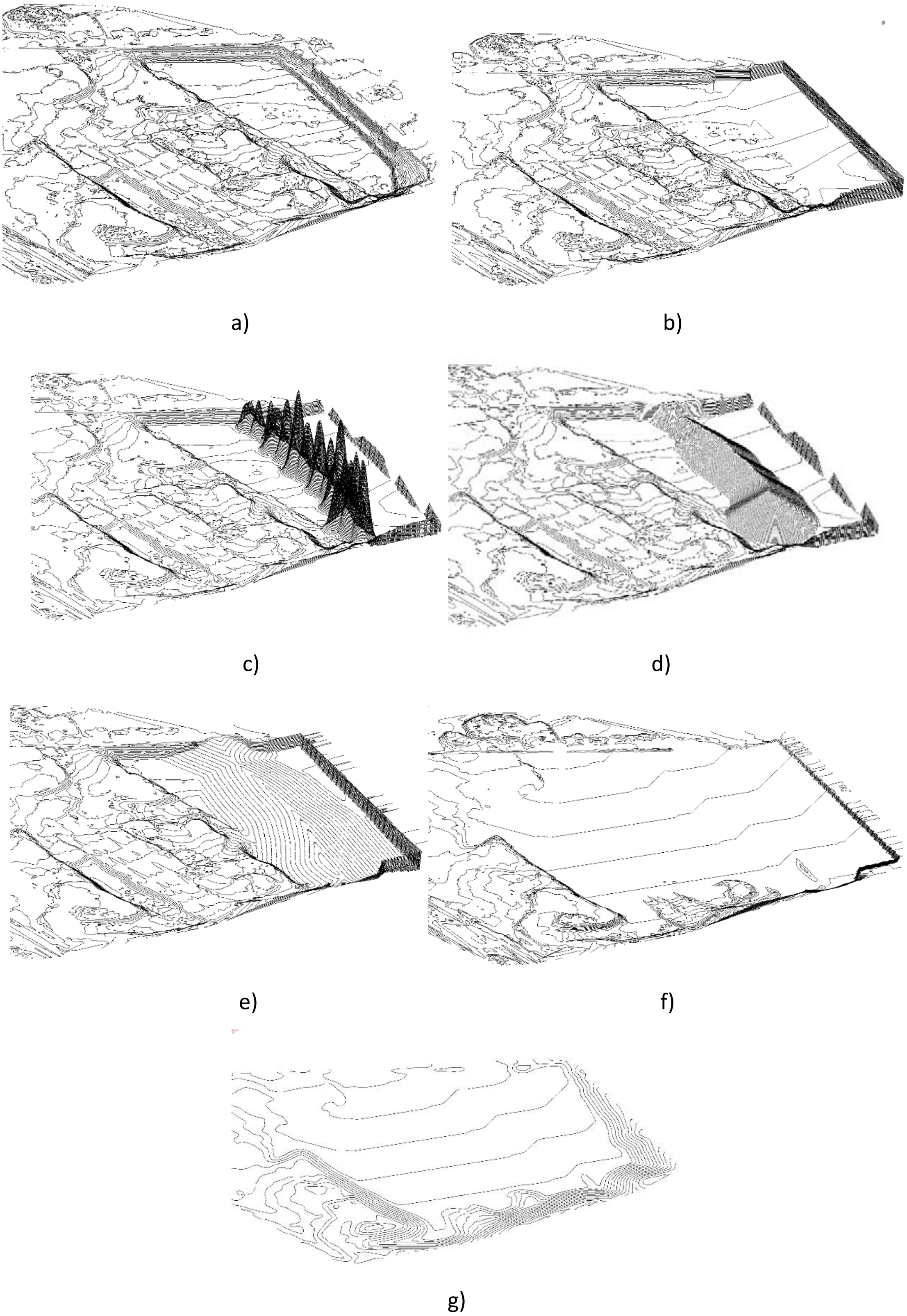

Figure 1 Design Example. a) Survey, b) Shell after coal removal, c) Modelled spoils, d) Spoils at angle of repose, e) Spoils at 1:5, f) Free-draining surface, g) Final rehabilitation design

3 Optimization of Earthmoving Operation

Once a landform has been designed that meets all the design criteria the final step is to construct the landform from the survey. Usually the cheapest way to construct the rehabilitated surface is using dozers. The dozer operation is complex and avoiding rehandle when aiming for a target surface often difficult ((Li, Liu, & Lu, 2015)). Discussion with rehabilitation fleet operators had revealed that the dozing fleet often moves far more material than is required to achieve the design surface.

Providing guidance to the dozing fleet would improve the efficiency of the dozing fleet and minimize costs. The perfect theoretical dozing plan would provide for every cubic meter of material provide a destination that it is to be moved to. It is however not possible to construct to such standards.

3.1 Mathematical Formulism

The design surface and the survey can both be defined as overlapping regular grids. Each point will therefore have two elevations: the survey and the design elevations. The two surfaces will be volume balanced (no material will need to be brought in or leave to transform the survey surface into the design surface).

The problem can be described as a standard transportation problem. Each point requiring cut to achieve the design surface is defined as a source (providing material) while every point requiring fill is defined as a destination (requiring material). The distance between all source and fill points is determined. The optimization problem can then be stated as:

Minimize the sum of the product of the material moved and the distance moved under the constraints that all sources are depleted (all cut is moved) and all destination requirements are met (all fill is provided for).

The standard transport problem is a linear problem and can be solved using a two-phase simplex algorithm. Due to the large size of the problems an excel add in was used to solve the problem. The size of the problem was also reduced by lumping together several points as a block. The required fill or cut for the block was then determined.

The optimized solution to the problem gives volumes as well as from-to coordinates that are required to achieve the design surface. Figure 2 below gives an example of the output of the algorithm.

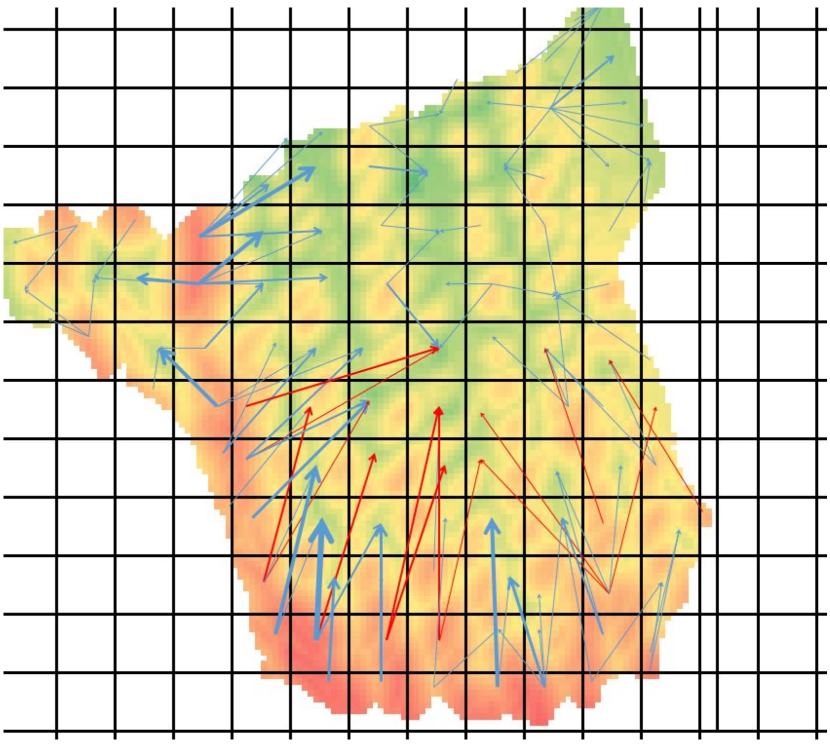

Figure 2 Output of dozing optimization algorithm

3.2 Practical Application

The provided information to achieve an optimal solution is too detailed to accurately implement on site. It is however possible to use the output of the algorithm to define a construction plan that is optimal and practical.

The approach used is to break up the area into shapes that are internally volume balanced. The predominant dozing direction in each shape can then be defined from the output of the algorithm. The dozer operator is given a shape as well as a dozing direction. By dozing in the predominant direction and not pushing material across the lines defining the demarcated shape the optimal dozing plan can be approximated. This approach has been implemented on site with positive feedback. A typical construction plan is shown below (Figure 3).

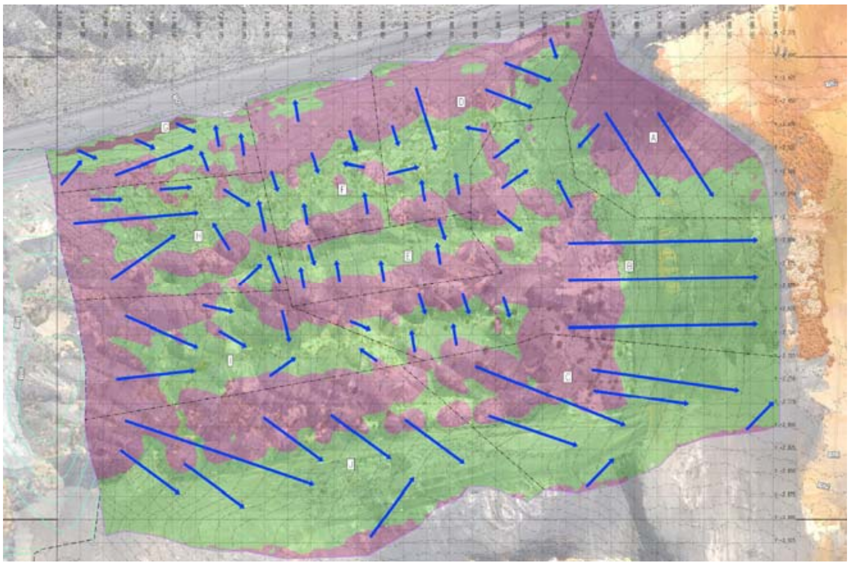

Figure 3 Optimal dozing plan

From the output of the algorithm it is also possible to calculate how much material is being moved what distance. This can be used to determine costs for the operation as well as allocating volumes to different fleets such as load and haul or dozing fleets. It was possible to use this approach to determine what the optimal dozing distance for a given site was which minimized the overall cost (Figure 4).

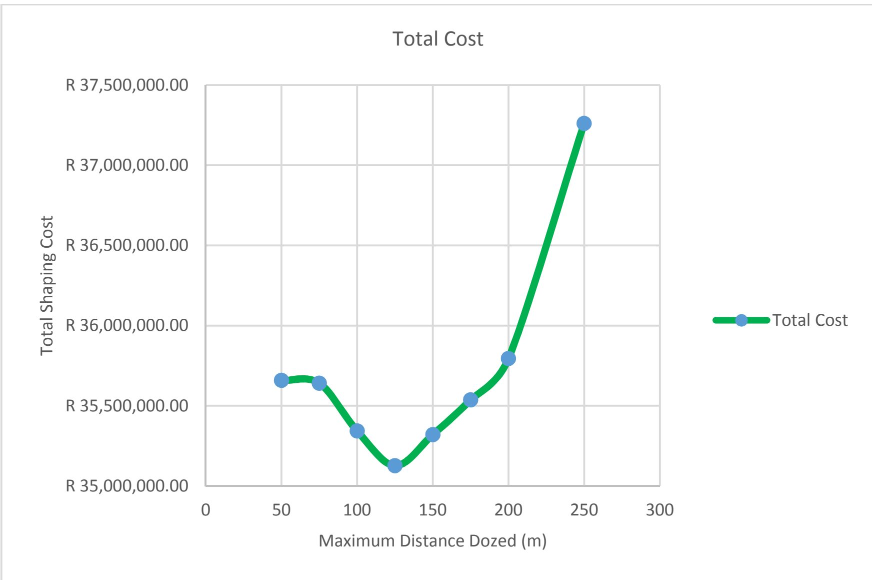

Figure 4 Material movement cost as a function of dozing distance

4 Conclusion

Several methods of optimization for rehabilitation design determination and construction were presented. The power of using simple cellular automata related systems to facilitate landform design was presented. Algorithms to flatten slopes to design requirements and calculating free-draining solutions are discussed. An optimal material movement strategy determination approach is also presented and discussed. All these algorithms have been used for design and have been implemented on site with success.

Acknowledgement

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The Life-Cycle of Mines - Adding Value to Host Communities by Integrating Environmental Remediation and Decommissioning

WE Falck *WEFalck Scientific Consulting and Advisory Services, France*

Abstract

Modern mining takes a life-cycle approach, that covers the temporal evolution of a site from exploration to the final end-state or re-use of a site. This is in contrast to the picture the public has of mining today, which is still shaped by the past, when mining companies often had a nonchalant attitude towards social and environmental impacts. Historically, this has its roots in shareholder-value considerations, when costs of environmental and social impacts were tacitly externalised. It has resulted in a large number of mining legacy sites world-wide, the remediation of which continues to require considerable (public) resources.

Mining and milling operations will permanently alter their sites and their surroundings. A complete return to greenfield conditions will not be possible. Open cast mines, spoil heaps, and/or tailings management facilities will remain at the surface. These features will become legacies with which the local population will have to live. A life-cycle approach to mine planning takes this into account and will involve the local population in the planning and decision finding processes. A mine has to integrate into the local socio-economic context and add value to the host communities, if possible beyond its active life-time.

Decommissioning of a mine requires resources and knowledge. Once the mine is closed, both will become scarce rapidly. It is, therefore, wise to integrate decommissioning into the operational plan. Again, works should be carried out as soon as infrastructure is deemed superfluous. While it is appreciated that planning ahead for years, or even decades, is difficult in a volatile economic environment, it is wise to develop a life-cycle management plan. Thus infrastructure can also be designed to facilitate decommissioning and decontamination, if required.

This paper will make a case for integrated operational, decommissioning, and closure plans that go beyond the active life of a mine with a view to minimise resources requirements, and environmental and societal impacts, while adding value to the host communities.

Keywords: *life-cycle management, remediation, decommissioning, social acceptance, host communities*

1 Introduction

There is no doubt that mining will continue to be needed, if humanity continues on the current path of development and even, if the developed countries severely redress their materials needs. A large proportion of our materials use is dispersive, to some degree at least, be it by corrosion or wear, or due to production losses. Therefore, recycling never can recover 100% of the original materials used. This applies even more to materials mined for their energy content.

However, the picture the public has of mining today is still shaped by the past, when mining companies often had a nonchalant attitude towards social and environmental impacts. Historically, this has its roots in shareholder-value considerations, when costs of environmental and social impacts were tacitly externalised. It has resulted in a large number of mining legacy sites world-wide, the remediation of which continues to require considerable (public) resources. Today not the least the Extractive Waste Directive (European Parliament 2006) requires operators to make arrangements for the safe management of residues from such activities.

Although often being only a temporary land-use, mining and milling operations will permanently alter their sites and their surroundings. A complete return to pre-mining conditions will not be possible. Open cast mines, spoil heaps, and/or tailings management facilities will remain at the surface. These features will become legacies with which the local population will have to live. A community that accepts a mine has to be aware that this imposes a perpetual relationship. In many instances mining residues have to be taken care of beyond the active life of the mine. This has to be understood by both, the mining company, as well as the host community. The need for perpetual care and maintenance necessitates that a durable relationship between the host community and the mine sites is being built, a concept first looked into in radioactive waste management (NEA 2007, 2010) and then extended to uranium mining sites (e.g. IAEA 2006). The social and in particular the environmental issues are the same for most types of mines. Such relationships have to be maintained beyond the time of active mining, perhaps into perpetuity. Local communities have a vested interest in the sustainable and sustained development of their region. A life-cycle approach to mine planning takes this into account and will involve these local stakeholders in the planning and decision finding processes. A mine has to integrated into the local socio-economic context and add value to the host communities, if possible beyond its active life-time.

However, mining legacies can also have beneficial effects and change the surrounding eco-systems in a way that may perceived as addding value by the local communities and other stakeholders. For instance, open-cast mines, gravel pits and quarries may provide the opportunity to create lakes and other types of aqueous eco-systems. It may be also noted that sometimes distinct features of mining legacies, such the characteristic cone-shaped waste-heaps of some mines, have become elements of the visual identity of mining communities, who demand their maintenance. Decommissioning and environmental remediation plans have to take this into account.

2 Decommissioning and environmental remediation

'Environmental remediation' is the process of transforming a site to an acceptable condition, according to regulatory requirements and suitable for its intended future use. Remediation goals are usually based on the risks that may be associated with the mining and milling residues or with soil and water contamination. The remediation process applies to all features that may have the potential to affect human health and the environment. Remediation encompasses inter alia site characterisation, identification of remedial action alternatives, implementation of a remedial action, and monitoring to assure the confinement or containment of (residual) contamination and of potentially harmful mining residues.

Conversely, the term 'decommissioning' describes the administrative and technical actions taken during the closure of mining or milling facilities, including the facilities to manage wastes from these extractive activities. Decommissioning is the process by which a facility is taken out of operation after final shutdown and includes the administrative and technical actions towards dismantling of all structures and components. This includes the removal of hazardous substances, such as process chemicals, oils or greases.

The classical engineering paradigm in residues management is to contain the alien material, in other words to design for resistance. As a result, such structures above ground have significant amounts of potential energy stored in them, which means that they require maintenance for ever. When designing impoundments for residues it is, therefore, wise to minimise this amount of potential energy, for instance by going underground. Impoundments are often designed with only the operational requirements in mind, not considering their long-term fate, requiring extensive remediation at the time of closure. Such works should not be left to the end, but be prepared during the operational phase.

Decommissioning and environmental remediation activities are subject to common driving forces. In particular, the regulatory requirements on emissions and safety, as well as the selection of acceptable end-states suitable for the site's future use influence the choice of technologies and strategies. Additional factors include cost efficiency, available (financial) resources, and stakeholder concerns. Because remediation and decommissioning are subject to the same driving forces, the careful identification of synergies between them may be helpful in optimising the use of available resources.

This highlights the importance of a forward-looking planning process. While in the past decommissioning and remediation have often been carried out as independent activities, optimisation of effort, cost, impact- and risk-reduction can be achieved by integrating them (Figure 1).

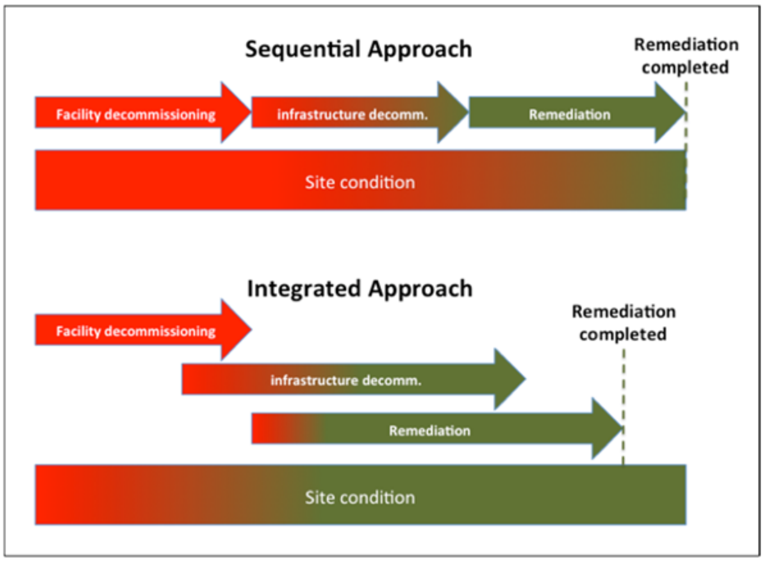

Figure 1 Sequential vs. integrated approach to decommissioning and remediation

The integrated approach requires a change in thinking: under the sequential approach, decommissioning is considered in isolation from the (later) remediation stages. Integrating both allows to

- deal with mining and milling waste management facilities that have reached their capacity whilst the mine/mill workforce is still mobilised;
- use existing infrastructure, such as liquid effluent treatment works;
- hand back early to the host community areas of land during operation or decommissioning:
- add value to the host community by mitigating impacts early in the overall process.

3 Life-cycle management

The European Unions Extractive Waste Directive (European Parliament 2016) implicitly calls for a life-cycle approach (Figure 2), as closure is specifically mentioned (cf. Article 5). Extractive waste management plans have to be drawn up, at least in outline, as part of the initial licensing process. These plans then need to be updated on a regular basis in order to take account of the actual situation, which may change as a function of market conditions, for instance. The basic aim is to move away from an ex post facto handling of liabilities to a more proactive and systemic approach, i.e. an integrated, life-cycle management approach.

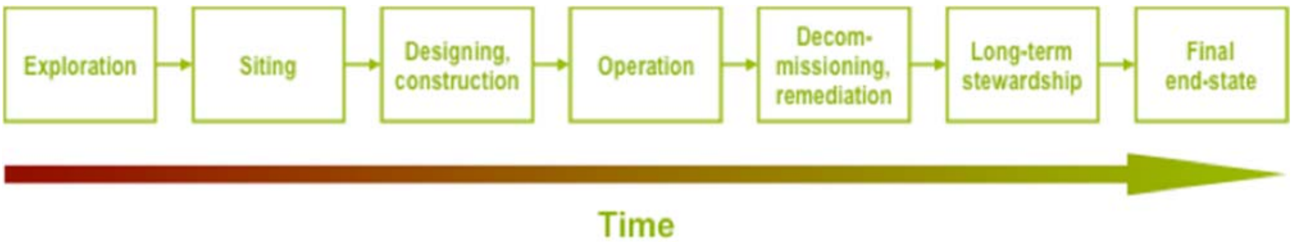

Figure 2 The 'life-cycle' of a mine

Life-cycle management involves incorporating into the decision-processes feedback and integrating lessons learned. It is generally agreed that incorporating decommissioning and site remediation requirements into the design of new facilities or the remaining life-cycle of existing facilities can help to avoid or minimise end-of-life liabilities. The life-cycle management concept does not treat each stage in the life of a mine or mill as an isolated event. Instead, each phase is viewed as having an influence on the future phases. This becomes particularly important, when a mine operates on low margins of profitability and is exposed to considerable market risks due to commodity price fluctuations and, hence, income/profit. Under such circumstances it is important not to run up large remediation liabilities, for which no resources may be available, when a mine is forced to shut down prematurely. Although today operating licenses are usually tied to adequate financial guarantees for decommissioning and remediation, the respective funds may not have accumulated enough yet. Life-cycle management also gives a perspective and a planning horizon for the host communities. While market conditions may be rather unpredictable over medium or longer time scales, a life-cycle management plan developed together with the host communities for a range of scenarios will allow them to adapt their own spatial, infrastructure, and economic planning. This in turn permits mining communities to better cope with any economic and social burdens arising from the various phases of the mine life-cycle, particularly the closure-phase.

4 Long-term stewardship issues

Life-cycle management also encompasses any monitoring and maintenance measure that may be required after remediation, a period commonly dubbed 'long-term stewardship'. Site re-use and provisions for long term stewardship (USNRC 2003) are closely related aspects in the life-cycle of a mine. Thus, the identification and selection of re-use options is a central issue that mine operators and host communities have to confront in making the transition from operation to decommissioning and remediation. The preferred future use for a site determines its post-mining end-state. Effective strategic planning provides a way to optimise this transition (IAEA 2006). The successful design and implementation of decommissioning and remediation projects requires attention to a common set of tasks. A successful decommissioning and remediation plan depends on the technical, political, and economic feasibility of the desired end-state.

Where remediation planning is not successful in identifying a sustainable end-state, subsequent further remedial measures may be required. Adopting a systemic life-cycle approach early in mine planning can not only result in a sustainable end-state, but the ultimate optimisation case is where the end-state generates value for the host community. This will not only help to (partially) offset costs, but would also be conducive to achieve a 'social license to operate' (SLO; e.g. Thomson & Boutilier 2011) for the mine and mill.

Stewardship means that the active remediation has been completed, only surveillance (monitoring) and maintenance of engineered systems needs to be kept up. Land-use controls may have to be put into place to ensure a use that is compatible with the implemented remediation solution. For instance, it may not be permissible to construct buildings on top of mining residue impoundments in order to prevent the spreading of contaminants or compromising engineered covers or their geotechnical stability.

5 Re-use options – added value to the host communities

Site development beyond the active life of the mine is important to the host community as they will have to live perpetually with the mining legacy (c.f. Falck et al. 2014). Hence, site re-use options are a problem of 'social choice': they involve a wide variety of concepts and criteria. Consequences of decisions are distributed in time, have distinctive time profiles and often are unknown at the time the decisions have to be taken. There is considerable uncertainty due to natural system complexity and to social indeterminacies. It will not be possible to respect all rationales for land-use development options simultaneously due to fundamental difference in social norms and values. Each future site use will produce different benefits, costs and risks with different time-profiles that will be perceived differently by each stakeholder. Seeking 'rational' justification for stakeholder choices between options based on preference is the standard economist's approach. However, stakeholders differ in their interests and perceived rights or dues and may actually propose solutions that are not based on tangible economic benefits, but may involve intangible benefits, such as maintining cultural and social identity. In European societies a participatory approach to decision-finding today is generally preferred. Such participatory approaches typically result in a 'social license to operate' (e.g. Moffat & Zhang 2014) for the mine and also the post-mining perspectives.

Involving the communities who may gain value from the site re-use will foster their vested interest. The objective is to create 'ownership' in the re-use scenarios that are compatible with the long-term site management requirements. In order to become effectively involved, stakeholders have to be involved from the very beginning in the planning processes, before significant decision have been made. 'End-of-Life' plans for the transition from active mining to the post-mining time need to be developed and provisions made for retaining the related institutional and cultural memory. Stakeholders have to be confident that the mine operators do not evade their responsibilities. They have to be confident that their wishes and preferences for the end-use of a site and its future development are adequately represented, but their expectations have to be matched to economic limitations and regulatory requirements.

The redevelopment potential of the mine-site depends on whether it can be remediated to conditions compatible with the intended use. The (re-)drawing of site boundaries and the disposition of certain features, such as impoundments for contaminated residues, will also have a strong influence on the usability and the redevelopment potential of a site.

There may be many different re-use scenarios, including housing, new industry (industrial park), recreational uses (golf course, park, ski-slope, boating lake, etc.), or preservation as socio-cultural heritage. Aspects to consider in evaluating alternative re-use scenarios include ease of access, convenient shape of plots, connection to services and other infrastructure, such as roads, railways, sewage systems, drinking water supply, electrical grid, etc., as well as geotechnical constraints.

The re-use potential of a mine-site may dependent on one or two key assets retained from the mine's operating life. These assets can provide an important catalyst to future economic development. Therefore, it is important to explore this re-development potential in advance, before making decommissioning decisions. These assets need to be retained and protected and could include:

- high quality electricity grid supply connections,
- airstrips, road, rail or sea access with off-loading facilities;
- sewage, district steam heating, potable water systems, and other piping networks;
- a local workforce with a high level of technical skill;
- prestigious old buildings, perhaps with historical significance (industrial archaeology);
- support services (catering, public transport etc.),
- machine shops, workshops and general production facilities; or
- large flat plots suitable for manufacturing or logistics buildings, perhaps with room for later expansion.

Integrating decommissioning with remediation allows for the partial release of sites, which then may generate additional revenue for the mine, thus off-setting (partially) the remediation costs.

Considering the Circular Economy Package (cf. http://ec.europa.eu/environment/circular-economy/index_en.htm) of the European Commission and CO_2 reduction targets, mining residues and other mining legacies may offer opportunities for re-utilisation. Particularly residues from more historic mining operations may be of interest for reworking, targetting e.g. 'critical' mineral raw materials (cf. http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en). Old mines, when flooded, may allow to extract geothermal energy (together perhaps with the extraction of metals from the mine waters), or the methane from coal mines may be captured and utilised. These approaches combine aspects of decommissioning and remediation with beneficial re-use and hence add value to the host communities.

6 Synergies between decommissioning and remediation

Careful consideration of the life-cycle of a site through strategic planning will assist in linking the decommissioning and the remediation plans to future use (Falck et al. 2009). This in turn will increase the likelihood that synergies between operations, decommissioning, and post-decommissioning are maximised. The term 'synergy' refers here to the savings made by sharing resources between the two activities. Such resources may include the workforce, infrastructure, waste management facilities, and (construction) materials. Thus the same or more can be achieved with less in possibly a shorter time. The identification of such synergies has to be based on a careful life-cycle planning, set against a preferred site end-state that has been developed together with the host community. Given that some mines and mills will be in operation for many years or even decades, this planning can only give the framework. Market developments will force changes upon the mine and host communities may develop other interests and goals as actors change. Hence, such planning will need to be continuously updated to reflect the reality.

Maintaining records to facilitate planning

Decommissioning and planning are greatly facilitated, if records of past activities and site-uses are kept. This allows for efficient characterisation for dismantling and remediation and to focus on objects and plots that may need particular attention. Such records may include plans, drawings, process descriptions, and reports on unusual events, such as chemical spills, erosion or flooding events. The records can be also an important element in communicating with the host communities, fostering trust that problems are not hidden, but made transparent (see also below).

Risk Management Synergies

Risk assessment is one of the central elements of remediation and of decommissioning planning because it can aid decision-makers in determining an end-state compatible with the future site re-use. Risk assessment is used as a planning tool to identify and manage possible environmental and occupational safety and health risks to workers involved in implementing the project. Separate risk assessments of each activity may lead to risk 'displacement' by the transfer of risk to other activities, rather than overall risk reduction. For example, contaminated soil removal may reduce on-site risk, but creates off-site risk associated with transportation, treatment and disposal. Integrating the risks across the full spectrum of the life-cycle of a mine can help to reduce the overall risk.

Materials and Waste Management Synergies

Decommissioning of plants may generate large amounts of surplus materials and varying volumes of waste that are quite different from the normal operational wastes. Through careful planning and sequencing of dismantlement operations, much of the waste can be segregated for recycling or re-use. Certain waste materials arising from decommissioning can be re-used for construction purposes in the mine or residue management facilities, while certain hazardous materials can be managed together with other process residues. A systemic view of all residues arising from mining and milling is the objective of the Extractive Waste Directive (European Parliament, 2006), which calls for re-utilisation as much as possible. Soil remediation around mining and milling infrastructure may generate large quantities of soil that has been contaminated by spills, dust dispersal, or chronic leakages of pipe work or storage facilities. After suitable segregation, such soils then can be managed together with the mining and milling residues. Indeed, certain contaminated materials may be processed in the mill to extract metal value and render the residues inert.

Community Involvement

As noted before, host communities will have a vested interest in the development of a mining and milling site undergoing decommissioning and remediation. While mine managers often think in terms of individual projects, stakeholders may have a more general perception of the site that does not necessarily distinguish between operation, decommissioning, and remediation. Active involvement of stakeholders during the design phase of projects will help in the identification of end-points and the definition of priorities with a view to add value to the communities in the post-mining phase. Structured interactions will help project managers reduce or avoid misunderstandings, especially when some elements of the overall effort at the site are controversial. Stakeholder involvement from the very beginning on may also help to create a sense of 'ownership' in the chosen paths and final site uses, leading to better compliance with any site use-restrictions and management requirements (cf. stewardship).

Regulatory synergy challenges

The transition of an active mine into the decommissioning and remediation phase is often characterised by a significant change in the regulatory regime. Regulatory and governance scheme vary widely across the world, but the dominant regulator during the operational phase typically is the mining authority. During decommissioning, remediation and subsequent long-term stewardship environmental regulators become increasingly dominant. This change in regulators and associated changes in paradigms from production and work-place health & safety to (long-term) environmental protection often constitutes a major challenge for mine managers and miners. There is also typically a spirit of co-operation between miners and mining authorities (who often have trained together, but then went down different professional routes), while relationships between miners and environmental authorities are often tensioned and characterised by mistrust and misunderstanding. A gradual transition from operation to decommissioning to remediation and finally to long-term stewardship will help to develop mutual understanding and adaptation.

Workforce and skill synergies

Notwithstanding the said emotional and paradigmatic challenges, the mine workforce typically has the skills to perform much of the decommissioning and remediation activities. It is, therefore, wise to try to retain these skilled workers. This is facilitated by decommissioning and remediating already those parts of a mine and mill that will not be required anymore during the operational phase. In this way, the change from operation to closure is not a sudden step, but a gradual transition, which aids in the retention of the workforce that then will have a multi-year perspective. In the case of premature closure, the amount of remaining closure works will be reduced and with it the size of the workforce required, leading to a reduction of post-operational expenditure. A gradual transition will also facilitate the absorption of those miners that are not needed anymore into the labour market, both locally and elsewhere. The host community will be given more time to cope with the change in the economic and employment conditions.

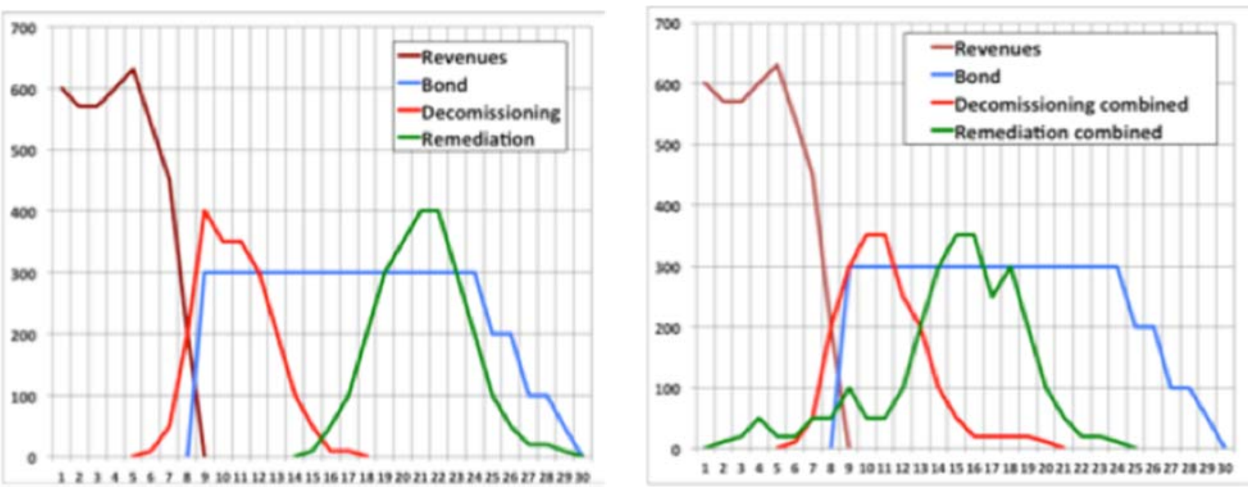

Figure 3 Cost vs. time for a sequential (left) and integrated (right) approach to decommissioning and remediation

Financial synergies

Co-ordinating decommissioning and remediation can save time and money. The availability of funds at any one time can be an issue that threatens the viability of a decommissioning and remediation programme. The programmes may need to be tailored to the flow of moneys (Figure 3).

This could mean to stretch out the time-scale of the programmes. Decommissioning and remediating parts of a mine and mill and the associated waste management sites that are not needed any more for the operation may have financial benefits.

7 Conclusions

A life-cycle approach that integrates the operational phase with decommissioning, environmental remediation and the final long-term management of mining and milling residues has the potential to generate a wide range of synergies. These synergies express themselves in form of savings in time and money and a reduction of the uncertainty over the future end-state of the mining and milling site and, hence, also over the future of the host community. Any mine operation depends on the market conditions for the commodity mined. Unfavourable market conditions can lead to premature closure and a considerable burden of decommissioning and remediation costs for which the mine may not have been prepared (yet). Early closure and decommissioning of surplus structures and concurrent remediation will distribute the associated cost over a longer time-span, thus reducing the final burden. Value for the host communities is not only created by a reduction of the uncertainty over the final end-state, but also by earlier release of plots for other types of development. The transition from the operational phase to the final end-state is also eased with respect to socio-economic impacts. These impacts are spread over a longer time span and, therefore, can be better absorbed by the host community. All these feature may not only add value to the host community, but may also aid in bringing about a higher degree of acceptance or even 'ownership', in other words facilitate the obtaining and maintaining the 'social license to operate'.

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Functional Benchmarking, Bounded Rationale and Looped Learning: a Case Study in Reducing Uncertainty in Planning for Closure of a Waste Rock Landform

SJ Finucane *Bioscope Environmental Consulting Pty Ltd, Australia*

SL Robinson *Bioscope Environmental Consulting Pty Ltd, Australia*

Abstract

In recent years, it has become more common for mining companies to close Waste Rock Landforms (WRLs) using concave slope designs. A company planning closure of its iron ore mine in the Mid-west region of Western Australia (WA) had initially proposed WRL closure based on a traditional linear slope design, but changed to a concave slope design when new studies demonstrated that this would provide better long-term stability and protection against erosion. However, the use of concave slopes in WRL closure is still relatively new in WA, and tall concave slopes are not common in the Mid-west region. Consequently, the mining regulator in WA requested that further information be provided to increase stakeholder confidence that the proposed closure outcomes could be achieved.

Typically, additional information on WRL rehabilitation and closure methods is obtained, at least in part, from field trials. However, with a footprint of less than 45 ha, the WRL in question is too small for adequate field trials. In order to increase confidence in the use of a currently uncommon closure design, the mining regulator agreed that a benchmarking study could be used to identify the key learnings from mines where tall concave slopes had been implemented, or were proposed, as part of WRL closure. The primary driver behind any benchmarking study is improvement. There is value in learning from contexts outside an organisation's usual frame of reference, but it is important to conduct this learning using a formal, structured approach that allows appropriate comparisons and provides information that can be used to drive actions for performance improvement.

The benchmarking exercise described in this paper is a form of functional benchmarking, where comparison is made to similar practices within an industry. Following its review of the study's report, the WA mining regulator stated that the exercise was "particularly useful and should be encouraged throughout industry" and a "potentially a powerful agent for use in mine closure [planning]".

This paper discusses sources of uncertainty in mine closure planning and the role of benchmarking in reducing this uncertainty before describing the methodology utilised for the benchmarking study. It then discusses the benefits and limitations of benchmarking, and outlines the way in which the outcomes of this benchmarking exercise were applied during the mine's closure planning process. The paper concludes that the use of functional benchmarking did indeed reduced uncertainty in planning WRL closure and built stakeholder confidence in the use of a concave slope design for WRL closure.

Keywords: *waste rock landform closure, functional benchmarking, iron ore mine closure, organisational learning*

1 Introduction

It has been common practice for Waste Rock Landforms (WRLs) to be rehabilitated using constructed slopes designed with linear cross sections (Jeldes et al. 2015) and berms to break up the long batter slope lengths. This was based on the understanding that erosion potential would be reduced as runoff accumulation would be controlled on each batter without affecting the lower batter; that slope lengths would not be long enough to high levels of erosion to occur; that berms would provide areas of decreased flow velocity and area of sediment deposition; and that if rilling or gullying did occur on a particular batter section, a berm would quarantine the lower lifts from the gully continuing unimpeded down the slope (Roddy & Howard, 2016). However, it was recognised in the early 2000s that these benefits did not necessarily occur primarily because the batter sections would become hydrologically connected if a berm was breached (Howard et al. 2010).

The problems arising from the use of linear WRL closure designs prompted closer examination of natural landforms to better understand how the long-term stability of closed WRLs could be improved. Natural slopes are seldom linear, but tend to be curvilinear with concave slopes as a result of evolutionary processes in fluvial systems and hillslopes (Jeldes et al. 2014, Jeldes et al. 2015). It has been demonstrated by Jeldes et al. (2014), Jeldes et al. (2015), Vahedifard et al. (2016) and others that concave profiles can significantly improve the stability of constructed slopes and yield less sediment than constructed linear slopes where erosion and large volumes of soil loss could occur if ground cover was not established quickly. As a result of these and other studies, mining companies began to consider the feasibility of using concave slope designs to close WRLs. This comprises construction of concave shapes in longitudinal (down slope) directions and the incorporation of more natural features to obtain improved stability and erosion resistance in a closed WRL (Jeldes et al. 2014).

A mining company (the proponent) planning closure of its iron ore mine in the Mid-west region of Western Australia (WA) had originally proposed a WRL closure design based on a traditional linear (bench/berm) design, but through assessment of the waste material characterisation it become apparent that a concave slope design would provide better long-term stability and protection against erosion. The new closure design consisted of a final landform with a series of concave slopes, the tallest of which would be 80 m in height. This design was discussed with, and generally accepted by, the then WA Department of Mines and Petroleum (DMP) (now known as the Department of Mines, Industry Regulation and Safety) during a presentation in June 2015. However, at that time, the use of concave slopes in WRL closure was still relatively new in WA and tall concave slopes were not (and still are not) common in the Mid-west region. Indeed, the proposed 80 m high slope would be the tallest single concave rehabilitated WRL slope in the Mid-west region. Consequently, the DMP requested that further information be provided to increase confidence that the proposed environmental outcomes could be achieved. Typically, this information would arise, at least in part, from field trials. However, with a footprint of less than 45 ha, this WRL is too small for adequate field trials. Therefore, the DMP agreed that a benchmarking exercise could be conducted to identify key learnings from those mines where tall concave slopes had been implemented, or were proposed, as part of WRL closure to provide that information and increase confidence in the proposed design.

2 Sources of uncertainty in mine closure planning

"Uncertainty" is a non-intuitive term that can be interpreted differently depending on the discipline and context in which the term is applied, but can be defined simply as "incomplete information about a particular subject" (Ascough et al. 2008). In their guide for mine closure planning, Sánchez et al. (2014) recognise that every planning process involves uncertainty and indeed describe mine closure planning as "an uncertainty management process".

Although many sources of uncertainty are recognised in the literature (see, for example, the discussion provided in Ascough et al. 2008; Lipshitz & Strauss 1997; or Maier et al. 2008), three key causes in mine closure planning are incomplete knowledge, variability of natural events and social processes (and their resulting unpredictability), and ambiguity that is reflected in diverging understanding of the factor or issue (Sánchez et al. 2014) (Table 1). Sánchez et al. (2014) recommend that uncertainties in mine closure planning be addressed systematically through a structured approach. We propose benchmarking as one such approach.

Table 1 Main causes of uncertainty in mine closure planning (Modified from Sánchez et al. (2014))

Causes	Description
Incomplete knowledge	Missing information Abundance or excessive information Conflicting evidence about a phenomenon Errors of measurement Groundless information Lack of understanding of the process or phenomenon in question
Variability or unpredictability	Characteristic that is inherent to a complex phenomenon
Diverging understandings of relevant issues	Multiple and potentially conflicting perceptions of the process or phenomenon in question Differences in values and beliefs between those involved in the articulation and analysis of the situation Different judgements on the serious of the situation

3 Benchmarking as a tool to reduce uncertainty

Environmental decision-making can be extremely complex due to the intricacy of the systems being considered and the different, and sometimes competing, interests of stakeholders (Ascough et al. 2008). To ensure that it is comprehensive, reliable and defendable, environmental decision-making needs to address any uncertainties that exist in relation to the issue under consideration. Where there is uncertainty associated with mine closure planning, a range of tools can be used to increase confidence that the proposed closure processes could reasonably be expected to achieve the desired outcome(s). These include closure risk assessments, stakeholder engagement, field trials and various forms of comparative review including benchmarking.

The primary objective for any benchmarking initiative is improvement. By comparing processes, practices or procedures, benchmarking is recognised as one of the most responsive evaluation tools for performance improvement within an organisation (Ajelabi & Tang 2010). However, as discussed by Fong et al. (1998), there is also value in learning from contexts outside of an organisation's usual frame of reference using a formal, structured approach that allows for comparison of an organisation's practices against the "best-in-class" and provides information that can be used to drive actions for performance improvement. Further, the proactive nature of benchmarking encourages the sharing of ideas and discussion for continual improvement (Fong et al. 1998).

Benchmarking is not about imitating, but rather focuses on adapting lessons learned to improve organisational or, as in this case, project performance. In simple terms, benchmarking is a learning process through which a company can find better ways of doing things (Ajelabi & Tang 2010). The study described in this paper is a form of "functional benchmarking", where a comparison was made to similar practices within an industry (Bhutta & Huq 1999; Ajelabi & Tang 2010). It was structured as a resource for organisational learning that used agreed data comparatively to identify potential strengths and weaknesses, and to identify areas for improvement within current plans (Charles & Wilson 2012). The methodology used for this exercise is described in Section 4.

4 Methodology

4.1 The benchmarking wheel

Benchmarking is a technical core of Total Quality Management, a subject characterised by a culture of continual improvement (Ajelabi & Tang 2010). Ajelabi & Tang (2010) discuss how many models and methods have been developed to explain and guide the benchmarking process, but note that all of these originate from the Deming Cycle which includes a minimum of four phases: plan-do-check-act. An example of this is the benchmarking wheel described by Bhutta & Huq (1999) which is based on the plan-do-check-act cycle, but comprises five steps (Figure 1). The benchmarking study described in this paper followed the steps defined in the benchmarking wheel illustrated in Figure 1. These steps are described in Section 4.2 – 4.6.

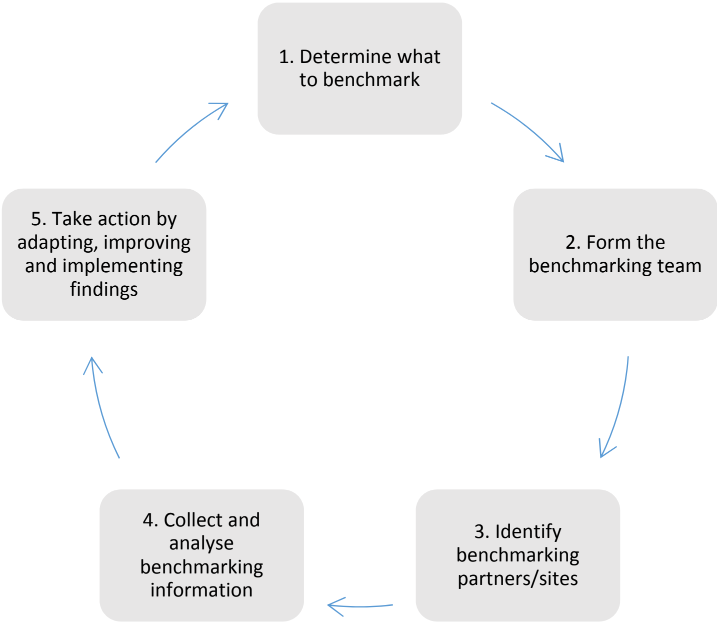

Figure 1 The benchmarking wheel (modified from Bhutta & Huq 1999 and Ajelabi & Tang 2010)

4.2 Step 1: Plan the study

Objectives play a crucial role in evaluating performance, reducing uncertainty and improving management practices. Consequently, it is important to set clear, measurable and agreed objectives at the start of the study, and to weigh different objectives in terms of their perceived importance to facilitate the comparison and prioritisation of management alternatives (Williams 2011). Bhutta & Huq (1999) note that corporate or divisional leadership teams typically decide what will be benchmarked and set the study objectives. In this case, this decision was made collectively by the proponent, the DMP and Bioscope Environmental, who determined that the objective of this study was to evaluate the use, or proposed use, of tall concave slope designs for WRL closure at other sites to identify key success factors and challenges. To meet the study objective, it was determined that the following questions would be asked during the benchmarking exercise:

- What were the key factors that have contributed to the success of rehabilitation and closure of tall concave slope WRLs?
- What were the key challenges experienced in rehabilitation and closure of tall concave slope WRLs?
- What were the lessons learned from the above that are relevant to the WRL at the subject mine site and could be used to improve its closure design?
- Is there benefit in conducting limited field trials in relation to selected aspects of revegetation?

4.3 Step 2: Form the benchmarking team

Benchmarking teams should comprise specialists from within the organisation and should have different backgrounds to facilitate brainstorming (Fong et al. 1998). It is important that top management fully supports the team and allows adequate time and resources for the benchmarking study.The team established for this benchmarking study comprised representatives of the proponent and Bioscope Environmental. Once it had formed, the team developed a plan that included designation of the roles and responsibilities of each team member, study milestones and a realistic completion date.

4.4 Step 3: Identify benchmarking sites

Step 3 comprises identification of benchmarking partners. This usually involves extensive research with industry websites and periodicals, proponent and consultant reports, conference proceedings and other technical literature (Fong et al. 1998). Engaging with other mining companies, industry organisations and regulators, Non-government Organisations and other parties can also identify suitable benchmarking partners. Increasing the diversity of participants in a benchmarking study has the potential to bring new thinking and expand the role of information, education and dialogue (Berkes 2007).

A preliminary list of sites that could be suitable for this benchmarking study was developed through a desktop literature search and discussions with the DMP (Table 3). The list was finalised in consultation with the DMP. Of the 12 sites selected, eight are existing or proposed iron ore mines in the Mid-west and Pilbara regions of WA. These regions have similar environmental characteristics and the mines were within the same commodity, so the influence of variation in these features on benchmarking findings would be reduced. However, sites located in other regions and/or mined commodities other than iron ore were also included if they had implemented, or proposed, concave closure designs for their WRL slopes.

Table 3 Benchmarking sites selected for this study

Site	Region	Commodity
Karara Iron Ore Project	Mid-west	Iron ore
Mungada East/Blue Hills Extension Project	Mid-west	Iron ore
Extension Hill Hematite Operation	Mid-west	Iron ore
Mid-west Iron Ore Mine A	Mid-west	Iron ore
Pilbara Iron Ore Mines A, B, C and D	Pilbara	Iron ore
Telfer Gold Mine	Pilbara	Gold
Coobina Chromium Mine	Pilbara	Chromite
Sunrise Dam	Goldfields	Gold
Wattle Dam	Goldfields	Gold

4.5 Step 4: Collect and analyse information

Step 4 of the benchmarking process is described by Butta & Huq (1999) as "perhaps the heart of the benchmarking process". In collecting data and other information, it is important to bear in mind that bigger datasets are not necessarily better datasets, particularly if founded on the uncritical collection of information (Holling 1978). For this benchmarking study, data and other information were collected for the selected benchmarking sites on slope and drainage design parameters, erosion control mechanisms, revegetation strategies, completion criteria and performance (where known). This information was sourced through a desktop literature review of publicly-available information, with information on WRL closure at Pilbara Iron Mines A-D collected during site visits by the proponent.

4.6 Step 5: Adapt and improve

The final step of a benchmarking study is to adapt other companies' best practices, functions or processes and implement specific improvements to those of the company for which the benchmarking study is being conducted. The outcomes of the benchmarking exercise were used as part of the closure risk assessment and to refine the closure design for the WRL at the mine for which this benchmarking study was conducted (see Section 5). This revised design, along with a report on the benchmarking study, were included in the Mine Closure Plan (MCP) for the site for assessment by the DMP.

5 Discussion

In decision making, the rationality of individuals has three unavoidable constraints: the amount of the information available; the limits of our thinking capacity; and the amount of time available in which to make a decision (Simon 1982). This is known as "bounded rationality", a term coined in the 1950s by Herbert A. Simon. For this benchmarking study, the main limitation related to the amount of information available. While it's not reasonable to expect that one or two companies or sites would hold all the information required for the benchmarking study (Fong et al. 1998), collecting adequate information for this study was challenging. At the time that this study was conducted there were (and still remain) few examples of tall (>40 m) rehabilitated concave slopes in WA and little available data on slope performance for these. Therefore, through discussions with the DMP, it was agreed that the benchmarking study would draw information from a range of sites in WA.

In an ideal world, all of the sites included in this benchmarking study would have been iron ore mines located in the same region as the mine for which this study was conducted. However, the iron ore mines in the Mid-west region included in this study had proposed or implemented linear slope designs for WRL closure (Karara, Mungada East/Blue Hills Extension, Extension Hill and Mid-west Iron Ore Mine A). While these sites provide useful information on WRL closure in similar environmental conditions and within the same commodity, the fact that none of these sites had selected concave slope designs meant that we needed to include sites that were further afield. Consequently, four iron ore mines in the Pilbara region that had proposed or implemented concave slope designs for WRL closure were included in the study (Pilbara Iron Ore Mines A - D). The other Pilbara mines included in this study had also proposed (Coobina) or implemented (Telfer) a concave slope design, as had the two Goldfields mines (Wattle Dam and Sunrise Dam). It was considered by both the proponent and the DMP that this diversity of sites would provide sufficient information for the purposes of this study.

The main benefit of the benchmarking study was the generation of knowledge that was used in closure planning for WRL closure and to increase confidence that the predicted environmental outcomes could be achieved. As a result of the benchmarking study, it was found that a high standard of WRL closure occurs when risk assessments, waste rock and topsoil characterisation, surface drainage studies and other investigations are conducted before closure earthworks are undertaken. Further, it was found that the use of well-qualified and experienced operators along with an appropriate fleet, along with careful attention to construction controls and tolerances, improved the likelihood of achieving acceptable WRL closure outcomes. The outcomes of the benchmarking exercise were used to refine the closure risk assessment and closure risk management measures for the mine for which this study was conducted. Subsequently, the revised WRL closure design, along with the MCP, were approved by the DMP.

Information generated through benchmarking studies can make a useful contribution to organisational learning, which in turns improves a company's capacity to make sound, risk-based decisions. In general, organisational learning can occur through three modes (Table 4). Single-loop learning is essentially learning that leads to improvement in existing practices without challenging goals or assumptions. Effectively, it is an operative level of learning that "follows the rules" and asks the question, "are we doing things right?" (Anon 2014). By comparison, double-loop learning explores innovative approaches, challenges assumptions and/or goals, and "changes the rules" while in triple-loop learning, focus is on the way in which we gained information ("learning about learning") (Anon 2014).

Table 4 Three types of organisational learning (Modified from Anon (2014))

Characteristics	Single-loop learning	Double-loop learning	Triple-loop learning
Type of work	Technical. Used when tackling routine, repetitive issues.	Technical/adaptive. Used when tackling complex, non-programmable issues.	Adaptive. Used when you want to learn how to learn.
Results in change or action?	Yes	Yes	Yes
Challenges goals, assumptions and mental models	No "follows the rules"	Yes "changes the rules"	Yes "learns about learning"
Challenges the learning framework	No	No	Yes
Focus	Improving	Understanding and improving	Transforming, understanding and improving

It could be argued that the benchmarking study described in this paper is an example only of single-loop learning as it resulted in improvements to an already-proposed practice (i.e. the use of a concave slope design for WRL closure). However, this ignores the way in which this process challenged the status quo and explored innovative approaches, which are characteristics of double-loop learning. Further, as this was the first (or one of the first times) that benchmarking had been used in the Mid-west region in place of field trials to increase confidence in the proposed WRL closure design, it also provided an opportunity to "learn about learning", which is characteristic of triple-loop learning.

Organisational learning is acknowledged as being of central importance to adaptive management and related governance models (Armitage et al. 2008; Fabricius & Cundill 2014). A well-designed project provides the opportunity for both technical and non-technical learning (i.e. learning about decision-making processes) while recognising the former tends to occur over relatively short timeframes while the latter occurs generally over longer periods (Williams 2011). For this case study, technical learning occurred in relation to concave slope designs for WRL closure which non-technical learning occurred in relation to the willingness of the regulator to use non-traditional method to increase confidence in the proposed WRL closure design.

In addition to the above, conduct of this benchmarking study has helped to improve organisational resilience. By engaging with individuals outside of the proponent's organisation, opportunities were created to build or strengthen linkages within the mining industry and its problem-solving networks. Resilience is further enhanced by dissemination information on the study within "communities of practice" (Armitage et al. 2007) such as those attending conferences such as Mine Closure 2018 and/or those who will later refer to the conference proceedings.

Following its review of the mine's MCP, the DMP commented that the benchmarking study was "particularly useful and should be encouraged throughout industry. DMP commends Bioscope Environmental on the review work undertaken to date, which is potentially a powerful agent for use in mine closure". It should be noted that the DMP has not decided that benchmarking can replace field trials in all instances, but has acknowledged that this approach was successful in reducing uncertainty regarding the WRL concave closure design in this instance. As more benchmarking studies are conducted in the context of closure planning, the practice itself and its applicability to closure planning will no doubt be refined and improved.

6 Conclusion

The primary driver behind any benchmarking study is improvement. There is the value in learning from contexts outside an organisation's usual frame of reference, but it is important to conduct this learning using a formal, structured approach that allows appropriate comparisons and provides information that can be used to drive actions for performance improvement. This paper demonstrates that functional benchmarking can reduce uncertainty in planning WRL closure and build stakeholder confidence that the use of a concave slope design for WRL closure can obtain desired environmental outcomes.

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Multi-Criteria Decision Approach to Support Selection of Post Closure Land Use

AHA Freitas *Golder Associates, Brazil*

RA Lessa *Golder Associates, Brazil*

TCC Bissacot *Nexa Resources, Brazil*

AC Lima *Nexa Resources, Brazil*

BX Silva *Nexa Resources, Brazil*

Abstract

The selection of post closure land use for mine sites is one of the most important phases in closure planning, because it can affect not only the closure actions, and therefore its costs, but also company investments during the operation phase, especially those to minimize socioeconomic impacts of closure. While several success examples of post closure land use exists, bringing one good experience from one site does not guarantee the same level of success in another location because of site specific conditions. Because these site specific conditions and often conflicting objectives of post closure land use, for example, to improve the quality of the environment, minimize risks and to maximize socioeconomic benefits for the society after closure, the proper selection of alternatives can be a difficult task. Aiming to structure and support the decision making process on selection of alternatives for post closure land use, a multi-criteria decision approach using the Analytic Hierarchy Process (AHP) and a simplified cost benefit analysis was developed and applied in several closure plans in Brazil. This methodology is discussed in this paper.

Keywords: *post closure land use; multi-criteria, decision, AHP*

1 Introduction

The definition of post closure land use for mine sites is desirable at early stages of the mine cycle because it allows the company to implement actions that can be beneficial and save costs in long term. These actions can include changes in the design and operation of mine facilities aiming to facilitate the use of the area after closure, what can reflect in reduction of closure costs, as well as socioeconomic investments focusing on the selected post closure land use.

On this last topic, considering that many mine sites are located in small towns, with strong economic dependence on the mine operations, it is desirable that the company can help to prepare the community to live without its economic contribution after the closure, aiming to mitigate part of the impacts related to decommissioning. In order to be more effective, including in terms of cost, this preparation needs to be aligned with the future use of the area. For example, in a hypothetical scenario where the future use of a mine site is defined for tourism, the preparation should include capacitation of the community for this type of activity and public and/or private investments that can favour its future development, as improvement in the infrastructure of the town to receive tourists. Considering a future allocation of the work force of the mine, the capacitation activities can include the employees of the company.

Defining a post closure land use is a question that sometimes is overlooked in long term planning. In other cases, the selection of post closure land use is based on simplified analyses that do not include sufficient information or are not clear about the criteria used to select a land use alternative. This last problem reflects in difficult to reproduce or review the analysis, what is required in several corporate standards for mine closure.

A common approach when defining post closure land use is to look at success cases in similar mine sites, however, site specific conditions play an important role on this success and need to be considered carefully. Such site specific conditions include physical, biotic and socioeconomic aspects, which can make the difference between a success case and a post closure land use that is not sustainable in long term.

When defining the post closure land use the company usually wants to mitigate the impacts associated with the mine operation and closure and, where possible, to add socioeconomic value to the mine site area in long term. This usually results in conflicting objectives, which makes the proper selection of post closure land use a difficult task. For example, a company may want to improve the quality of the environment, to mitigate the environment impacts caused by its operation, and at the same time to generate a large number of jobs, to minimize the economic impacts of closure. Different post closure land use alternatives will likely be more favourable to one aspect than to other, and a proper comparison of these alternatives with two dimensions may be not as straightforward as it looks like. This complexity increases with the number of information to be assessed, including the number of alternatives and criteria for decision making.

Considering the importance of a proper definition of post closure land use and the challenges to make decisions related to this topic, a multi-criteria decision approach using the Analytic Hierarchy Process (AHP) and a simplified cost benefit analysis was developed. This methodology has been applied in several closure plans in Brazil and it is described in this paper.

2 Methodology

According to Gomes et al. (2006), decision consists of the process of gathering information, attribute importance to this information, identify the alternatives for a problem and select one of the alternatives. Clemen (1996) states that decisions are usually difficult because of multiple and conflicting objectives, the complexity of the decision processes, inherent uncertainty and different perspectives involved, and present the decision making process structured in the following steps:

- Identification of the problem and objectives for the decision making;
- Identification of alternatives;
- Problem decomposition and modeling;
- Selection of the best alternative;
- Sensitivity analysis;
- Verification of necessity of addition analysis; and
- Implementation of the selected alternative.

The problem that justified the proposed methodology was the selection of post closure land use for mine and industrial sites, and the objectives when selecting the alternatives were defined as:

- Maximize alignment with socioeconomic context.
- Maximize socioeconomic benefits.
- Minimize environmental impacts.
- Minimize human health, ecological and safety risks.
- Maximize sustainability in long term.
- Maximize potential improvements to the corporate image of the company.

Considering to treat the decision problem as a maximization function, the objectives above indicated as minimization were considered as to maximize reduction. This resulted in objectives to maximize reduction environmental impacts and maximize reduction of risks.

For the purposes of decomposing and modelling the decision problem related to selection of post closure land use the Analytical Hierarch Process (AHP) (Saaty; 1990, 2008) was used. The objectives listed above were defined as decision criteria in the first level of the hierarchy.

Minimizing closure costs when selecting the post closure land use was also considered as one objective and was originally included as a decision criteria in the first level of the hierarchy. However, this ended up resulting in an exercise of economic valuation when comparing the economic criteria with the other criteria. Although this was a valid approach for incorporating the economic criteria in the decision making, the discussion and understanding of the results by decision makers in companies proved to be difficult. The main problem was the intrinsic concept of economic valuation of non monetized items (e.g. compare an increase of X USD in closure costs with an improvement in corporate image), which is not usual among decision makers in mining and industrial facilities. As an alternative, the economic dimension was included as part of a cost benefit analysis, which is described later in this paper.

Alignment with legal requirements was also considered as an objective, but as a cut off criteria, rather than a criteria for comparing post closure land use alternatives. This means that in the case an alternative did not meet the regal requirements applicable, it was excluded from the analysis.

The decision hierarchy was developed to a second level including criteria and indicators o represent each of the objectives in the first level. These indicators were then classified qualitatively in low, medium and high, to represent the level of compliance of each alternative to the decision criteria in the second level.

A technique defined in the AHP methodology (Saaty; 1990, 2008) was used to estimate the relative priority (importance) of the criteria in the decision problem hierarchy. It consists of a pair-wise comparison of relative importance of each criterion with respect to the goal of the parent criterion using a qualitative scale. The qualitative scale is related to numeric values, which can be used to calculate a priority vector that corresponds to the relative importance of the criteria in the decision making process.

The application of the method consisted of:

- Define the relative importance of the criteria used in the hierarchy.
- Classify each alternative with regards to the level of compliance with these criteria.
- Add up the values corresponding the level of compliance with the criteria for each alternative, using the relative importance.

This resulted in scores for each alternative, corresponding to the level of compliance with the proposed decision criteria and objectives. As indicated above, considering a maximization function, the alternatives with higher potential to meet the proposed objectives had the higher scores. These scores were normalized to facilitate comparison.

As discussed above the economic criteria was included in the form of a cost benefit analysis, where the benefit was represented by the scores obtained in the multi-criteria analysis for each alternative and the costs consisted of an order magnitude of closure costs to make the area feasible for each alternative of post closure land use. The closure costs can differ for example, when one alternative consider reusing part of the facility while other consider to remove the facility and to rehabilitate the area.

The results of the cost benefit analysis were expressed by the ratio between the closure costs and the points in an arbitrary scale, representing the scores of the alternatives indicated above. A lower cost benefit, representing a higher potential to meet the decision objectives with lower costs was desirable.

3 Data and Results

The proposed methodology to support the selection of post closure land use was applied in several mine and industrial sites, including sites controlled by Nexa Resourses in Brazil and Peru.

In order to illustrate the application of the methodology, the results of a mine site controlled by Nexa Resources are presented in this paper. This mine site included:

- Underground mine.
- Open pits and waste rock piles.

- Tailings dam.
- Water dam.
- Industrial facilities.
- Administration facilities.
- Areas not used for mining operations that have restricted use according to local legislation (areas need to be used for forest conservation).
- Areas not used for mining operations that do not have restricted use according to local legislation.

The methodology was applied for each group of areas indicated above, which were grouped based on similarity of potentialities and restrictions for post closure land use. Alternatives were identified for each group of areas, considering potential synergies of use. In some cases the alternative for one area was considered only if it was selected for another area.

Figure 1 presents the relative importance of the criteria in the first level of the decision hierarchy, which was calculated using the AHP method. A multidisciplinary team of professionals provided inputs that resulted in these importances. The local socioenvironmental context and corporate policies were considered for these inputs. These results show higher importance to reduce human health, ecological and safety risks, reflecting corporate policy and the conditions of the site, followed by maximization of socioeconomic benefits, reflecting a strong economic dependence of the local community on the mining operations.

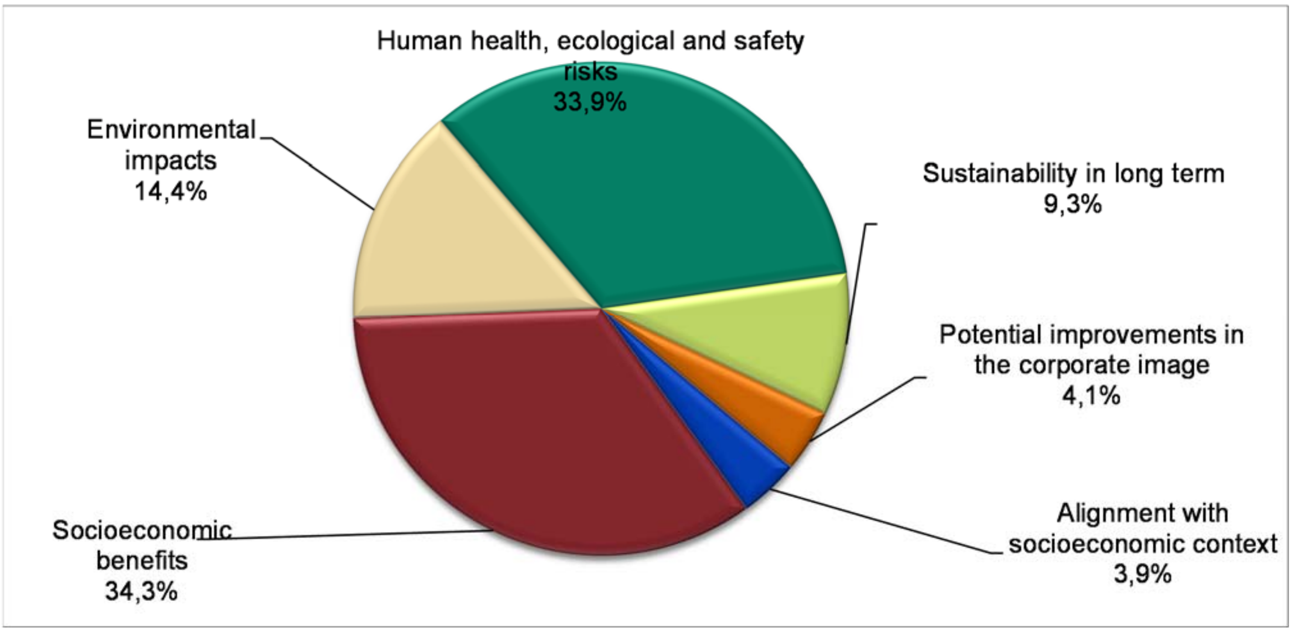

Figure 1 Relative importance of the criteria in the first level of the decision hierarchy

Figure 2 presents the scores resulting from the multi-criteria analysis for the group of areas corresponding to open pits and waste rock piles. Alternative A, corresponding to rehabilitation of the area and implementation of a conservation unit without access to public, presented the higher score, followed by alternative C, corresponding to implementation of a cultural, educational and research centre. The alternative of cultural, educational and research centre was considered for this area only in the case of synergy with other areas. That means that this alternative would be selected for this area only if selected also for other areas in the mine site.

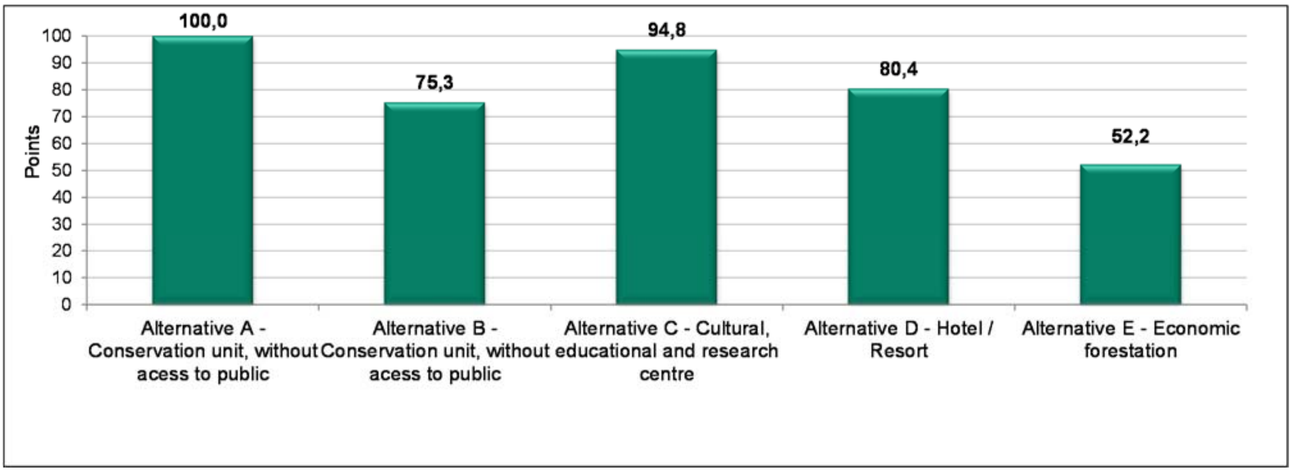

Figure 2 **Scores of the alternatives considered for the areas including open pits and waste rock piles**

Figure 3 presents the score for each criteria in the assessment of alternatives for the areas including open pits and waste rock piles. That is a breakdown of the information presented in Figure 2. Alternative A presented a presented a higher score mainly because the criteria corresponding to minimization of risks. By limiting the access to public, potential receptors to risk factors were reduced compared to other alternatives. In the case of the alternative corresponding to cultural, educational and research centre, the criteria with the highest score was the maximization of socioeconomic benefits. This alternative would not only generate jobs and income, but would also serve as an option of recreation of the local population, with potential to increase their welfare.

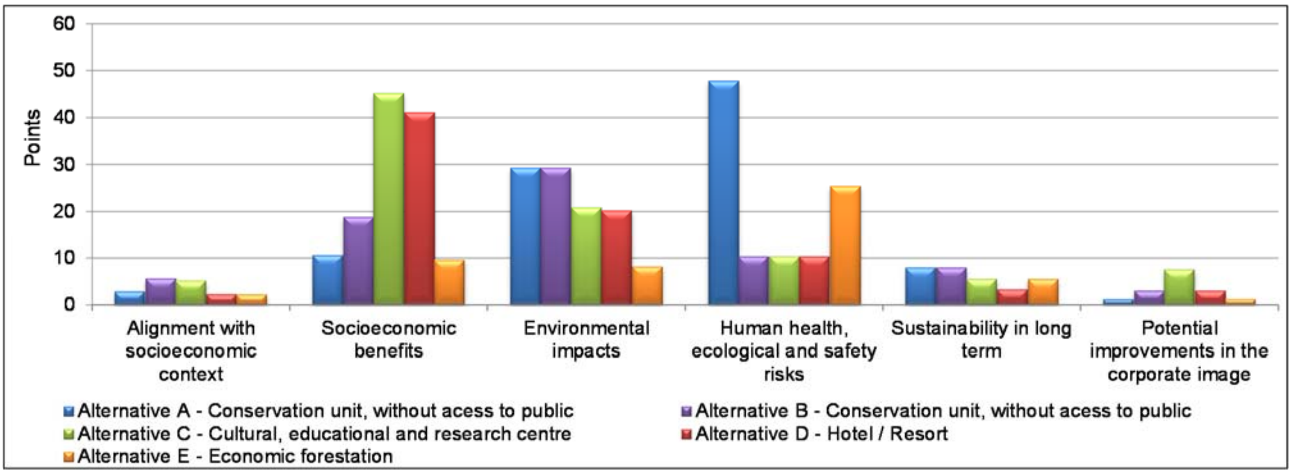

Figure 3 **Scores of each criteria in the alternatives considered for the areas including open pits and waste rock piles**

Figure 4 presents the results of the cost benefit analysis (red line) for the alternatives considered for the areas including open pits and waste rock piles. Alternative C would result in a lower closure cost compared to alternative A, because a lower level of environmental rehabilitation could be applied. This resulted in a lower cost benefit ratio for alternative C compared to alternative A and alternative C with the lowest cost benefit among those alternatives assessed. Therefore, considering the criteria and importance used in this assessment, the alternative corresponding to cultural, educational and research centre would be preferred for this area using the proposed methodology.

Similar assessments were carried out for the other group of areas, resulting in the selection of post closure land use for the areas of the mine site as indicated in Table 1.

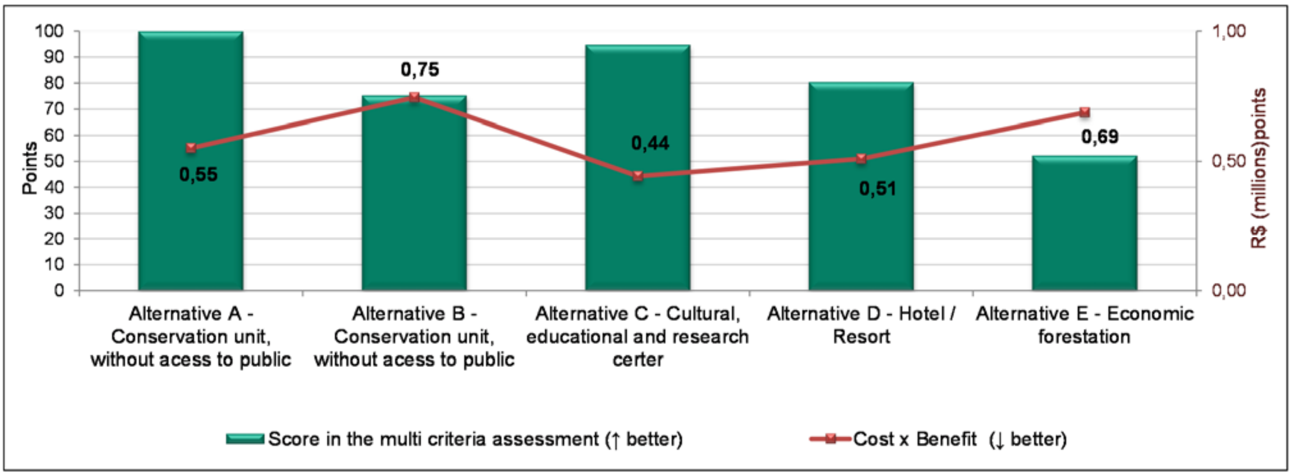

Figure 4 Cost benefit results of the alternatives considered for the areas including open pits and waste rock piles

Table 1 Post closure land uses selected for the mine site

Group of areas	Selected post closure land use
Underground mine	Cultural, educational and research centre
Open pits and waste rock piles	
Tailings dam	
Water dam	
Industrial facilities	
Administration facilities	
Areas not used for mining operations that have restricted use according to local legislation	
Areas not used for mining operations that do not have restricted use according to local legislation	Agriculture

4 Conclusion

A methodology to support the selection of post closure land use for mine and industrial sites was developed, using a multi criteria decision assessment based on the AHP method and a simplified cost benefit analysis.

This methodology was applied in several mine and industrial sites, and proved to be useful to support decisions related to post closure land use. One of the main advantages about the use of this method was the possibility to structure the decision process in a way that can be easily discussed in the context of mining and industrial operations, making clear for the decision makers the rationale behind analysis. A clear and more reproducible decision process is expected result in a better engagement of the decision makers, what is positive factor for the success of post closure land use for mine and industrial sites.

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Sustainable Long-term Planning of the Kostolac Coal Basin Opencast Mines Closure

T Subaranovic *University of Belgrade, Serbia*

I Ristovic *University of Belgrade, Serbia*

N Pavlovic *Opencast Mining Centre, Belgrade, Serbia*

Abstract

Sustainable and timely planning of opencast coal mines closure includes a number of activities relating to the entire service life of mining with the fulfillment of economic, environmental and social conditions. The process of opencast coal mines closure planning is much more demanding and complex than it was a few years ago. Bearing in mind the economic, environmental and legislative changes, as well as the sustainable development of mining, opencast coal mine closure can be planned, sudden, unplanned and temporary. When it comes to closure of opencast coal mines, it is required to timely prevent, or reduce the negative long-term impact on the environment to a minimum, and enable rapid creation of self-sustaining natural ecosystems. The possibility of using the space of closed opencast mines and external landfills in the function of renewable energy sources (wind, solar and biomass) is especially interesting, from both ecological and economic aspects, because innovative renewable energy and storage solutions can establish productive secondary lives for inactive mine sites. At the same time, it is necessary to continuously monitor the implementation of opencast mine closure in all phases of rehabilitation and reclamation of the degraded area, including risk probabilities and control of reliability of the realization of all types of reclamation with an eco-control model. However, due to mining activities, productive alternative uses for the site, and therefore potential revenue sources, are limited.

An example of good practice is the long-term planning of the Kostolac Coal Basin opencast mine Cirikovac closure, in the function of storing the ash from the thermal power plant. Other important projects include forming a wind farm at the locations of the outer dump sites of the open pit mines Klenovnik, Cirikovac and Drmno, as well as completing a prefeasibility study to determine the optimal use possibilities of the surface mine Drmno area after the final phase of the internal dump formation according to the developed methodology.

Keywords: *coal basins, planning process, risk analysis, eco-control, wind farm*

1 Introduction

The closure of a coal mine, in terms of sustainable development, is a set of related activities that begin by preliminary planning of closings, and ends up achieving long-term stability of the terrain and establishment of a self-sustaining ecosystem. Applying this concept has achieved satisfactory effects in terms of environment.

Proper planning and measures for mine closure are issues required to be resolved by the mining sector of the state, in compliance with international environmental standards such as ISO 14001, in order to:

- Provide adequate resources to implement plans for the environment protection during operation and closure, and that
- Plans for closure are designed with taking into account possible changes of geological and technological conditions on the site and community expectations.

The aim of establishing a strategic framework for mine closure is to promote nationally consistent approach for managing the closure on all levels of the state's competence. Therefore, there are established harmonized concepts for the mine closure, which are to be applied with greater consistency together with development of legislation by required government and mining sector program.

When planning mine closure, it is necessary to: protect human health and ensure safety, to reduce or eliminate negative environmental impacts of mining, to enable the successful use of land, and to intensify social and economic benefits during sustainable development and operation of the mine. From the very beginning, mine closure planning includes conceptual solutions becoming more detailed over time (Figure 1) (Pavlovic et al. 2012). In the stage of conceptual decisions, the general solutions and goals are to be set. Through detailed planning, a selection of the possible options for closing is going to be made, the implementation methodology is going to be determined, and monitoring and a developed economic analysis are going to be defined.

Planning of mine closure should begin during the development of the Prefeasibility Study, design phase and permitting for the mine, with an upgrade during the operation (Figure 1). The lack of a mine closure plan update can lead to serious environmental and economic consequences (ICMM 2008). Planning ensures that the process of closure is cost-effective and in due time.

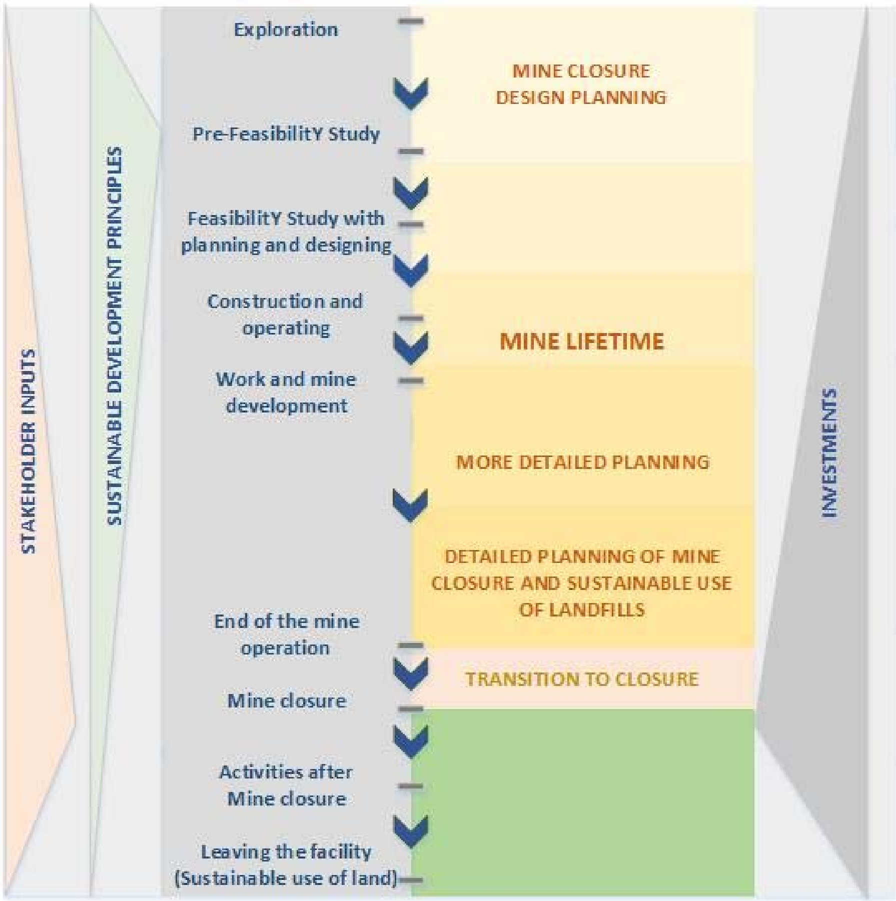

Figure 1 Mine closure planning

As a planning rule, risk-based approach has to reduce costs and uncertainty. Current trends in closure planning involve technical review and risks analysis, as well as the compensation costs in terms of engineering and the environment, monitoring and reliability and eco-control of reclamation realization in all closing phases. Mine closure plans include all parameters of the natural environment and the mining system, including geology, geo-engineering, hydrogeology, hydrology, geochemistry, biology, environmental science, social, and permitting and land management factors.

Closure of a mine can be planned, sudden or unplanned and temporary, according to the Mining Law.

Planned closure involves preparation of the Conceptual Closure Plan, under which the evaluation of the closure plan is performed in due time. The closure plan is based on the level of the existing bio-physical and socio-economic information, and details on planning and development of the mine. As the project progresses, the Closure Plan is to be updated regularly and processes are supposed to reflect changes in the mine development, operational planning, and environmental conditions. Planned closure requires a preparation of the Plan for ceasing the opencast mine operations a few years before closing, and a systematic implementation of this plan.

In the event of a sudden and unplanned closure, an accelerated process of closing is implemented. This includes immediate preparation and implementation of the Plan for the closure (based on the already existing Closure Plan), taking into account the non-operating status of the terrain. When all the calculated measures and requirements during the closure are inadequate to fund, then the funds are being provided from other company sources.

As a result of economic or operational circumstances, it is possible that mining has to be stopped, so a mine will be temporarily closed. Temporary closure of this nature is normally planned and assumed in terms of restarting mining. Control and maintenance processes include immediate preparation and implementation of the closure plan, taking into account the potential for future operations on the field. It is recommended that, where it is feasible and economically reasonable, to carry out the reclamation in all the disturbed areas, even if it is unlikely that some of these areas are going to remain undisturbed in the future. Field reclamation, and efforts to prevent potential contamination of the environment, should be implemented in accordance with the conception of the final closure.

The dynamics of closure planning require regular review to reflect the changing circumstances during mine operation. The closure plan should be modified in the event of any operational changes, new regulations or new technology and should be comprehensively reviewed regularly.

The wider objectives of mine closure planning are:

- Environmental and public health and safety protection, with safe and reliable closure practices;
- Reduction or elimination of adverse impacts at the environmental when the mine finishes operations;
- Establishment of conditions that are consistent with pre-set targets for the final sustainable land use;
- Reducing the need for the long-term monitoring and maintenance of the environment through the establishment of effective physical and chemical stability of the mine area.

2 Long-term coal mines closure planning process

Usually a coal basin has multiple active mines with dumps, or one mine with the potential of opening other mines, which means a possible continuation of mining. A long-term spatial and geometric basin analysis is a continuous process in time and space, regardless of whether it's about the continuation of mining or the completion of mining (Drebenstedt et al. 2014). This also includes the process of analyzing all relevant characteristics: geological, geotechnical, hydrogeological, hydrological, pedological, ecological, social and economic. In case of a possible continuation of mining, the cycle is closed with the final closure of all mines, including the internal and external dumps in the basin (Figure 2).

The need for a deposit of technogenic raw materials (gravel, sand, ash, gypsum and waste) may arise. Based on the spatial and geometric analysis and the mentioned analysis of characteristics, risk analysis and techno-economic studies, the possibility of depositing technogenic raw materials in the basin area is confirmed or rejected. Of course, this is a case where such raw materials exist in the process of coal mining or in the thermal power plant's final combustion.

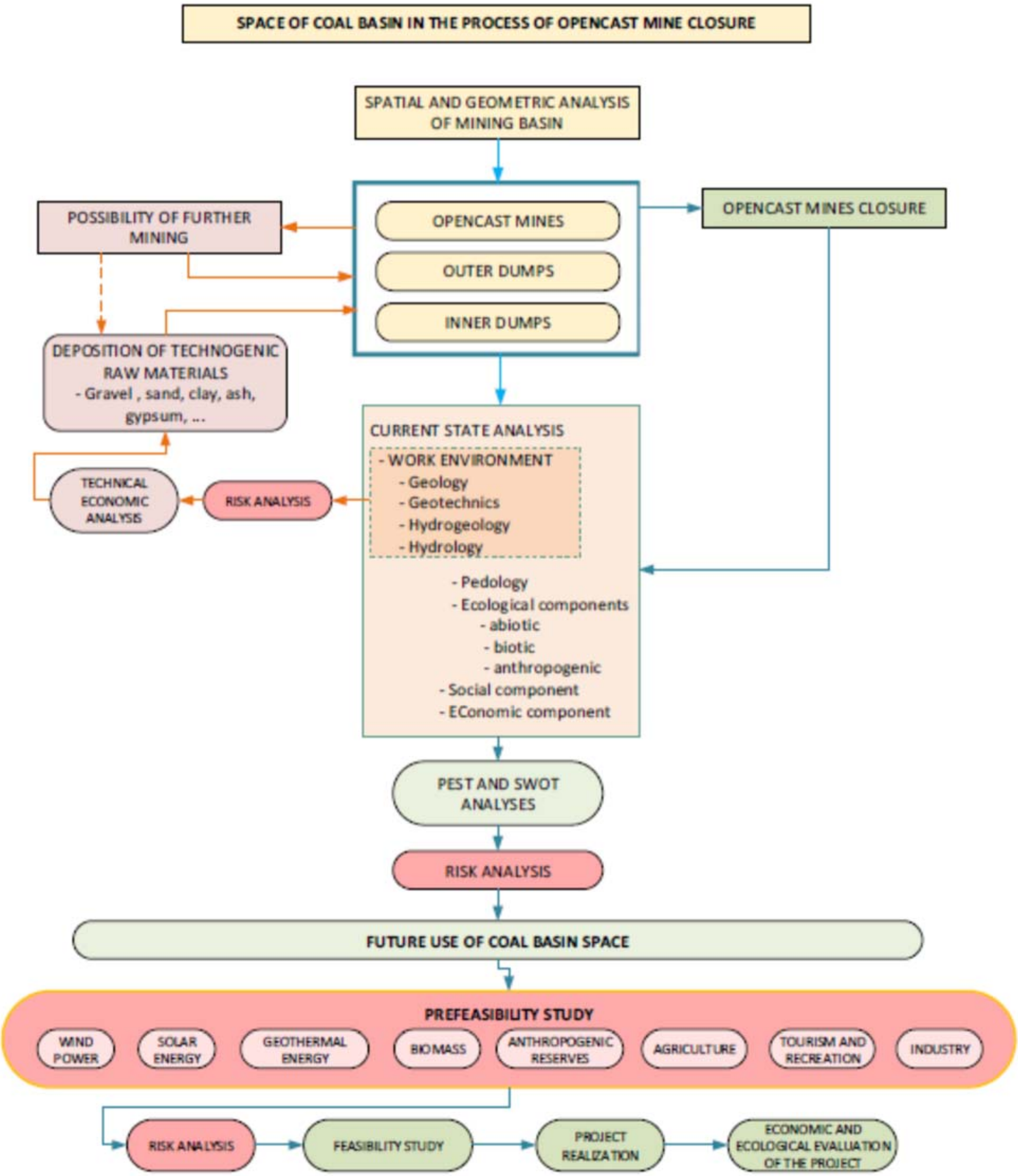

Figure 2 The process of realization of possible domains for rehabilitation of closed open pit mines in coal basins

After the mining ends in the basin area and the open pit mines are closed, with or without the deposit of technogenic raw materials, the analysis of all the characteristics of the basin commences, as well as the analysis of the existing situation from the political, economic, social and technological aspects (PEST), after which SWOT analysis and risk analysis follow, in order to form a framework and a conceptual plan for the future use of the coal mining area. The basin area can be used in the domain of energy generation (wind, sun, geothermal and biomass), usage of anthropogenic reserves, as well as in the field of agriculture, tourism and recreation and various types of industry. It is possible for this space to be used in multiple domains, therefore its usefulness isn't limited to just one.

Based on the conceptual plan, the process of working on the prefeasibility study, risk analysis and choice of solutions for further use of the mining basin area follows. The feasibility study is then made on the basis of the prefeasibility study, after which the project follows, and later the realization of the project. The realization of the project is followed by continuous monitoring and eco-control, as well as risk and reliability analyses. In the end, the cycle is closed with the process of economic and ecological evaluation of the completed project.

The development of renewable energy sources on the space of closed open pit mines is a realistic option if there is proven cost-effectiveness. In which case, this is not only an appropriate alternative use of these sites, but also a potential source of income within sustainable mining.

3 Risk analysis and eco-control model

3.1 Methodology of risk assessment

To verify the selection of options for the mine closure plan and sustainable use of land, risk patterns that allow a relatively quick and easy way to identify the best alternative for multi criteria decision making issues are commonly used. Patterns are created as the ratio of the probability of risk occurrence and criteria which is to be considered, in relation to the consequences.

Risk analysis includes the possibility of an event which could adversely affect the achievement of the set goals, as well as cause missing the opportunity for achieving the goals related to the closure of the open pit mine and realization of the usage domain of the rehabilitation area.

The most commonly used methodology in risk assessment is based on the interaction between the likelihood that the risk will arise and the consequences that a risk might cause for a business activity, process or for the company as a whole (Robertson et al. 2009). The risk assessment includes the history of certain events (nature, frequency, consequences). Bearing in mind the joint impact of both risk parameters, the risk is presented as a product of numerically assessed levels.

As a starting point for the analysis of internal and external risks, the potential risks of the realization of a closing program for open pit mines are defined based on the PEST and SWOT analyses. Defining the potential risks is crucial for the strategic plan of the coal mining basin development.

Estimates for the probability and consequences of risk events are defined and shown in Tables 1 and 2.

Table 1 Risk consequences

Event consequence	Consequence estimate of an event	Damage description
Insignificant	$K_1 = 1$	≤ €50,000
Minor	$K_2 = 2$	€50,000 - €500,000
Moderate	$K_3 = 3$	€500,000 - €5,000,000
Major	$K_4 = 4$	€5,000,000 - €50,000,000
Severe	$K_5 = 5$	≥ €50,000,000

Table 2 Probability of risk occurrence

Event probability	Probability estimate of an event	Description
Rare	$K_6 = 1$	Once or less in 10 years
Unlikely	$K_7 = 2$	Once in 7-9 years
Possible	$K_8 = 3$	Once in 4-6 years
Likely	$K_9 = 4$	Once in 1-3 years
Almost certain	$K_{10} = 5$	Once or more in 1 year

On the basis of risk and probability measures, the risk assessment matrix is shown in Table 3.

Table 3 Risk assessment matrix

Consequence / Probability	Insignificant $K_1 = 1$	Minor $K_2 = 2$	Moderate $K_3 = 3$	Major $K_4 = 4$	Severe $K_5 = 5$
Rare event $K_6 = 1$	LOW RISK	LOW RISK	LOW MEDIUM RISK	LOW MEDIUM RISK	MEDIUM RISK
Unlikely event $K_7 = 2$	LOW RISK	LOW MEDIUM RISK	MEDIUM RISK	MEDIUM RISK	MEDIUM RISK
Possible event $K_8 = 3$	LOW MEDIUM RISK	MEDIUM RISK	MEDIUM RISK	MEDIUM RISK	HIGH RISK
Likely event $K_9 = 4$	LOW MEDIUM RISK	MEDIUM RISK	MEDIUM RISK	HIGH RISK	EXTREME RISK
Almost certain event $K_{10} = 5$	MEDIUM RISK	MEDIUM RISK	HIGH RISK	EXTREME RISK	EXTREME RISK

Ratings of the matrix are obtained by multiplying the assigned score for the impact level with the probability estimation:

- Low risk - ratings 1 and 2
- Low medium risk - ratings 3 and 4
- Medium risk - ratings 5, 6, 8, 9, 10 and 12
- High risk - ratings 15 and 16
- Extreme risk - ratings 20 and 25

In general, a risk can be acceptable or unacceptable.

An acceptable risk, which includes insignificant, minor and moderate risk, implies exposure to a risk which is tolerated without taking any measures. The risk is also acceptable in situations where the cost of taking measures is disproportionate to the potential benefits, but it can be controlled with measures or plans to reduce or mitigate the consequences of risks.

An unacceptable risk is usually passed on to a third party or being avoided by abandoning activities which carry such a risk. Transferring risk to a third party or sharing a risk with a third party is practically the best response to significant and unacceptable risks. In those events where extremely dangerous consequences can occur, it is necessary to further verify the likelihood of such an event in order to define the required level of risk mitigation activities. The non-acceptance of a high and extreme risk by avoiding most often causes the abandonment of an activity which carries such a risk.

3.2 Reclamation eco-control model

Based on the closing plan, cost estimates for closure are carried out, which should be regularly reviewed in order to comply with changes in the mining circumstances. It is necessary to continuously monitor implementation of the mine closure in the phase of rehabilitation and reclamation of the degraded area, with a *Reclamation eco-control model* (Pavlovic 2002).

The set reclamation system, connected to the effect of the surface mining on land degradation, might dispose of three situations (E_0, E_1 and E_2). The normal situation of the reclamation system is marked by E_0, the situation E_1 represents imperil within the permitted time limits, while the situation E_2 represents an extreme ecological situation time when imperil of the environment exceeds the permitted time limits. Then, a more active reclamation causes its reduction in degradation and transfers from situation E_2 into situation E_1, and further on into situation E_0. For the evaluation of the probability of situations P_0, P_1 and P_2, it is necessary to resolve the system of differential equations. But it is more convenient to derive these equations directly from the directed graph of states using the mnemonically rule: For each condition the total outgoing flow of probabilities is equal to the total incoming flow. For ecosystem reclamation, a graph of three situations is formed in the shape of a chain (Figure 3). Transition intensities a_0 and a_1 are put beside the arrows leading from left to right, and intensities b_1 and b_2 are put beside the arrows leading from right to left. For this process, limit probabilities of conditions are expressed by the following formulas:

$P_0 = 1/(1+(a_0/b_1)+(a_0a_1/b_1b_2))$; $P_1 = a_0P_0/b_1$; $P_2 = a_0a_1P_0/b_1b_2$, total sum which equals to one.

On the grounds of the total probability, ecological reclamation risks under criteria of extreme situation occurrence are determined, and are as follows: $P_2 = 1-P_0-P_1$.

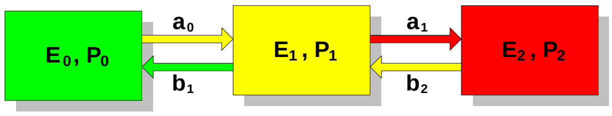

Figure 3 The three conditions shown as graphs

4 Examples of opencast mines closure in Kostolac coal basin

The Kostolac coal basin is located about 100 km east of Belgrade and covers the central part of the Danube region. The Velika Morava River marks the western boundary of the basin, while the Danube marks the northern boundary. The eastern border is next to the village of Rama, while the southern border is about 5 km north of town Pozarevac. This basin covers an area of approximately 145 km^2, with a longer axis of approximately 23 km in the direction of northeast-southwest, and a shorter axis of about 9 km in the northwest-southeast direction. It’s divided into four deposits: Drmno, which is an active opencast mine in the farthest east part of the basin (opencast mine Drmno), Cirikovac, which occupies the central part of the Kostolac Basin (closed opencast mine Cirikovac), Klenovnik (closed opencast mine Klenovnik) and the western part of the Kostolac Basin (Smederevsko Pomoravlje), which occupies the western part of the basin, from the Velika Morava river until the border with the Cirikovac deposit (Figure 4).

The coal from the Kostolac basin, or more accurately, from the opencast mine Drmno, is used for combustion in the thermal power plants with a continuous operation of four blocks, with total power of about 1000 MW. The total annual output of coal from the Kostolac coal mines is around 10,000,000 t. Coal mining in the Kostolac basin began in 1870, with underground mining. There were 3 underground mines in total, from which coal was mined until 1974. Overburden removal for the opencast mines of the coal basin Kostolac began in 1942, after which coal mining began in 1943.

Figure 4 Opencast mines and overburden dumps of the Kostolac coal basin: Open pit mine Drmno (OPM), OPM Drmno inner dump, OPM Drmno outer dump, City of Kostolac, OPM Klenovnik, OPM Klenovnik outer dump, OPM Cirikovac inner ash dump, OPM Cirikovac outer dump Petka, OPM Cirikovac outer dump Mlava-Mogila, Coal Basin Kostolac West

In accordance with the set methodological approach (Figure 1) and the Mining Law in the Republic of Serbia, all opencast mines of the Kostolac coal basin have a mine closure plan in all phases of project documentation development. The preservation of the environment is mainly reduced to detailed technical and biological recultivation in this documentation. Based on a detailed techno-economic analysis, the area of the closed opencast mine Cirikovac is used for depositing ash from the thermal power plants as an anthropogenic material (Figure 5). After recently adopting the *State Energy Development Strategy until 2035* and the *Strategy for Development of Electric Power Industry of Serbia* has conducted a serious analysis on the realization process for possible renewable energy domains of rehabilitation of the closed opencast mine areas in coal mining basins. For this purpose, a Feasibility Study was made for the construction of a wind farm in the area of outer dumps Drmno, Cirikovac and Klenovnik and gave generally positive results, with an assessment of wind power suitability being 60% - 70% in the Kostolac basin area as given in Figure 5 (publications-irena.org).

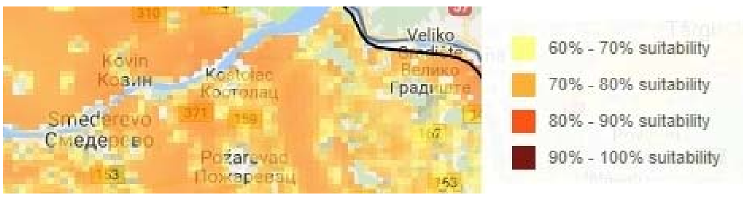

Figure 5 Wind energy suitability in the Kostolac basin

In total, 20 wind turbines with approximately 70 MW are planned to be built, with an investment of about 140 million euro. There will be 7 turbines located at the outer dump of the Drmno mine, 3 wind turbines at the Cirikovac mine outer dump Petka, 4 wind turbines at the Cirikovac mine outer dump Mlava-Mogila, and 6 wind turbines at the Klenovnik mine outer dump.

For the active opencast mine Drmno, whose closure is expected in 2054, the Prefeasibility Study is being prepared in order to consider possible options for the sustainable use of the inner dump space.

4.1 The closure of opencast coal mine Klenovnik

Coal mining at the opencast mine Klenovnik began in 1973 and ended in 2009. In this period, about $9*10^6$ t of coal have been excavated and about $48.1*10^6$ bm^3 of overburden. The long delay of its rehabilitation realization increased the likelihood of risks, so that the planned Probabilities of risk occurrence due to security endangerment and Probabilities of risk occurrence due to imperil of environment and community interests, were within limits of the MEDIUM RISK *(Consequences - Minor (K_2 = 2)*Probability - Possible (K_8 = 3) = 6)* (Table 3).

The planned operations on the field related to the technical reclamation, after the completion of the working phase, include additional planning for the outer and inner dump sites, since the majority of works on the geometric design of space was completed during mining (Faculty 2011).

Technical and biological reclamation of the opencast mine Klenovnik was partially implemented. It was reclaimed for about 80% of the outer dump site area beside the Drmno-Kostolac road. Reclamation and landscaping of the opencast mine depression and inner dump site have remained. Reclaimed areas in the opencast mine Klenovnik occupy 684,000 m^2, i.e. about 33% of the total area.

Within the reclaimed and arranged regions, it was determined to establish a Mining Museum. This can be accomplished by rational reuse of the existing headquarter building of the opencast mine Klenovnik and landscaping the area around the headquarter building to accommodate exhibits (continuous and discontinuous mining machines). The aim is to preserve the technical and technological heritage, education and the promotion of tourist offer in conjunction with the archaeological complex Viminacium.

Based on the existing situation on the opencast mine Klenovnik, with the conceptual reclamation solution and spatial arrangement of the existing exploitation field of mine Klenovnik, an area of 2,089,900 m^2 (opencast mine and inner dump site: P_1 = 1,235,100 m^2, outer dump site P_2 = 854,800 m^2) is covered.

Comparing the opencast mine Klenovnik time of closure to the time of the end of coal mining, it is clearly concluded that the reclamation in condition E_2, with a probability P_2 (Figure 3), is when it represents an extreme ecological situation, that is, when endangering the environment exceeds the permitted time limits. Transition from condition E_0 to E_1 happened over the period of 24 months, while condition E_1 to E_2 happened over a period of 12 months. Transition from condition E_2 to E_1 with probability P_1 is scheduled for 8 months, and from condition E_1 to E_0 with a probability P_0, subsequent 10 months. The calculated probability values are provided in Table 4.

Table 4 Probabilities of the planned reclamation conditions on opencast mine Klenovnik

Condition/Probability	**E_0/P_0**	**E_1/P_1**	**E_2/P_2**
Probability	0.588	0.247	0.165

The conditionally normal situation (E_0 and E_1 conditions) of the existing reclamation system has a high probability of realization (84%), and it is necessary to undertake relatively few activities to ensure the planned dynamics.

The concept of spatial arrangement is based on the valorisation of the newly emerging natural and anthropogenic conditions, method of technical and biological reclamation and dynamic of rehabilitation and landscapes planning implementation.

According to the new project of building a wind farm, 6 wind turbines are supposed to be built on the eastern part of the outer dump Klenovnik (Figure 6).

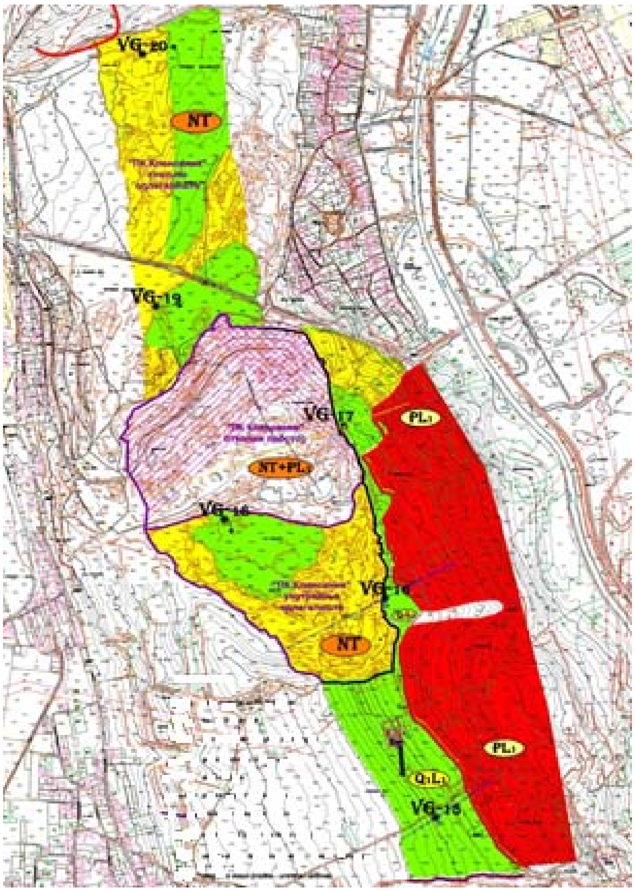

Figure 6 Opencast mine Klenovnik outer dump with the locations of the 6 wind turbines (VG 15, 16, 17, 18, 19 and 20)

Bearing in mind the specificity of the examined outer dump, which is an anthropogenic product, and the conditions of its formation, it is concluded that it has complex hydrogeological conditions.

For the purpose of examining the sites for the planned wind turbines, 4 piezometer installations were built, with groundwater being registered only at VG-20, where the level was measured at a depth of 5.60 m. Considering the structure of the location and the spatial position, the water in question is soil retained water, i.e. that this measured groundwater level is actually a locally retained water in a slightly clayey, waterproof environment (Geoput 2016).

The analysis of the conditions for the occurrence of liquefaction at this location has shown that there is no potential for the occurrence of liquefaction, and according to the indicators of the consequences and probability of the events and in relation to other geomechanical factors, the realization of this project has MEDIUM RISK (Consequence - Moderate (K_3 = 3)*Probability - Unlikely (K_7 = 2) = 6) (Table 3).

4.2 The closure of opencast coal mine Cirikovac

Opencast mine Cirikovac was opened in 1973, and mining was finished in 2009, up to when it excavated about $43*10^6$ t of coal and about $166*10^6$ bm^3 of overburden.

There was about $75*10^6$ bm^3 of overburden dumped from the opencast mine Cirikovac to the west outer dump site Petka, about $36*10^6$ bm^3 of overburden to the outer dump site Mlava-Mogila, and about $55*10^6$ bm^3 of overburden to the inner dump site.

The technical reclamation concept of outer dump sites Mlava-Mogila (Figure 9) and Petka (Figure 10) consists of handling and leveling the entire area, while biological reclamation includes planting acacia and black pine on slope surfaces. On the horizontal surfaces, sowing of grass seed mixture is planned, and in the second phase the cultivation of field crops, such as corn, barley, wheat and others.

The long period from termination of mining on the opencast mine Cirikovac significantly increased the probability of risk, so the planned Probabilities of risk occurrence, due to security endangerment, and Probabilities of risk occurrence, due to imperil of environment and community interests, when it comes to outer dump sites Mlava-Mogila and Petka, are within the limits of LOW RISK (Consequence - Insignificant (K_1 = 1)*Probability - Unlikely (K_7 = 2) = 2) (Table 3).

Since the commencement of reclamation is significantly in delay, it is clearly established that the mine was transferred from condition E_0 to condition E_1, with a probability condition P_1, in 26 months, and to condition E_2 with probability P_2, for the next 12 months (Figure 3), while it represents an extreme ecological situation when endangering the environment exceeds the permitted time limits. The transition from condition E_2 to condition E_1 for a period of 8 months is planned, and from condition E_1 to condition E_0 during the next 6 months. The calculated probability values are provided in Table 5.

Table 5 Probabilities of the planned reclamation conditions on opencast mine Cirikovac

Condition/Probability	E_0/P_0	E_1/P_1	E_2/P_2
Probability	0.726	0.164	0.110

A conditionally normal situation of the existing reclamation system has a high probability of realization (89%), and it is necessary to undertake very few activities to ensure the planned dynamics of ash and slag dumping.

The Main mining project for permanent termination of operations at the opencast mine Cirikovac represents a unified whole, with designed solutions of technological organization of the area affected by mining works. Leveling of the mining field terrain, creating slopes and depressions are resolved on the basis of geological structure, engineering-geological conditions of the working environment, disposition of the existing facilities, roads of mining circle and environmental conditions.

After the termination of mining, works were carried out at the opencast mine on preparing the ground for disposal of ash and slag. Excavated opencast mine Cirikovac space is scheduled for ash and slag disposal, up to 92 m of elevation (Figure 7) (Mining Institute 2014). The entire surface of the dump site will be covered with foil, which has the role of protection, in order to prevent the influence of the wind to make ash fly and prevent the penetration of surface water through the dump site. In order to prepare the base for biological reclamation, after the ash disposal, the inner dump will be covered with the last layer of foil.

The disposed material (ash and slag) from the thermal power plant Kostolac B, is handled based on the European regulations in the category of hazardous waste, and therefore it was necessary to provide secure protection that will ensure that the negative impact of the dump site does not endanger human life and the environment.

Based on the recommendations by the European standards in this field (Council Directive 1999/31/EC of 26 April 1999 on the dump site waste 399L0031), after the disposal of ash and slag is completed, protective foil should be set up on the entire dump surface (about 131 ha). The material from the inner dump site is to be disposed over the protective foil, to a thickness of 1.5 m.

The total excavated area of the opencast mine, where ash and slag are dumped, is about 198 ha. The existing inner ash dump of open pit mine Cirikovac is presented in Figure 8. Works on the implementation of this facility are undergoing according to a plan. Probabilities of risk occurrence due to security endangerment and Probabilities of risk occurrence due to imperil of environment and community interests, are within the limits of MEDIUM RISK (Consequence - Major (K_4 = 4)*Probability - Possible (K_8 = 3) = 12) (Table 3).

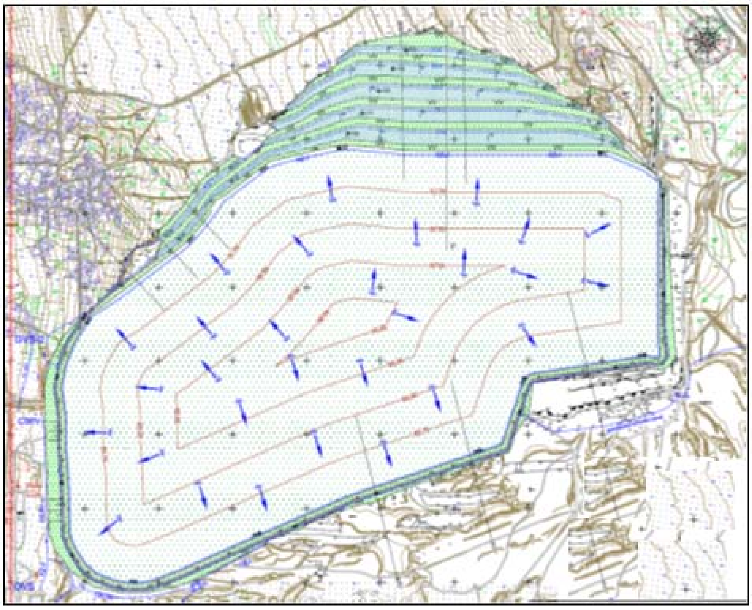

Figure 7 The final layout of Cirikovac inner ash and slag dump

Figure 8 Inner ash dump site of open pit mine Cirikovac

Seedlings of acacia will be planted on horizontal surfaces and indigo plants will be planted on slopes. Biological reclamation will be carried out on the material that has been deposited over the protective foil in two phases, namely: in the first phase grass-legume mixtures will be set, while in the second phase the cultivation of field crops is envisaged. The completion of the ash dump reclamation in the excavated area of the opencast mine Cirikovac will take a long period of time, but at this stage of planning indicate that Probabilities of risk occurrence due to security endangerment and Probabilities of risk occurrence due to imperil of environment and community interests are within the limits of MEDIUM RISK (Consequence - Minor (K_2 = 2)*Probability - Likely (K_9 = 4) = 8) (Table 3).

Comparing the time of the opencast mine Cirikovac remediation completion, with the time of the end of ash dumping, it is clearly concluded that the reclamation in condition $E_{2,}$ with a probability P_2 (Figure 3), is when it represents an extreme ecological situation, that is, when endangering the environment exceeds the permitted time limits. The transition from condition E_0 to E_1 happened over a period of 10 months, while condition E_1 to E_2 happened over a period of 2 months. The transition from condition E_2 to E_1 with a probability P_1 is scheduled for 3 months, and from condition E_1 to E_0 with a probability P_0 the subsequent four months.

The calculated probability values are provided in Table 6.

Table 6 Probabilities of the planned opencast mine Cirikovac ash dumping conditions

Condition/Probability	E_0/P_0	E_1/P_1	E_2/P_2
Probability	0.5	0.2	0.3

The conditionally normal situation (E_0 and E_1 conditions) of the existing reclamation system has a relatively low probability of realization (70%) and it is necessary to undertake a lot of activities to ensure the planned dynamics.

According to the new wind farm construction project, three wind turbines are planned to be built in the western part of the Petka outer dump of the opencast mine Cirikovac (Figure 9) and four wind turbines in the northwestern circumferential part of the outer dump Mlava-Mogila (Figure 10).

Based on the results of the existing research on conditions for the occurrence of liquefaction at the site of Petka, it has been concluded that there is a potential for the appearance of liquefaction in the investigated area with a 19% probability (Geoput 2016). Therefore, even with the great possibility of its appearance and other geomechanical factors, the realization of the project has a permissible MEDIUM RISK (Consequences - Moderate K_3 = 3)*Probability - Likely (K_9 = 4) = 12) (Table 3).

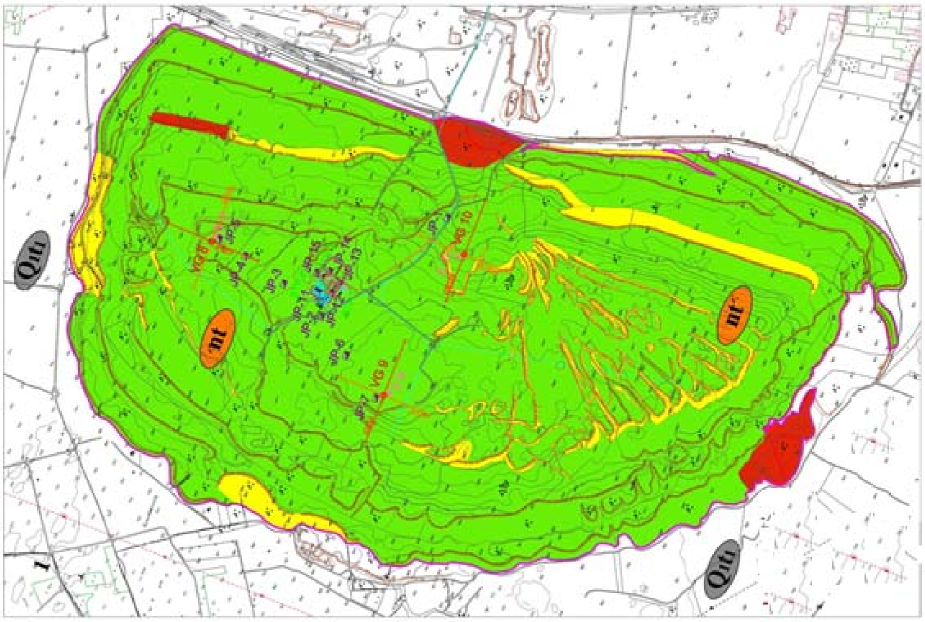

Figure 9 The location of three wind turbines on opencast mine Cirikovac outer dump Petka (VG 8, 9 and 10)

Groundwater was not detected in any exploration well at the Mlava-Mogila outer dump during targeted research at the locations of the planned wind turbines. The analysis of conditions for the occurrence of liquefaction on the site showed a high 14% probability (Geoput 2016). According to the probability of events and index of the liquefaction potential and other parameters, the danger of the project realization is defined as a permissible MEDIUM RISK (Consequence - Moderate K_3 = 3)*Probability - Likely (K_9 = 4) = 12) (Table 3).

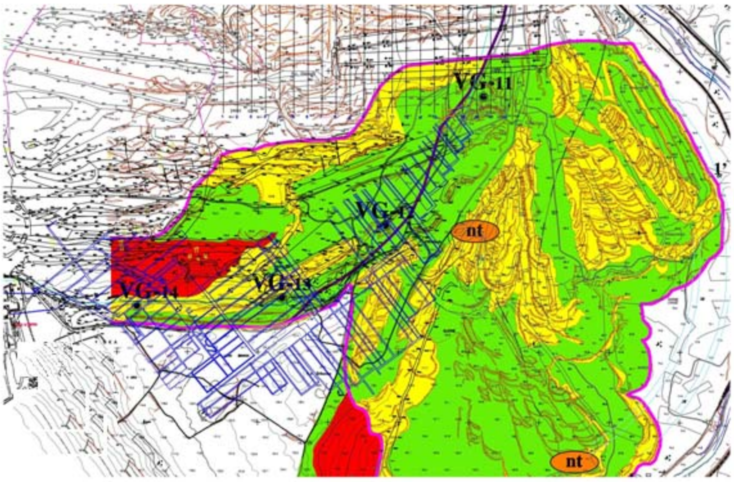

Figure 10 The location of the four wind turbines on the opencast mine Cirikovac outer dump Mlava-Mogila (VG 11, 12, 13 and 14)

4.3 Open pit mine Drmno outer and inner dump site rehabilitation realization

Active open pit coal mine Drmno, operating as a part of Electric Power of Serbia, is located south from the right coast of the Danube, about 110 km east of Belgrade with the annual output of $9*10^6$ tons of coal. Outer dump site is situated east from the Drmno open pit mine, spreading at around 200 ha. Dumping at the outer dump site at the open pit mine Drmno begun in 1983 and was finished in 1997. During that period of time 75,000,000 m^3 of material has been dumped.

At the degraded terrain created by the dumping at the outer dump site of Drmno open pit mine, reclamation has been selected. With that purpose in mind, the dump site was meliorated to a condition that is suitable for agricultural production, meadows and pastures. In this case, the probabilities of risk occurrence due to security endangerment and probabilities of risk occurrence due to imperil of environment and community interests were within the limits of a LOW MEDIUM RISK (Consequence - Minor $K_2 = 2$)*Probability - Unlikely ($K_7 = 2$) = 4) (Table 3).

Existing surfaces have been given a shape that ensures ecologically favourable fitting in of these surfaces with the environment, and conditions have been created for biological reclamation in an extent that the available dumping technology makes that possible. By engineered measures of technical reclamation conditions have been met for the final forming of surfaces of the outer dump. The preparation of the dump for the biological reclamation was done through leveling horizontal and slightly inclined surfaces with the appropriate slope for water leakage. Reforestation was planned for the bigger angle slopes. Reclamation was completed in five years.

Reclamation of the outer dump site of opencast mine Drmno has been done in the period between 2006 and 2010 (Faculty 2004). Throughout the reclamation works, the terrain weather and technological parameters have been monitored as to have an eco-control of the completion and planning possibilities. Very high probabilities of the reclamation system operation have been achieved in this period. The condition of the complete extreme ecological situation happened in 2008, which led to emergency measures for sanitation of the eco-system of the outer dump site in 2010. These measures have enabled the realization of the functioning system with a probability of 99%, so all the planned works have been successfully completed on schedule in 2010, with the reclamation of the remaining 112,500 m^2 dump site surface.

According to the new project of building a wind farm, it is planned to build 7 wind turbines on the peripheral parts of the opencast mine Drmno outer dump (Figure 11). In this way, the level of sustainable and economically justified utilization of the finished outer dump Drmno will be significantly increased.

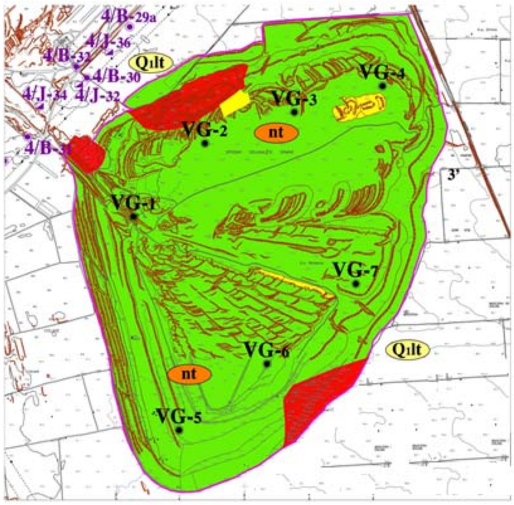

Figure 11 The location of the seven wind turbines on the opencast mine Drmno outer dump (VG 1, 2, 3, 4, 5, 6 and 7)

During the targeted research at the locations of planned wind farms, groundwater was only discovered in the exploratory well of VG-2 in which a piezometer is installed. The groundwater is located in this well at a depth of 9.9 m (Geoput 2016).

Within the existing documentation, an analysis of the liquefaction potential of the subject area was also performed. Based on the results of the existing research on the conditions for the occurrence of liquefaction at the location of the opencast mine Drmno outer dump site, it has been shown that there is no potential for the occurrence of liquefaction. Because of this and other geomechanical parameters, the risk of construction realization is defined as a MEDIUM RISK (Consequence - Moderate (K_3 = 3)*Probability - Unlikely (K_7 = 2) = 6) (Table 3).

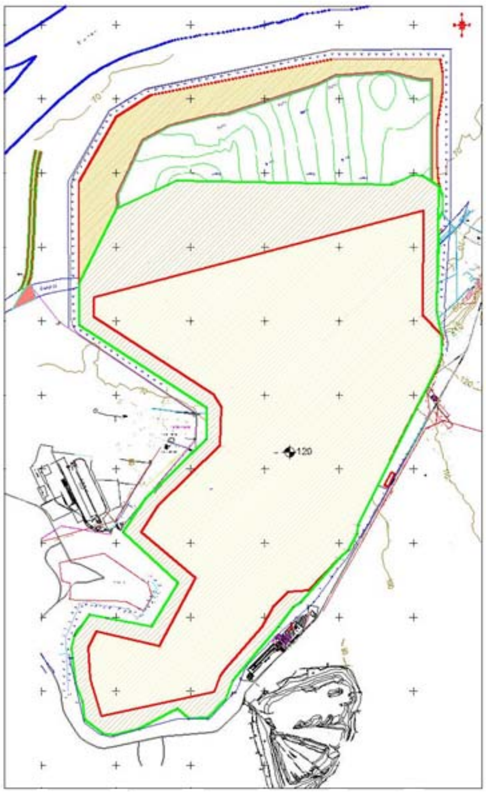

Figure 12 Final contour of the opencast mine Drmno with the inner dump in 2054

The end of coal mining and the formation of a complete inner dump on the Drmno opencast mine was predicted to be in 2054 (Figure 12). The final formation and reaching the final height of the inner dump from the south to the Drmno village has been predicted to be executed by 2030, including technical and biological recultivation. The production of cassettes for the disposal of technogenic raw materials (namely gypsum from 2020 and ash from 2025) from the thermal power plant, is planned in the western part of the inner dump. A definitive solution for the rehabilitation and sustainable use of space for the total area of the dump of about 30 km^2 is expected by 2020 with the development of the Feasibility Study.

4 Conclusions

The planning of coal mines closure begins with preliminary closure planning and ends with the establishment of a self-sustaining ecosystem. This concept achieves satisfying effects in the environment. It should start at an early stage during development of prefeasibility study. It’s continued throughout the whole project design, while always attaining obligatory permits. The realization of mining closure projects needs to constantly adapt to possible strategic alterations. Planning ensures that closure process is performed viable, cost-effective and timely with constant monitoring of the Probabilities of risk occurrence due to imperil of environment and community interests.

From the standpoint of risk and more efficient environment, reclamation is essential, as well as constant monitoring of biological and technical reclamation and sustainable land domain plan implementation. The proposed risk and reclamation eco-control models enable optimization of work dynamics upon engineering, but they’re also very important for auditing the completion of the mine and dump reclamation in time and space, as well as rehabilitation domain processes. This enables accurately timed interventions and complete control of the reclamation project from the aspects of normal, tolerated, deteriorative and extreme conditions of a reclamation system.

When it comes to opencast mines closure realization, which is conditioned by physical, ecological, natural, technical or economic constraints, the process of opencast mines closure can be planned, unplanned or temporary. Opencast coal mines in the Kostolac basin where coal mining is completed provide excellent examples of planned closure. The planned activities on the realization of the project solutions for the technical and biological recultivation of the final dump contours are in the finishing phase. Subsequently, additional techno-economically justified projects for the formation of ash dumps on the opencast mine Cirikovac, as well as the construction of a wind farm on stabilized outer dumps in accordance with the state strategies of energy development and Electric Power of Serbia have been initiated.

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Regulation on Mine Closure in Indonesia

RS Gautama *Bandung Institute of Technology, Indonesia*

J Sudrajat *Ministry of Energy & Mineral Resources, Indonesia*

Abstract

Modern mining activities in Indonesia just started in the late 19th century during Dutch colonial time. Important milestone of mining during that time was the start of coal production from an underground coal mine in Sawahlunto area in West Sumatra, wellknown as Ombilin Coal Mine in 1892 following a massive infrastructure construction work including 155 km railway track from Padang port to Sawahlunto. The first half of 20th century was characterized by the era of mining development. Some important mines had been developed to extract tin, coal, gold, nickel and bauxite ores. After being slumped for almost 50 years, significant resurrection started again in 1980s with steadily increasing of mining production. Recently Indonesia is among important producer of several mining product such as steam coal, nickel and copper ores.

As a relatively young mining country Indonesia does not have many experiences in dealing with mine closure. When tin mining activity in Singkep island was stopped in early 1990s due to the crash of tin price, there was no regulation on mine closure at that time. The unplanned mine closure in Singkep island generated significant economic and social impacts to the area. Although regulation on mine reclamation has been issued in 1995 that introduced the concept of mine reclamation guarantee, first comprehensive regulation on mine closure was just enacted in 2008. It was the decree of the Minister of Energy and Mineral Resources no. 18 year 2008 on mine reclamation and closure. There was the obligation of the existing mines to develop the 5-yearly mine reclamation plan and mine closure plan.

Then a new mining law no. 4 year 2009 was being issued and mine reclamation and mine closure was included in the law which was followed by government regulation no. 78 year 2010 that describes more detail on mine reclamation and mine closure. According to these regulations mine closure plan is required when a mine will apply for production stage together with technical & economic feasibility study and environmental impact assessment. New guideline on mine reclamation and mine closure is just being issued this month in the form of Ministerial decree no. 26 year 2018 and Ministerial regulation no. 1827 year 2018. This paper will describe the history of mine closure regulations in Indonesia including the scope and requirements for mining companies in Indonesia and some mine closure cases.

Keywords: *mine closure regulation, reclamation guarantee, mine closure guarantee*

1 Introduction

Indonesian archipelago lies in one of the most complex active tectonic zone on earth where Euro-Asian lithospheric plate collide with the northward-moving Indo-Australian and the westward-moving Pacific plates (see figure 1). This regional geological setting blesses Indonesia with abundant of mineral resources. Presently Indonesia is recognised as significant player in global mining industry with significant production of coal, copper, tin and nickel. Indonesia also continues to one of the world's largest exporters of thermal coal (pwc, 2017).

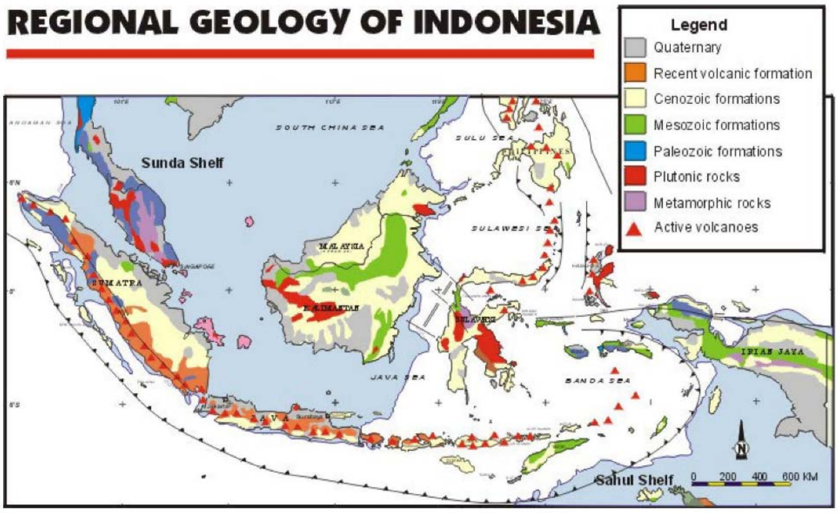

Figure 1 Regional geology of Indonesia (Daman & Sidi, 2000)

In fact, the history of modern mining industry in Indonesia started in the 19th century although tin from Banka island had been one of commodities of the ancient kingdom of Sriwijaya in the 8th century in their trade relation with China. Unfortunately there are only limited written information about tin mining activities during that time. The activities to explore the mineral resources in Indonesia started in the 1850s during Dutch colonial era. One of significant findings was the coal deposit in Sawahlunto (West Sumatra) which came into production in 1892 after a massive infrastructure construction such as railway from Padang port approximately 155 km. This mine, well known as Ombilin coal mine, is in the process of closure. The first half of 20th century was the time of development of mining of various minerals such as coal, tin, gold, bauxite and nickel. Some of these mines are still in operation with much larger scale of operation. Some of them, especially gold and bauxite mines, have been closed due to the exhausted deposit.

The period of 1942 to 1970 was the gloomy period of Indonesia mining industry. The production of most mineral products decreased significantly, mostly because of lack of capital and expertise. The new order in the governmental system in 1966 and the mining law of 1967 was the turning point of mining industry with the openness to international mining companies to operate in Indonesia. Since 1990 production of ore and coal increased steadily and at present Indonesia is among the important global players in coal, tin, nickel and copper.

As a relatively young mining country, Indonesia has not many mine closure cases which generate significant impacts to the local society. Most cases are related to small scale mining activities such as quarry of construction material. Following the global trend on the importance of mine closure management, the government of Indonesia realised that regulations on reclamation and mine closure should be developed. Since most of the mines in Indonesia are surface mines, the regulations are integrating the mine land reclamation and mine closure.

2 Chronology and scope of regulations on mine reclamation & closure

It was in 1982 when Indonesian **environmental law no. 4 year 1982** was enacted which stated the obligation of every business activity to identify, mitigate and manage its environmental impacts. The implementation of that law was government regulation no 29 year 1986 on environmental impact assessment study, environmental management plan and environmental monitoring plan. Since mining is one of activities with potential environmental impacts, in 1995 the **Minister of Mines & Energy** issued the **decree no. 1211 year 1995** on prevention and mitigation of environmental impacts of mining activity. This decree introduced the importance of mine reclamation as the activity to rehabilitate the disturbed area caused by mining as well as post mining as the period after mining activity ceases and ex-mined land relinquishment.

The decree underlined the obligation of every mining company to submit the annual environmental management plan, which consisted of land use plan, techniques & methods, work schedule, area to be reclaimed, type of vegetation and estimated budget, and introduced reclamation guarantee. There was also the obligation to submit mine closure plan one year before the mining stopped or the expiration date of mining license. More detail technical guideline on reclamation guarantee was described in the **decree of Director General of Mines no. 336 year 1996**. Reclamation guarantee is defined as guarantee fund for reclamation provided by the mining company and approved the government. It is based on the reclamation budget as stated in the 5-year reclamation plan and already includes the cost for third party to do the work if the mining company fail to fulfil its obligation to do reclamation. The reclamation cost component consists of direct cost and indirect cost. Direct cost should include cost for demolition of mine infrastructure, land preparation, revegetation, acid mine drainage prevention and mitigation, and civil works. Indirect cost is actually cost for the third party and includes cost for equipment mobilisation and demobilisation, planning and design as well as administrative cost and third party's profit.

The reclamation guarantee shall be put in the bank in the form of time deposit in national bank and under the name of Director General of Mines of Department of Mines & Energy qq the mining company, or irrevocable letter of credit or bank guarantee, or accounting reserve for public company with own capital more than US$ 25 million. The fund can be withdraw by the company in stages (60%, 20% and 20%) after the implementation being reviewed by the government.

There were lot of changes in Indonesia in early years of 21st century. Regional autonomy policy, as regulated in local government law of 1999, decentralised many governmental affairs including in mining sector. The authority to issue mining permit has been handed over from central government to the local government at regency level. The environmental policy was also influenced by the global trend as the results of earth summit in Rio de Janeiro in 1992 and world summit in Johannesburg in 2002. During that time two gold mines and one coal mine operated by international companies were ceased in 2002 and 2004. On the other hand mining activity increased significantly in term of number of mines as well production level and appropriate regulation was necessary. **Decree of Minister of Energy and Mineral Resources no. 18 year 2008** on mine reclamation and closure was signed in June 2008.

This decree introduced the principles in conducting reclamation and mine closure which consisted of environmental principles, occupational health and safety principles and mineral conservation principles. The environmental principles covers:

a. The quality of surface water, groundwater, sea water, and land as well as air should comply to the environmental standards
b. Stability and security of waste rock dumps, tailing dams, ex-mined land and other man-made structures
c. Biodiversity
d. The use of ex-mined land according to the designated land use
e. Social, cultural and economic aspects

Five year reclamation plan should consist of:

a. Land use before and after mining
b. Land clearing and opening plan
c. Reclamation program
d. Reclamation budget

The approved reclamation plan should be revised if there are changes in mining method, land use, spatial plan or environmental feasibility. The concept of reclamation guarantee was the same with the previous regulations, only one addition of fund deposit scheme which include the insurance issued by state owned bank or Indonesian branch of foreign bank.

More detail description in that decree was related to mine closure. Mine closure plan that should be submitted by the mining company when applying the operational permit should consist of:

a. Profile of the mining area

b. Description of mining activity
c. Post mining condition
d. The results of public or stakeholder consultation
e. Mine closure program
f. Monitoring program
g. Organisation
h. Mine closure budget

The approved mine closure plan should be revised when there are changes in mining method, life of mine, mining facility and infrastructure, land use, spatial plan or environmental feasibility. The latest revision will be two years before mining stops.

Post mining guarantee is defined as fund provided by the company to conduct mine closure program to achieve the agreed success criteria. Mine closure budget is calculated according the following:

a. Direct cost, which include
    a. Demolition of buildings and infrastructure
    b. Reclamation of ex-mined land, processing facility and supporting facilities
    c. Management of hazardous material and waste
    d. Maintenance
    e. Monitoring
    f. Social, cultural and economic aspects
b. Indirect cost:
    a. Equipment mobilisation and demobilisation
    b. Design and planning work
    c. Budget for administrative work and third party's profit
    d. Supervision

The post mining guarantee should be put in the bank with the scheme of time deposit that will be valid until the whole mine closure program has been completed. It was also introduced the scheme for instalment of post mining guarantee.

In 2009 new **mining law no. 4 year 2009** was enacted. The obligations of mining permit holder are:

a. Implementation of good mining practice
b. Financial management according to Indonesian accountancy system
c. Increase the added value of mineral and/or coal
d. Implementation of community development and empowerment
e. Comply with the environmental support capacity

Good mining practice includes the following aspects:

a. occupational health and safety
b. mining safety & security
c. environmental management and monitoring including reclamation and mine closure
d. mineral and coal resource conservation
e. mining waste management

Then **government regulation no 78 year 2010** on mine reclamation and closure was issued as the implementation of law no 4 2009. This government regulation was in fact re-writing the concept of reclamation and mine closure as described in the decree of Minister of Energy and Mineral Resources no. 18 year 2008 with some adjustment and aligning with mining law no 4 year 2009. In this regulation the environmental principles include at least:

a. the protection of surface water, groundwater, seawater, land and air quality to comply with the environmental standards according to the law
b. protection and rehabilitation of biodiversity
c. assurance of stability and safety of waste rock dumps, tailing dam, ex-mined land and other man-made structures

d. use of ex-mine land in line with its designated land use
e. consider the local social and cultural values
f. protection of groundwater quantity

Occupational health & safety principles include:

a. protection of worker's safety
b. protection of worker from occupational illness

Conservation principles include:

a. optimum mining
b. effective and efficient mineral/coal processing technology
c. optimize the marginal deposit, low grade mineral and coal
d. un-mined mineral and coal resources inventory

The mine closure plan should cover following aspects:

a. profile of the mining area: location, accessibility, ownership and designated land use, initial environmental setting and other activities in the surrounding
b. mining activity description: initial reserve, mining method, processing, and support facilities
c. post mining final environmental condition: residual deposit, land use, morphology, surface and groundwater, aquatic and terrestrial biology
d. post closure program:
    a. reclamation on ex-mined land and land outside mining area
    b. maintenance of rehabilitation area
    c. community development and empowerment
    d. monitoring
e. organisation and implementation schedule
f. post mining success criteria
g. estimated mine closure budget

In the development of mine closure plan, the mining company should consult the central and local governments and the community.

Regarding reclamation guarantee, there are four schemes in the government regulation no 78 year 2010, namely escrow account in state owned bank, time deposit in state owned bank, bank guarantee and accounting reserve. Post closure guarantee could only be put in the form of time deposit in state owned bank.

Technical guideline for reclamation and mine closure to give more clarification on matters in the government regulation no 78 year 2010 was issued in the form of decree of Minister of Energy and Mineral Resources no. 7 year 2014. This decree replaces the decree no 18 year 2008. Recently the **Minister of Energy and Mineral Resources** just issued **decree no 26 year 2018** on implementation of good mining practice and supervision of mineral and coal mining to integrate all aspects of supervision of mining activity that previously are scattered in various decrees and regulations. Mine reclamation and closure is included in that decree to replace the decree no. 7 year 2014.

In this new guideline, reclamation plan should also describe the success criteria both in the form of revegetation and other form of reclamation proposed by the mining company, such as settlement, tourist, water resources or cultivation area. There is also revision in the criteria for company who is eligible to put its reclamation guarantee in the form of accounting reserve. The company should be listed in Indonesia Stock Exchange at least 40% of the total shares, or paid-up capital more than US$ 50 million.

Related to mine closure plan, budget for community development should be aimed to increase the entrepreneurship of the community to maintain the economic condition of the area. And mine closure budget should be calculated in future worth refer to government obligation rate in Indonesian Rupiah or in US Dollar.

The summary of regulations related to mine reclamation and closure is shown in Figure 2. And the instalment scheme of mine closure guarantee is shown in Table 1.

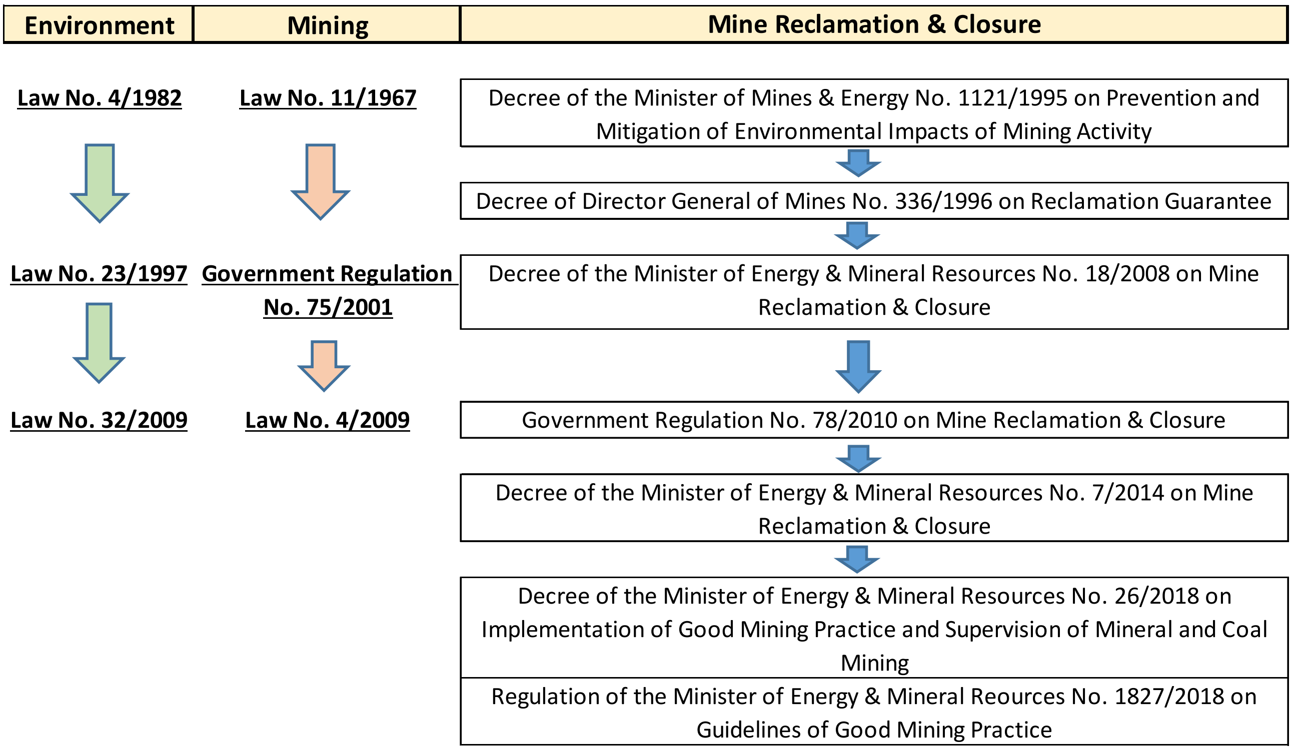

Figure 2 Summary of regulations on mine reclamation & closure

Table 1 Instalment scheme of mine closure guarantee

Life of mine (years)	Year #1	Year #2	Year #3	Year #4	Year #5	Year #6	Year #7	Year #8	Year #9	Year #10	Year #11	Year #12	Year #13	Year #14	Year #15	Year #16	Year #17	Year #18	Year #19	Year #20
1	1.000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	1.000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	1.000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	0.500	0.500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	0.111	0.333	0.556	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6	0.063	0.187	0.313	0.437	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7	-	0.063	0.187	0.313	0.437	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	-	0.030	0.123	0.180	0.300	0.367	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	-	0.028	0.030	0.102	0.173	0.300	0.367	-	-	-	-	-	-	-	-	-	-	-	-	-
10	-	0.020	0.028	0.040	0.092	0.153	0.300	0.367	-	-	-	-	-	-	-	-	-	-	-	-
11	-	-	0.020	0.055	0.095	0.163	0.177	0.225	0.265	-	-	-	-	-	-	-	-	-	-	-
12	-	-	0.016	0.020	0.050	0.090	0.157	0.177	0.225	0.265	-	-	-	-	-	-	-	-	-	-
13	-	-	0.012	0.016	0.020	0.050	0.088	0.147	0.177	0.255	0.235	-	-	-	-	-	-	-	-	-
14	-	-	0.010	0.030	0.050	0.063	0.080	0.100	0.130	0.150	0.180	0.207	-	-	-	-	-	-	-	-
15	-	-	-	0.010	0.030	0.050	0.063	0.080	0.100	0.130	0.150	0.180	0.207	-	-	-	-	-	-	-
16	-	-	-	0.009	0.027	0.045	0.057	0.073	0.091	0.118	0.136	0.164	0.188	0.092	-	-	-	-	-	-
17	-	-	-	0.008	0.025	0.042	0.053	0.067	0.083	0.108	0.125	0.150	0.173	0.083	0.083	-	-	-	-	-
18	-	-	-	0.008	0.023	0.038	0.048	0.062	0.077	0.100	0.115	0.138	0.159	0.077	0.077	0.078	-	-	-	-
19	-	-	-	0.007	0.021	0.036	0.045	0.057	0.071	0.093	0.107	0.129	0.148	0.071	0.071	0.071	0.073	-	-	-
20	-	-	-	0.007	0.020	0.033	0.042	0.053	0.067	0.087	0.100	0.120	0.138	0.067	0.067	0.067	0.067	0.065	-	-

Source: Regulation of the Minister of Energy & Mineral Resource No. 1827 year 2018

3 Discussion

In this section we will discuss the important mine closure cases which more or less influenced the development of regulation related to mine closure. Current status related on mine closure supervision by the Ministry of Energy & Mineral Resources will also be discussed.

Case #1: Tin mining in Singkep island

Modern tin mining operation in Singkep island started in the early 20th century during the Dutch colonial period. After the Indonesian independence in 1945 the mining operation in Bangka, Belitung and Singkep islands became mining operation area of the state owned tin mining company, PT Timah. This company became the main economic and social machine to the areas. Most of the public infrastructure were provided by PT Timah including hospital and electricity. When tin price crashed from approximately US$ 16,000/ton in 1981 to only US$ 5,500 in October 1985, tin mining companies in most tin countries, including PT Timah, suffered significantly. It was the decision of the management and approved by the government to reduce the workforce significantly and some of its mining activities. The most important decision was to reduce the mining activity in Singkep island. As much as 2,400 workers were being laid off which of course changed the local economic and social condition drastically. The total pull out was happened in 1993 and during 1990 and 1996 Singkep island experienced a negative population growth of -1.54% because many people migrated outside the island to find a better opportunity. There were also environmental issues when the mining activity stopped in the form of pit lakes. Tin being mined in Singkep was mainly alluvial placer deposit and the mining method was hydraulic mining. When PT Timah decided to totally stop its operation in Singkep island in January 1, 1993 there was no regulation related to mine closure. Therefore the impacts were not properly managed, especially the social, cultural and economic impacts.

Case#2: Gold mines in East Kalimantan and North Sulawesi

PT Kelian Equatorial Miing (PT KEM) owned by Rio Tinto and its local partner was operating gold mining activity in Kelian area, East Kalimantan under contract of work scheme with the Indonesian Government signed in 1985 with an area of 286,233.5 hectare. The production started in 1991 with on average production level of about 15 tonnes of gold and 13 tonnes of silver annually from a single open pit. Having approximately 53 million tonnes of gold ore, pit operations were completed in 2003 but the activity continued to process low grade ore stockpiles until mid-2004. Being a part of Rio Tinto mining, mine closure of this mine had been prepared thoroughly. McGuire (2003) underlined the key risks for mine closure were long-term management of permanent structures such as dam, spillways and waste dumps, acid rock drainage management, achievement of environmental closure standards, orderly retrenchment of employees as well as relinquishment of the sites. The Kelian Mine Closure Steering Committee consisted of PT KEM, Rio Tinto, community and government representatives had been developed. Every aspects including environmental, social and economic aspects had been considered in mine closure plan and approved by the stakeholders. The implementation had been thoroughly supervised and reported to the government.

Another case is a gold mine located in North Sulawesi owned and operated by PT Newmont Minahasa Raya under contract of work with Indonesian government. The gold production started in 1996 and in 2001 mining activity ceased because the ore deposit was exhausted. The activity was continued to process the ore stockpile until 2004. Mine closure plan was approved by the government in 2002. Stakeholders consisted of central government, local government, local community were involved in the development of mine closure plan and the company committed to be responsible to the success of its mine closure with a more stringent standard criteria. Several teams had been appointed: team to monitor the mine closure process, asset assessment team, and team to review the success of forest reclamation.

Case#3: Coal mine in Kalimantan

The Petangis coal mine in East Kalimantan commenced operations in 1993 and operated until 2002. The average production was one million tonnes of coal per year. This mine was operated by PT Kendilo Coal Indonesia, a subsidiary of PT BHP Billiton Indonesia. Total mining area, consisting 7 pits, were 613 ha. Mine closure program focused on revegetation of disturbed ex-mine land. The company, together with local government, conducted program to transform the ex-mined area into forestry area which also included water tourism facility, forestry research centre and cultivation area for local deer and aquatic biota.

During the closure of both gold and coal mines the only regulation of mine closure was decree of the Minister of Mines & Energy no. 1121 year 1995 which only stated the obligation to submit mine closure plan one year before the mining stopped. The process and practices proposed by both mining companies became best lessons-learned for the government, both central and local, in managing the mine closure issues to be considered in the development of mine closure regulation.

Current condition

The authority to issue mining permits and to supervise the mining activity is on the hand of local government at provincial level according to governmental law no. 23 year 2014 after more than 10 years under the regency level since 2001. It was the period when thousands of mining permits had been issued and the period of lack of supervision. At present the central government supervise only the mining permits with the scheme of contract of work (for ore mining, COW) and coal contract of work (CCOW) as well as special mining permit (IUP). Currently the total mining activities under supervision of central government are 219 companies that consist of 171 companies already in operation-production stage and 48 companies in exploration stage. From total 171 companies in operation-production stage, only 85 companies or 50% already have approved mine closure plan, distributed into 10 COWs, 49 CCOWs, 12 IUP for mineral and 14 IUP for coal.

The picture on the local governmental level is even worse since there are more than 6000 mining permits in Indonesia and totally only 285 mine inspectors to supervise and monitor the mining activities. At the moment there are 183 inactive or left over mined out voids covering an area of 3225 ha. These are among other the challenges for the government, especially the ministry or mining office in local government, to properly supervise and monitor the mining activities under their authority to fully comply with the good mining practice as stated in the laws and regulations. Mining activity should bring benefit, both financial benefit as well as intangible benefit in term of social, cultural and economic development of the surrounding communities, not only during operation but also after the mining stops.

4 Conclusion

Indonesia has only limited experiences in dealing with mine closure. Lessons learned from important mine closure cases in 1990s and 2000s and of course from other countries were the basic consideration when developing first comprehensive regulation on mine reclamation and closure in 2008. The improvements of regulations in recent years are actually to harmonise with other related laws and regulations. It is the challenges to the government (central & provincial) to supervise and monitor the implementation of regulation on mine reclamation and closure by the mining companies since there are more than 6000 mining licenses or permits distributed in all part of Indonesian archipelago.

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Landscape and Visual Considerations in Mine Closure – An International Overview

SJ Higson *SLR Consulting, England*

T Paul *SLR Consulting, Ireland*

A Merkle *SLR Consulting, Ireland*

Abstract

Consideration of the potential landscape and visual effects associated with development is an established part of international Environmental Impact Assessment (EIA) and the global mining industry has published commitments and guidelines relating to the environment, local communities and sustainability. This paper will provide an overview of the landscape and visual considerations, including the technical and regulatory background, in the context of mine closure.

The paper will describe the main ways of determining landscape and visual opportunities and constraints for mine closure planning, from initial conceptual stages, through to detailed operations/phasing, decommissioning and reclamation/ rehabilitation. Mitigation measures to avoid, reduce or minimise landscape and visual effects will also be discussed.

Potential landscape effects will typically occur upon individual elements and features within the site itself, aesthetics or perceptual aspects, overall character and key characteristics. Visual amenity and effects upon views of offsite receptors in the immediate surrounding area will often include people living in the area (local residents and communities), people who work there or passing through on road, rail or other forms of transport, as well as people visiting promoted landscapes or attractions (tourism) and people engaged in recreation of different types (leisure). Selection of representative public viewpoints will usually inform the design and assessment process.

Mine closure projects need to consider the location and appearance of above ground equipment and structures, buildings and services, final pit voids, potential waste dumps and tailings dam, as well as any water or sewage treatment facilities and power and infrastructure connections. This would include loss and (re)placement of vegetation, watercourse and access, visual exposure and/or strategic screening, directions of working / stockpiling. Proposed post closure land-use and preferred character for the restored landscape should also be considered after removal of infrastructure and services, grading of landforms, soils and substrate, conforming to the character of the local area in terms of scale, colour and texture, pattern, etc., and return of land to a stable and productive condition.

This paper will also showcase the latest geo-spatial mapping and analysis technologies, computer generated modelling, imaging and presentation techniques for stakeholder engagement and those receptors potentially affected by the process or outcome of mine closure. This will include examples of virtual reality modelling, visualisations and photomontages.

Keywords: *landscape, visual, aesthetics, EIA, mine closure*

1 Introduction

Consideration of the potential landscape and visual effects associated with proposed development is an established part of international Environmental Impact Assessment (EIA) and the global mining industry has published commitments and guidelines relating to the environment, local communities and sustainability.

Whilst mining operations are usually temporary in nature, as reserves are won and worked through, the mine closure phase (when operations cease and infrastructure is no longer required) will usually represent the main legacy for an area and its people. Taking into account landscape character, aesthetics and / or views and visibility at this stage (alongside other environmental and human health and safety issues) is an important aspect of achieving sustainable mining development.

This paper sets out the technical and regulatory background to landscape and visual assessment and how such considerations should be included within a mine closure plan.

The main ways of determining landscape and visual opportunities and constraints for mining closure planning are described, covering the various stages likely to be undertaken. Landscape architects, with the help of the latest computer-generated mapping, modelling and presentation techniques can help identify those receptors potentially affected by the process or outcome of mine closure and contribute positively to stakeholder engagement procedures.

2 Technical and Regulatory Background – Landscape as part of the Environment

The United Nations' 2030 Agenda for Sustainable Development sets out 17 goals relating *inter alia* to economic growth and human settlements, agriculture, infrastructure and energy, land, water and biodiversity (United Nations, 2015). A principle-based approach to environmental challenges is advocated, such as promoting greater environmental responsibility and encouraging the development and diffusion of environmentally friendly technologies.

The published plan of action follows several international conventions and initiatives which commit Member States' governments *inter alia* to assess development activities that are likely to have a significant adverse impact on the environment, such as Principle 17 of the Rio Declaration on Environment and Development (United Nations, 1992).

The Equator Principles III are the latest version of the financial industry benchmark for determining, assessing and managing environmental and social risk and which have been adopted by a number of international financial institutions. The aim of these principles are to ensure that major projects are developed in a manner that is socially responsible and reflect sound environmental management practices (Equator Principles Association, 2013).

2.1 General Landscape and Visual Matters

In technical terms, the concept of "environment" has evolved from an initial focus in the 1960s on purely biological or physical components, to a wider definition of the total environment and topics such as cultural heritage, socio-economics and tourism and, in particular, the landscape (IAIA, 2009). For example the New South Wales Government defines the environment as "*all aspects of the surroundings of humans, whether affecting any human as an individual or in his or her social grouping*" (NSW Government, 2016).

The European Landscape Convention which came into force on 1 March 2004 promotes the protection, management and planning of European landscapes and organises European co-operation on landscape issues. Under Article 1, the term landscape is defined as:

> *"a zone or area as perceived by local people or visitors, whose visual features and character are the result of the action of natural and/or cultural (that is, human) factors. This definition reflects the idea that landscapes evolve through time, as a result of being acted upon by natural forces and human beings. It also underlines that a landscape forms a whole, whose natural and cultural components are taken together, not separately." The Council of Europe (2000)*

The United Nations Environment Programme lists landscape as one of the issues that should be considered during the assessment of likely significant effects for proposed development (UNEP, 2004). Similarly the

World Bank Guidelines identify aesthetic value as part of cultural property (World Bank, 1991 and subsequent updates) and the International Finance Corporation (IFC) identify the creation of potential visual impacts (including light) as a component of pollution (IFC, 2012).

In relation to the mining sector, the IFC / World Bank Group's Environmental, Health and Safety Guidelines for Mining describe how surface mining activities may result in negative visual impacts to resources associated with other landscape uses, such as recreation or tourism (IFC, 2007). Robertson & Shaw (2006) include consideration of land use and post closure aesthetics in their assessment criteria and indicators for mine closure projects. UNEP *et al* (2005) in 'Policies, practises and guidelines for sustainable mining and the closure of mines' refer to how aesthetic appeal forms part of the overall value placed on land (alongside biological assets and natural environmental services).

2.2 Region or Country-Specific Landscape Considerations

Individual countries have specific regulations and guidance relating to environmental management and where landscape and visual considerations may be required.

In Europe, the European Union (EU) EIA Directives (European Parliament and Council, 1985-2014) identify the landscape as a factor likely to be significantly affected by quarries and open-cast mining of a certain size and as such must form part of any environmental impact assessment (in Annex IV).

The UK country regulations interpret and implement the EU EIA Directive individually for England, Northern Ireland, Scotland and Wales. For example in England, landscape is included as an EIA topic (under Schedule 4, Part I) and consequently is to be included in environmental statements (The Stationary Office Ltd., 2011). The National Planning Policy Framework (DCLG, 2012) requires planning authorities in England to provide for the restoration and aftercare of mineral sites at the earliest opportunity and that this is carried out to high environmental standards and the web-based Planning Policy Guidance (DCLG, 2014) requires any new minerals site or any significant extension to an existing mineral working to include a landscape strategy.

Similarly, landscape is also a topic to be included in Environmental Impact Assessment Reports (EIAR) in Ireland (EPA, 2017) and the Irish guidelines for Environmental Management in the Extractive Industry (EPA, 2006), includes a section on landscape, restoration and after-use. Landscape change and visual intrusion are included as key environmental issues. The guidance recommends planning and design to minimise landscape impacts and the return of land to beneficial after-uses, such as agriculture, forestry or amenity, on a progressive basis where possible. The recently published National Planning Framework (Project Ireland 2040) refers to how *"aggregates and minerals extraction will continue to be enabled where this … provides for appropriate site rehabilitation."* (Government of Ireland, 2018).

In Finland, the Mine Closure Handbook (Heikkinen et al 2008) discusses how site rehabilitation, should encompass both landscape restoration as well as the prevention or mitigation of any potential environmental and safety risks, with desirable attributes including general neatness, landforms in harmony with surroundings, revegetation to appropriate land use and an aesthetically pleasing landscaped environment.

In Australia, the Minerals Council of Australia provides policy and guidance for its members including Enduring Value (Minerals Council of Australia 2015) which sets out key principles for the relationship between the mining industry and its stakeholders. Principle 2 seeks to integrate sustainable development principles into company policies and practices and Principle 6 includes commitments to rehabilitate land disturbed or occupied by operations in accordance with appropriate post-mining land uses, provide for safe storage and disposal of residual wastes and process residues and design and plan all operations so that adequate resources are available to meet the closure requirements of all operations.

The Land Stewardship Policy (Minerals Council of Australia 2012) also specifically recognises that *"while some previously mined areas are rehabilitated to pre-existing condition or better, other mined areas result in substantial transformation of the landscape. It is the minerals industry's goal to ensure that this land is available for subsequent economic activities, conservation or community use*."

The Government of Western Australia (DMP, 2015) identifies visual amenity as a mine closure issue and describes how the aim should be to "*restore the landscape to conditions similar to the surrounding (non-mined) environment, including physical, biological and chemical processes*".

Within the US, Palmer (2016) describes how visual impact assessment became a mainstream administrative procedure with the implementation of the National Environmental Policy Act of 1969, which required environmental impact statements (EIS) for major federal actions. Smardon (2016) also references this legislation and how its passage led to the requirement to incorporate environmental values into the decision making process, in particular with reference to aesthetics and the development of visual landscape management systems.

The Mining Association of Canada 2008 commits to establish, finance and implement comprehensive closure plans that, wherever practicable, return mine sites to viable and diverse ecosystems that will serve the needs of post-mining use, recognizing that mining can permanently alter landscapes.

Within some African countries there are similar regulatory requirements. For example, the requirement for EIA to support applications for environmental permits for mining developments and other similar undertakings has been in place in Ghana since 1999 due to the Environmental Assessment Regulations (Ghana Environmental Protection Agency). This includes metal mines and non-metal mines and stone quarries and sand and gravel quarries where the total area is greater than 10ha or where any portion is within an environmentally sensitive area. The regulations include "*areas of unique cultural and tourist value"* within the definition of environmentally sensitive areas.

Landscape degradation was identified as one of the environmental issues associated with large scale mining with the Democratic Republic of Congo country, along with water and air pollution; radioactive contamination; and deterioration of social welfare (UNEP, 2011).

2.3 Multi-disciplinary Approach to Corporate Commitments

There is a clear regulatory requirement for new mining development or mine closure projects to consider landscape and visual effects and this is usually alongside a range of other technical environmental inputs as part of project planning and management, refer to Figure 1. Site safety will always be a priority and mining operations may require certain measures to be adopted for safety reasons.

Both industry bodies and individual operators within the global mining industry have published commitments and guidelines relating to the environment, local communities and sustainability, for example through corporate social responsibility. Requirements from funding partners such as World Bank are also a key driver to environmental management and performance.

A company's financial accounts in annual reports will also need to take account of any potential decommissioning and restoration costs associated with asset retirement obligations (such as a condition of a planning permission), with fair value for any liabilities being recorded, for example as per, Financial Accounting Standard 143 (FASB, 2001).

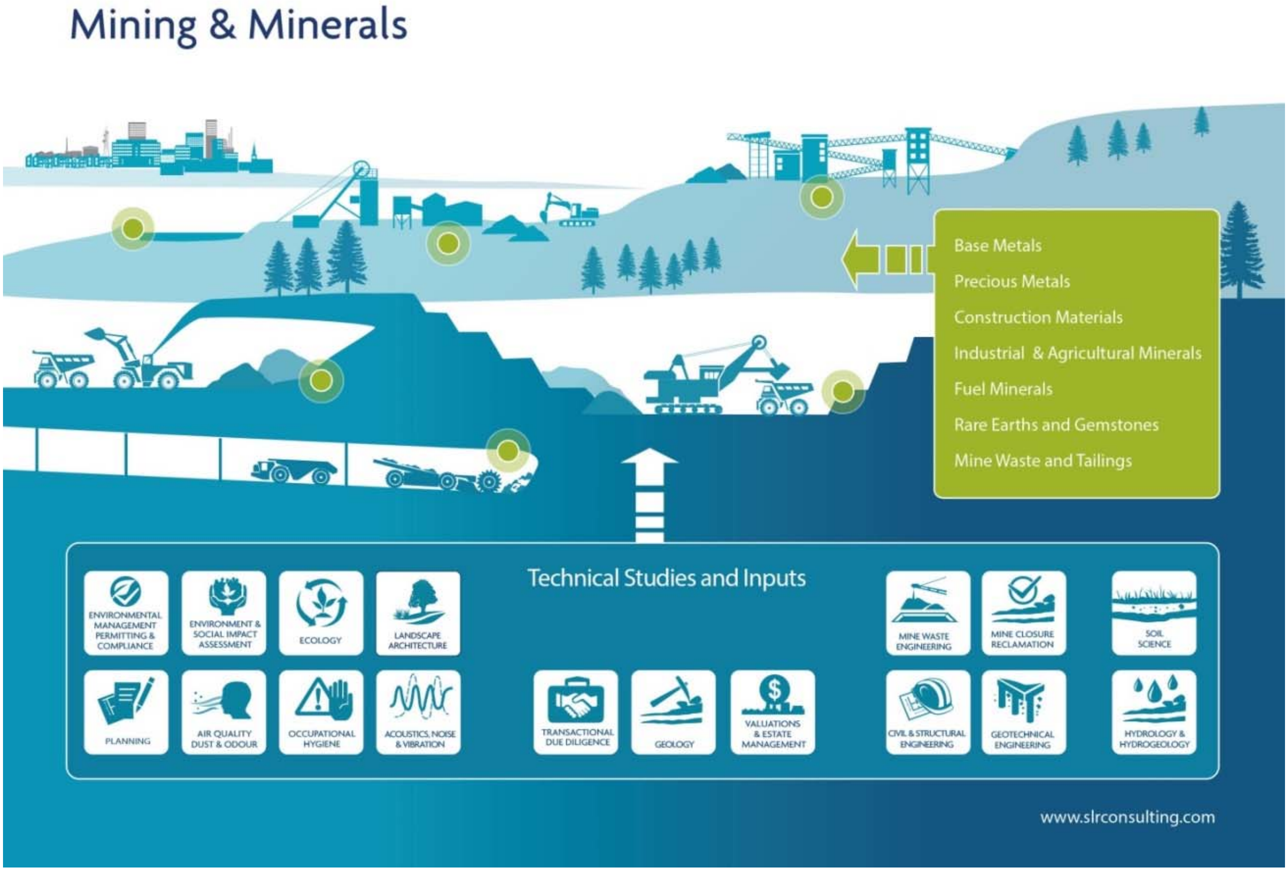


Figure 1 Multi-disciplinary studies and inputs to mining and minerals projects

Landscape can often be the overarching concept, which enables studies or inputs from other specific technical aspects to be incorporated and considered collectively and spatially within the constraints (or opportunities) at each site or project.

The typical multi-disciplinary considerations for mine closure plans are detailed in Figure 2, below and in particular this emphasises how such input can be integrated into the formulation of a landscape masterplan. A landscape masterplan might then define the main elements or features within a mine closure site, their relationship to adjoining land or settlements, habitats or viewpoints. It might specify contours and elevations, treatments or management approaches to be followed within certain parts of the site.

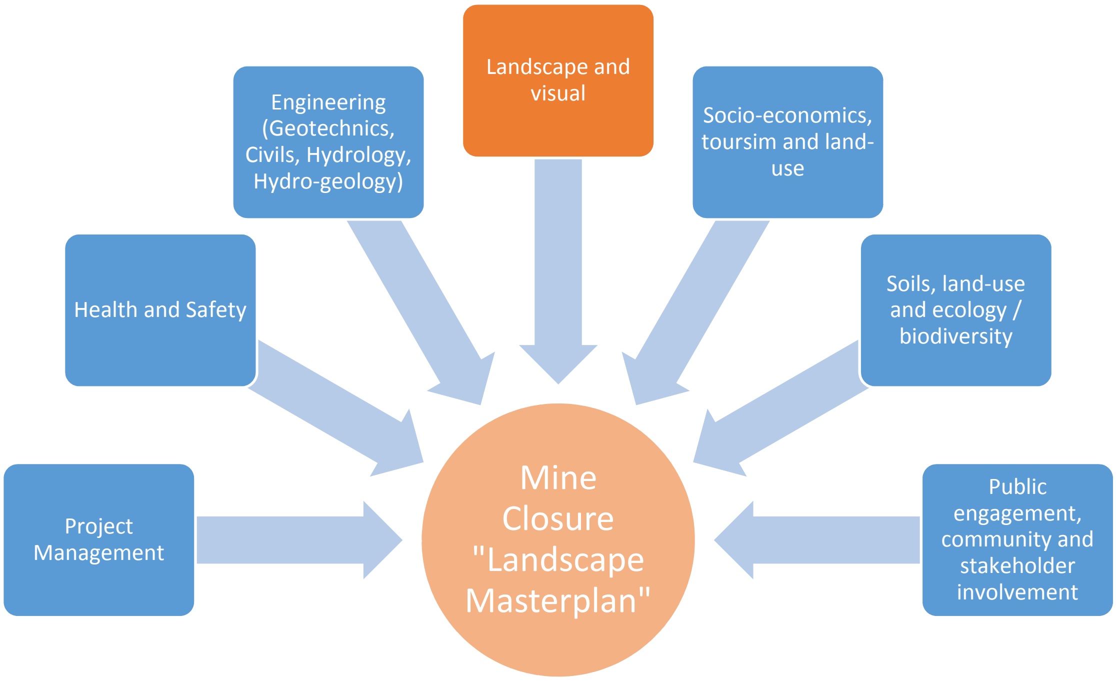


Figure 2 Typical multi-disciplinary considerations for mine closure plans

3 Landscape and Visual Considerations in Mine Closure

Landscape and visual impact assessment is widely used in the mining and minerals industry during planning and development stages and is a key tool for developing and demonstrating how a proposal might be acceptable to a decision-making authority. The third edition of the Guidelines for Landscape and Visual Impact Assessment (hereafter referred to as GLVIA3) describes how effects should be considered upon landscape as a resource in its own right and on people's views and visual amenity (Landscape Institute and Institute for Environmental Management and Assessment, 2013).

Potential landscape effects can be summarised as relating to:

- individual elements and features within a site;
- aesthetics or perceptual aspects which can possibly extend over wider surrounding areas; and
- overall character and key characteristics.

Effects upon visual amenity and the views of offsite receptors in the immediate surrounding area will often include:

- people living in the area (local residents and communities);
- people who work there or passing through on road, rail or other forms of transport;
- people visiting promoted landscapes or attractions (tourism); and
- people engaged in recreation of different types (leisure).

Representative viewpoints will usually be selected to inform the design process, whereby changes to views resulting from mining development can be visualised and assessed.

Staged Approach to Considering Landscape and Visual Effects

Landscape and visual considerations can be integrated into various stages of mining closure planning, from initial conceptual stages, through to detailed operations/phasing, decommissioning and reclamation/ rehabilitation. Potential mitigation measures should seek to avoid, reduce or minimise landscape and visual effects as far as possible.

Table 1 Typical mine closure stages with landscape and visual mitigation measures

Stage	Mitigation measures to avoid, reduce or minimise landscape and visual effects (to be evaluated at each site)
Initial Conceptual Stages (includes exploration, pre-feasibility and feasibility and construction)	Undertake baseline surveys and consider landscape character of site and surrounding area and any valued elements and features that could be avoided or replicated within mine site (landforms, boundaries, land cover and influence of human activity, etc.). Review aesthetic and perceptual aspects, such as scale, pattern and enclosure, colour and texture. Identify post closure land-use and preferred character for the restored landscape. Identify any locally sensitive viewpoints / visual receptors / key focal points or compositions that would benefit from protection from and / or improvements to the appearance of the mine site. Viewpoints will include users of recreational routes and visitor destinations, transport corridors, occupants and visitors to residential areas or individual houses. Review spatial arrangements of mine site components and develop mine closure masterplan drawing. Develop understanding of size and scale of components (pit voids, waste dumps, tailings, etc) within landscape context.
Detailed operations / phasing	Review opportunities for early completion of certain areas, particularly buffer zones around boundaries, outer banks of waste dumps or tailings dams. Review detailed visibility / visual exposure of site components and opportunities to modify direction of working, create screening mounds or planting strips. Consider different heights of perimeter vegetation (existing or new planting and its anticipated growth rates over time). Monitor any completed areas for establishment, function and growth rates.
Decommissioning (near or at the cessation of mineral production)	Removal of above ground equipment and structures, buildings and services, power and infrastructure connections, as appropriate. Clear site of any other debris, hardstanding, etc. Remove water or sewage treatment facilities.
Reclamation / Rehabilitation (return disturbed land to a stable and productive condition)	Seek opportunities to replicate locally characteristic elements and features within and around the mine closure area and preferred character for the restored landscape. Complete grading of final pit void and waste dump landforms and placement of soils / soil-forming materials and substrate. Review stability and erosion. Re-vegetation on any disturbed surfaces. Consider different types of vegetation establishment (grassland, woodland or forest cover) to develop patterns to reflect and mimic those in the surrounding areas. Reinstate watercourses and access. Monitor any completed areas for establishment, function and growth rates. Implement post closure land-use and undertake aftercare monitoring and secondary treatments. Review aesthetic and perceptual aspects. Review views and visibility / appearance from surrounding areas.

Table 1 takes the typical mine closure stages (after ICMM, 2008) and identifies relevant potential landscape and visual mitigation measures that could be considered by an operator. Ideally a mine closure masterplan drawing should be developed to enable a detailed spatial understanding of components within the broader landscape setting and the relationship to key visual receptors / viewpoints.

Mine closure projects will need to consider the location and appearance of final pit voids, potential waste dumps and tailings dam, as well as the removal of any above ground equipment and structures, buildings and services, any water or sewage treatment facilities and power and infrastructure connections.

Mitigation would typically include the adjustment of site levels / final re-profiling of an acceptable and stable landform, soil reinstatement and (re)placement of lost vegetation, reinstatement of watercourses and faunal corridors, as well as access. The post closure land-use and preferred character for the restored landscape may seek to replicate original pre-worked condition and/or characteristics of surrounding areas. Often this would seek to return the land to a productive condition.

Practical Examples of Landscape and Visual Considerations

Table 2 presents a series of photographs of landscape and visual considerations at mine closure projects.

Aesthetic and perceptual considerations would include variations in scale, pattern or enclosure, colour and texture and an assessment of whether the components of the mine closure can be integrated and assimilated into the surroundings or whether they would contrast and appear out of place.

For example, a large steep sided rock dump may contrast with a broad flat valley to a greater degree than if located within a more rolling topography characterised by other natural hills. Limiting the height of stockpiles and dumps may retain longer distance and open views, whilst the shape of ridges and skylines could also be a consideration.

In visual terms, retaining stand offs and strips of vegetation and landform to work behind may reduce visual exposure of certain components. Formation of an outer landscaped strip may enable subsequent operations to be hidden.

The removal of structures as part of decommissioning may reveal other elements or features. Any changes to views should be evaluated in relation to pre-identified focal points and compositions.

Discolouration of watercourses can also be a visual effect associated with mining development and may be apparent upon receptors at some distance from a site and otherwise visually separate from it.

Progressive working and restoration should aim to be carried out over the shortest timescale possible, to avoid excessive areas of disturbance. Ideally this should use direct placement of material to avoid double handling although this is not always possible with a mine closure project.

Table 2 Examples of landscape and visual considerations

	Photo 1 illustrates how the profile of a proposed waste dump mound at a Tungsten mine in England can reflect local character and rolling skyline of natural hills in the area.
	Photo 2 illustrates soil storage mounds around a brickworks and clay pit, England providing localised screening of activities behind. This material will then be available for restoration at the end of the development. Tree and shrub planting can also be used to provide additional height and enclosure.
	Photo 3 shows a tailings storage facility (TSF) at a zinc mine in Ireland. The dam walls have established grassland which provides a green cover to help assimilate the structure with the surrounding agricultural area. The photograph also illustrates how retained mature vegetation in the foreground partially screens the TSF.
	Photo 4 illustrates how the early, progressive restoration of section of sand pit face helps to reduce the visual impact of an active sand and gravel pit in Ireland. The restoration to grass and heathland cover reduces the overall area of exposed sand face.

4 Mapping, visualisations and presentations

Landscape Architects around the world harness new technologies to review and consider landscape and visual issues, for example mapping, visualisations and presentations to stakeholders.

The use of some of the below technologies can help with the understanding of mine closure projects and determining any potential risks.

Unmanned Aerial Vehicles / Drones

Geo-spatial mapping and analysis technologies, such as un-manned aerial vehicles / drone surveys have improved the capture and availability of data that can be used in mine closure plans, and in particular when dealing with landscape and visual considerations. Topographical information and landcover can be captured for remote and inaccessible locations.

Photogrammetry software enables images to be captured from a range of angles and used in representative 3d image based point clouds. Recent software advances has also enabled this from consumer grade cameras.

A drone can also be used to test the visibility of structures or landform at certain heights, by flying vertically at known locations and capturing horizontally positioned photographs. This image can then be reviewed to check what would be visible from that elevation. Table 3 presents a series of drone captured images obtained to assist with landscape and environmental mapping projects.

Table 3 Examples of drone-captured mapping images

	Still from video 1 captured as part of assessment for a proposed dam in Tivishi Limestone Gorge, Georgia. Topographical information such as cliffs and gorges, watercourses, vegetation cover and settlement patterns can all be captured for remote and inaccessible locations and presented as video footage.
	Photograph 2 shows a view from an elevated position within a quarry in Ireland in which the boundary vegetation screens views of known residential properties beyond and it can therefore be reasoned that a proposed structure would also be screened at this height and location, from these properties. .

Photomontage and Visualisations

Capturing high quality photographs from known locations can be used as part of baseline work and then 3D modelling and photomontages can enable perspective views of the development to be generated and effects and options tested, such as the location and dimensions of the waste dumps or open pits relative to intervening landscape features and the proposed character of the afteruse treatments. The Landscape Institute (2011) has published guidance on photography and photomontage in landscape and visual impact assessment, including cameras, setting up and recording data, printing and viewing images.

Table 4 presents a series of photomontage images and stills from animations which were prepared to assist with landscape and visual aspects of mine closure projects.

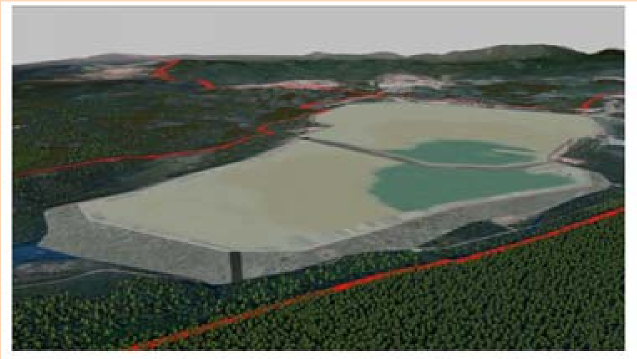
This includes 3d modelling of development area and adjacent mounds, revegetation / grass cover and tree planting, as well as prediction of water levels in quarry voids.

Computer generated modelling, imaging and presentation techniques of the mine closure proposals can enable very effective stakeholder engagement and those potentially affected by the process or outcome of mine closure.

Table 4 Examples of visualisations (photomontages and animations)

	Photomontage 1 shows phased development of the extension to a granite quarry in Scotland. The overburden material has been placed around the edges and grassland and tree planting provides a green cover to help assimilate the structure with the surroundings. The photomontage also illustrates how the quarry void would recharge with water following cessation of operations to provide a new waterbody. The visualisations are based on views from a key recreational viewpoint, an ancient monument overlooking site.
	Photomontage 2 is an example to show the proposals for the reclamation of waste disposal site at a gold mine in Ghana, with final grassland cover.
	Photomontage 3 is an example of a waste rock pile and conventional tailings management facility for a proposed gold mine in Northern Ontario. The images illustrate the size and scale of the development relative to the viewpoint and demonstrate the horizontal nature of the existing skyline.

Still from animation 1 is an example of a restored open cast coal pit, Wales. The animation uses models to show stages of the development from its existing state to working and then closed. The elevated viewing positions show how the pit would flood after working to form a waterbody, with hotel development around the margins. The overall landscape framework of recreational lakes, grassland and woodland habitats to can be better appreciated and compliment the design drawings.



Still from animation 2 is an example of the progressive development and restoration of a gold mine tailings facility in Africa. The images are based on engineering designs provided which have been taken into 3d modelling software and rendered to illustrate the types of colours and textures expected over the course of the project. The client requested this work to assist them with consultation with authorities and engagement with other stakeholders.

Virtual Reality

Virtual reality is being increasingly deployed to appreciate development proposals, whereby 3d models are presented in conjunction with commercially available headsets. Figure 3 shows sketch illustrations of how photomontages and visualisations can be converted and used within a 360 degree immersive environment.

Virtual reality can then be used to show animated pathways of development to illustrate visual effects for travellers along a roads or footpaths.

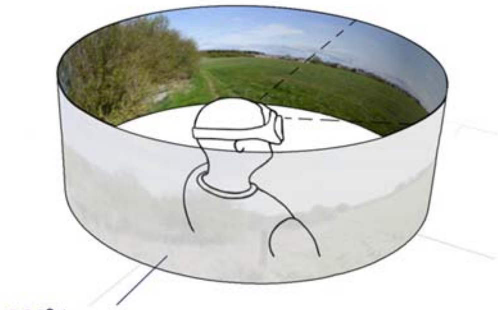


Figure 3 Converting photomontages to a 360 degree immersive environment

5 Conclusion

Consideration of the potential landscape and visual effects associated with development forms part of modern mining and mine closure planning. Such consideration helps to improve overall environmental performance, sustainability, stakeholder engagement, and responsiveness to local communities.

This paper has described the technical and regulatory background to landscape and visual assessment and how such considerations should be included within a mine closure plan. The main ways of determining landscape and visual opportunities and constraints for mining closure planning are described, covering the various stages likely to be undertaken.

The latest computer-generated mapping, virtual reality (VR) modelling and presentation techniques have wide application in the mining & minerals sector and can contribute positively to stakeholder engagement, public perception and local community understanding of mine closure during each stage of the closure process.

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Risks in Planning and Designing for Mine Closures

I Hutchison *SLR Consulting, Canada*

M Nahir *Department of Indigenous Affairs and Northern Development, Canada*

Abstract

The authors have been extensively involved in the planning, design and construction of mine closures, particularly in northern Canada and the United States. This paper focuses on the ever increasing complex human interactional and technical processes involved in planning, designing and closing mines. Issues that have occurred include poor definition of closure objectives, inadequate consultation with stakeholders, lack of attention to applicable regulations, inadequate levels of engineering, incomplete application of decision analyses in selecting preferred closure alternatives, lack of integration of design and operations into closure planning, lack of transparency, and lack of pre-planning amongst others. Also of importance has been the inability of companies to reliably project both the active closure costs, as well as the long-term monitoring and maintenance costs.

The origin of many of the issues is the lack of closure planning leadership and a disciplined process that has become accepted by the various entities involved in mine closures. As a result, there is usually considerable scope and cost uncertainty. The risks that closure plans have to be re-done, designs that do not fully address the closure objectives, and closure construction requiring retrofitting, are unnecessarily high.

The authors describe a more formalized decision-making process that at its center incorporates a more detailed definition of closure objectives and selection of alternative to meet these objectives, as well as comprehensive decision analyses. Guidance is provided for clarifying objectives, requiring transparency and consultation, and for a framework of standardized planning and design documents that make the process more predictable and efficient. A case history involving the closure planning for a mine in the Yukon, Canada is provided to illustrate the application of the finalized decision-making process. This paper also provides two case histories of mine closures where a decision tree methodology is being used to map out future scenarios for complex mine closures, and also to provide the basis for determining probabalistic based closure cost estimates that provide useful information for closure planning funding and budgeting purposes.

Keywords: *alternatives, cost estimating, consultation, decision analysis, engineering, objectives engagement, planning, resilience, stakeholders*

1 Introduction

Mines that were abandoned in the late 1900's through the early 2000's frequently have closure plans that are inadequate by today's standards, typically not addressing acid rock drainage that developed and providing for inadequate surface reclamation. At these sites, closure becomes a new project involving characterization of site conditions, closure planning and the associated engagement with stakeholders, closure design and construction followed by an adaptive management period during which the closure measures are adjusted to perform as intended, and then an extended long-term care and maintenance period.

As described in this paper, the experiences and lessons learned have been derived over the last decade of constructing mine closures at close to twenty mine sites, generally at remote locations in the Yukon and Northwest territories in Canada, as well as in more developed areas such as California in the US. These experiences are not unique to government-controlled sites and the authors believe there is value in applying the lessons learned to both abandoned and new mine closure planning.

This paper focuses on the complex inter-relational and technical processes involved in planning, designing and closing abandoned mines, particularly those that have reverted to government funding and that are subject to all the long-term care and maintenance closure planning phases described above. Issues that typically occur include:

- A large number of stakeholders with varying agenda and objectives;
- Poorly defined closure objectives;
- Poorly conducted consultation;
- Poorly conceived remedial or closure engineering alternatives;
- Lack of formalized decision making and approval processes;
- Inappropriate levels of engineering for planning purposes;
- Design lives that are too short and inadequate robustness in the designs;
- Closure design and construction that lacks resilience; and
- Mine closure becomes a process rather than a short-term project, resulting in extended care and maintenance costs that can increase the overall closure costs by a factor of two or more.

The above issues typically lead to adversarial relationships with and between stakeholders due to closure planning re-dos, closure construction re-dos, and ultimately costly schedule delays and construction cost increases. The authors elaborate on how each of the above issues contributes to these risks and provide suggestions that are helpful in avoiding or minimizing these pitfalls.

2 Large Number of Stakeholders

Frequently there are a large number of stakeholders with varying objectives that need to be consulted on the mine's closure plans and designs. These stakeholders can include:

- Governmental agencies who fund mine closures and are responsible to the taxpayers potentially have other responsibilities that compete for funds;
- Indigenous populations who have a strong interest in "healing the environment" and preserving their traditional land uses, which include hunting, fishing, harvesting, as well as areas that are historically and culturally important;
- Local communities with interests in preserving the environment and protecting beneficial resources, frequently aquatic resources;
- Provincial and territorial governments who are charged with enforcing applicable and relevant requirements, regulations and environmental goals, as well as protecting socio-economic interests;
- Non-governmental Organizations (NGOs) who promote their specific agenda, which can range from community protection and development and environmental restoration, amongst others;
- Local contractors and builders who are interested in local economic benefits afforded during closure construction; and
- Local, regional and national consulting companies that have varying degrees of skill, and who influence the planning and design process.

There is generally a high risk of not satisfying all stakeholders during the closure planning process. One of the main underlying reasons is that there is usually a very large range of costs that can be incurred at a site and that there is almost an exponential increase in costs for very gradual improvements to the protection of human health and environmental restoration. In many cases a perfect solution is not possible and as such the only viable options are those that manage hazards and reduce risks. This makes it difficult for stakeholders with varying objectives to reach consensus at an optimum point that achieves an equitable balance between expenditure on the one hand, and protection and restoration on the other. There is no definable "sweet spot" that the stakeholders can gravitate to.

A typical cost versus closure environmental standards curve is provided in Figure 1. The curve depicted is based on an actual case history. During the closure planning and permitting phases of the mine, the following closure alternatives, each with increasing levels of protection (and the associated amount of engineering) were considered.

- **Alternative A: Protection of Human Health & Reclamation.** In order to achieve this basic objective, the mine site would be selectively revegetated, the pit would be surrounded by safety berms, barriers and signage, all mine access roads would be bermed off and reclaimed to prevent easy access, and all buildings and shafts used for mine opening removed or covered. Deed restrictions would be placed on properties containing mine waste to prevent disturbance of these wastes or development on top of the waste. Ongoing long-term inspections, maintenance, and monitoring would be provided.
- **Alternative B: Alternative A plus Protection of Human Health and Environmental Improvement.** Under this scenario the terrestrial and aquatic habitat immediately surrounding the mine site would essentially be stabilized to prevent the effects of poor quality seepages and metal containing mine rock from spreading, and to reduce access of species to locally impacted water and soil. Closure would include all the measures under Alternative A above, plus more extensive soil covers and re-vegetation, as well as rock drains to convey and cover impacted seepage water, constructed wetlands, etc. The area immediately surrounding the mine site and streams near the mine would remain impacted compared to pre-mining conditions, but still support viable ecosystems.
- **Alternative C: Alternative A & B plus Projection to Water Quality Goals.** This alternative would include all the measures incorporated in Alternatives A & B, but would also include seepage and leachate collection and management. In this case this would involve pumping seepage and leachate to the pit for seasonal storage and provide for in-pit water treatment and discharges from the pit during flow periods when there is sufficient natural runoff to provide for dilution to meet prescribed water quality goals.
- **Alternative D: Waste Relocation.** This alternative would involve relocating the tailings and waste rock to new lined facilities constructed to current day standards, as well as flooding the pit to a high enough level to prevent oxidation of the mineralized rock in the pit wall by increasing the height of the engineered dam built across the low point along the pit rim.

As seen from Figure 1, costs continually increase for Alternatives A through D. The cost increases exponentially, with the maximum being almost five-times the Alternative A cost. This almost exponential shape of the curve is very typical for the closure of many historic and abandoned mine sites. This is because the number of practical mitigation options is limited as a result of not designing the mine for closure at the initial mine design and operations stages.

Because of these rapidly increasing costs, it is extremely important to carefully and systematically define closure objectives and move through the planning process to avoid unnecessary high expenditures, which add little additional benefit. How this can be more effectively accomplished is to:

- Clearly define closure objectives;
- More carefully conduct and document the closure planning consultation process;
- Improve selection of closure alternatives by systematically selecting closure components that meet specific objects and manage identified risk pathways;
- Adapt a more formalized decision analyses approach in selecting which alternative best meets the objectives as a whole;

- Use of a knowledgeable technical advisory group which will work through the technical program to provide guidance and improve project buy-in; and
- Conduct appropriate levels of engineering through the alternatives analysis, planning, and construction processes.

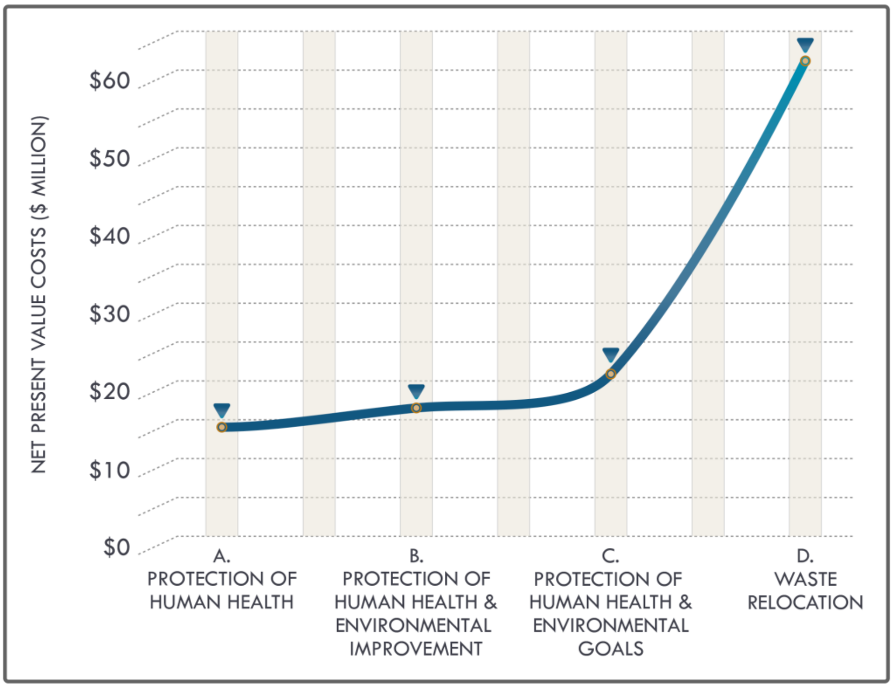

Figure 1 Level of protection vs. closure NPV costs ($ US)

Examples of issues that have been encountered with each of the above steps and suggestions for improvements are discussed in the remainder of this paper. While not foolproof, the authors maintain that these improvements can increase the resilience of closure plans, substantially improve the closure designs and reduce the risks of future issues arising.

3 Closure Objectives

Examples of closure objectives that have been used include:

- Prevent, minimize or mitigate any adverse effects on the health and safety of people using the land and water;
- Prevent, minimize or mitigate adverse effects on the environment;
- Reclaim disturbed areas to support future community and traditional land use; and
- Maximize training, capacity building, and employment and business opportunities for local residents and aboriginal groups.

The issue with these objectives is that they are too broad to be of specific value in the planning process. As they are, they may not support the selection of reasonable engineering alternatives or a formalized alternatives comparative analysis. Considering the range of stakeholders listed above, it is likely that each will interpret these objectives differently. Consider the situation where a mine tailings management facility (TMF) is located within a streambed and as a result poor quality water seeps to groundwater and discharges to surface waters. One interpretation of the above objectives would be to restore surface water and groundwater in the area immediately downstream from the TMF to drinking water and aquatic government standards. This would likely require relocation of the tailings (which has occurred) or encapsulating the tailings beneath an impermeable cover with subsurface seepage cutoff systems and a groundwater pump and treat system to clean up groundwater. At the other extreme, this objective could be interpreted as allowing for attenuation that occurs in groundwater and the dilution that occurs in surface water to meet standards some distance (several tens or hundreds of meters) downstream from the TMF. To achieve this would require a low permeability cover to be placed over the surface of the tailings and runoff diversion ditches to convey clean water around the TMF. The difference in benefits of going from meeting the latter objectives to the former could be considered relatively small since it is highly unlikely that water within a the immediate proximity of a TMF would ever be used as a water supply. Since the cost differential between these two interpretations can be a factor of 5 to 10 or more, it becomes apparent a much clearer objective needs to be stated.

Future land use for a closed mine is frequently only dealt with in a cursory manner. As a result, the authors have encountered sites at which the proponent assumes future use will be limited, while stakeholders assume it can be re-utilized for pre-existing use, or an even higher end use. In another case, consideration was being given to re-opening the entire closure plan for an existing closed TMF because the land use associated with the original plan was not documented or incorporated in a legal framework and because of the preference of one or more of the many stakeholders. Land use restrictions are often frowned upon, but in many cases they are essential to provide risk management for the long term. For example, closure of a TMF either by covering *in-situ*, or by relocation and cover, requires that access to its surface be restricted in order to protect the effectiveness of the cover placed on the tailings. To suggest a tailings or waste rock facility should be closed to support traditional land use may not be practical or desirable. In many cases, aboriginal groups see the remediated mine site as permanently disturbed land to be avoided. In all cases they are primarily interested in ensuring the safety of country foods and the health of the community and its individuals.

Where possible, it is desirable to develop clearer and quantitative sub-objectives. Examples of clearer objective statements are:

- Provide for a closure surface that does not erode and which is ultimately sufficiently vegetated to soften the as placed contours and creates landforms such a vegetated areas, as well as open areas with minimal vegetation and rock slopes that are similar to those that occur in the surrounding natural terrain;
- Prevent groundwater impacts above baseline or background conditions within a specified area that is larger than the TMF footprint; and
- Prevent unsafe contaminant concentrations from occurring in country foods potentially used by aboriginal and local populations.

This level of detail is precisely what needs to be discussed during consultation in order to establish some common ground. All too often, the authors have seen consultants establish a range of engineering alternatives that address the more general objectives stated above either to a lessor or greater degree, and then attempt to get consensus on this moving target.

4 Consultation

It is important to provide stakeholders with sufficiently clear information for use in drawing conclusions on the closure alternatives. Sufficient time needs to be allowed for the stakeholders to discuss and comment on closure objectives and alternatives, however, while difficult to do, it is necessary to establish a realistic time frame for finalizing decisions in order, to prevent the process from extending over too long a period while leaving the risks associated with the abandoned mine remaining unmitigated. It is also important to address all stakeholder comments and concerns and to explain where compromises need to be made, since there is a need to achieve a balance between their sometimes competing interests.

It will be important to have proper representation by stakeholders. Typically each stakeholder nominates trusted technical experts often funded by the closure proponent, so that technical options can be developed and analysed in a timely manner.

Useful approaches for conducting effective consultations include:

- Use of experts in the area of consultation in order to identify stakeholders, to plan out a consultation process, to assist in the preparation of informational materials, to conduct actual consultation sessions, and to communicate the results of the consultations. All too often the process is not well executed and as a result the stakeholders end up not trusting the results;
- Development of a technical working group composed of subject matter experts nominated by each stakeholder will provide information and analysis on an on-going basis back to communities and other stakeholders;
- Subject matter experts (such as risk assessors, engineers, etc.) should be experienced enough to convey complex technical issues clearly, in lay terms, and be able to put issues into clear perspective. The authors have frequently encountered cases where highly technically skilled individuals with the best intentions fail to connect with their audience and convey the essence of what their analyses and opinions reveal;
- Carefully explain what human health and environmental risks both the mined materials and the natural environment pose. Some of the more difficult concepts to describe include; (1) those risks associated with the natural environment, especially in mineralized areas with steep terrain, where conditions do not necessarily meet soil or water quality goals; and (2), that while mined materials contain elevated concentrations of constituents of concern, their impacts on risks are moderated by the remoteness of the sites and the natural avoidance of the disturbed areas by fauna, for example;
- Use of work-shops and public information sessions to; (1) explain site conditions, risks, future land use options and constraints, closure objectives, and the closure alternatives and costs and what each can achieve; (2) solicit input from those present regarding their concerns and preferences, particularly why they have certain preferences; and, (3) provide feedback and the results of the closure planning describing how their input was used in the decision analyses. It is important that the funding agency, together with its experts, leads these procedures and provides for transparency but does not let certain stakeholders take charge or disrupt the proceedings;
- Use of a formalized decision analysis process that clearly illustrates to what extent each of the alternatives considered controls the risks, meets the closure objectives and accommodates stakeholder preferences. It is useful to show what trade-offs were made in selecting the preferred alternative and how each stakeholder groups' issues and concerns were addressed in the decision making process; and
- Detailed and comprehensive documentation of the discussions held at work-shops and meetings, the decision making process and how each stakeholder's concerns have been addressed. Frequently there is insufficient documentation, thus making it difficult for those involved in the implementation process to understand whether and how their concerns have been addressed and what trade-offs have been made.

Strong leadership of the consultation process is required. It is important to communicate the range of feasible closure options that are available, what it will take to get them installed, their costs and their strengths and weaknesses. Educating stakeholders on what the actual risks are and what the various options can and cannot achieve, is an important part of the process.

Finally, the authors have seen cases where the consultation process was either rushed or unable to engage sufficient stakeholders. In many of these cases, stakeholder interest has revived after closure plans have been implemented, justifiably claiming that appropriate procedures were not followed and increasing the risk of having to re-do work, thus incurring unnecessary costs and delays.

5 Closure Alternatives

The authors have frequently noted that considerable time and effort is devoted to developing alternatives for further analysis, but that following this there is no systematic and defensible approach to analysing the alternatives. This makes it more cumbersome to get through the planning process and to defend the preferred alternative.

An approach the authors have found to be most effective (US EPA, 1988, Environment Canada, 2011) involves a four-step process that includes:

- Listing all of the technologies that can be applied. In order to ensure that all of these are considered, assemble them under basic closure approach categories including: (1) institutional controls; (2) isolation of mine waste by surface water and groundwater diversions, (3) encapsulation of the waste; (4) treatment of the waste; and (5) relocation of the mine waste;
- Screening of those technologies that do not apply to the site, are infeasible, or are more costly than another technology that performs equally as well. This step demonstrates that the closure planning is unbiased and considers all feasible technologies. It also provides a basis for defense in the event that in the future a stakeholder or government agency wants the closure plan changed because a specific closure technology was not considered; and
- Assemble the remaining technologies into a series of closure alternatives as described below; and
- Conduct an unbiased and comprehensive comparative analysis of the alternatives to select the preferred closure plan. This includes development of a narrowed set of alternatives to a Class 4 (AACE, 2005) pre-feasibility level to allow for proper scope definition and a reasonable level of cost accuracy.

The authors have developed a matrix mapping approach that makes it easier to assure that all the correct alternative plans are assembled. An example is shown in Table 1. The matrix maps out and identifies which selected alternatives meet which of the applicable risk pathway and closure goals. It is important to note that we consider both risk pathways, as well as closure goals as this provides for a more resilient closure plan. These two parameters are shown in the "Closure Drivers" column in the table. In some cases, a third set of drivers, "Regulatory Compliance", is also considered as there may be important regulations that need to be considered and it is important to understand which alternatives either do not meet, partially meet, or fully meet, these requirements. For the sake of simplicity, this driver has not been included in Table 1.

Alternatives, each representing a specific basic closure technology, are considered first as this highlights which risks and goals the particular technology can or cannot manage or meet. These basic technologies typically include institutional controls (such as deed restrictions, access controls, etc.), waste isolation using surface and subsurface drainage systems, waste encapsulation using covers, and waste removal and placement in a new lined and capped facility. Mapping out which of the risk pathways are alleviated and which of the closure objectives are met by each technology makes it very clear which of these technologies should be combined into the more realistic alternatives. These are shown on the right hand side of the matrix. For example, if there is only one basic technology that deals with a specific risk pathway or goal, then that technology needs to be included in each of the alternatives on the right hand side of the matrix. An example is institutional controls that may be the only means of preventing future construction or excavation on a closed waste management unit in order to maintain its integrity in the long term.

Where various technologies are capable of satisfying specific risk pathways/goals, then each one of them can be included in separate combined alternatives so that their pros and cons can be weighed against each other in the decision analysis process that follows.

Table 1 Closure alternatives selection for a TMF (simplified)

Closure drivers	Basic technology alternatives					Alternatives incorporating combinations of technologies			
	1. Institutional controls	2. Water diversions	3. Cover in place	4. Seep collection & treatment	5. Relocation of tailings	A. (1) plus (2)	B. (1) plus (3)	C. (1) , (3) plus (4)	D. (1) plus (5)
Risk pathway									
Soil ingestion	○		○		○	○	●	●	●
Fish ingestion	○	○	○	●	●	○	●	●	●
Closure objectives									
Prevent HH risks	○		○	○	○	○	●	●	●
Protect D/S fisheries		○	○	●	●	○	○	●	●
Compatibility with existing land uses	○		●	○	●	○	●	●	●
Erosional stability		●	●		●	●	●	●	●
Minimize Long- term Active Care	●	○	○		○	○	○		○
NPV costs ($ million-excluding monitoring)									
	0.6	1.8	40.4	16.9	250	2.2	40.8	55.8	250.5

LEGEND: ● Fully Effective ○ Partially Effective or Effective in either the short- or long term, but not both

6 Formalized Decision Making Process

The origin of many of the issues encountered during the closure planning process can be traced back to the lack of adherence to a formalized process for the selection and analysis of closure alternatives, as well as to a process that clearly demonstrates how the input of the various stakeholders involved in mine closures is taken into account. Frequently, decisions are made on what is topical at the time and in favour of the most vocal stakeholders. Also, frequently, closure planning uses formalized methods of weighted parameters, but then uses scoring methods that are arbitrary at best. Furthermore, the authors have seen occasions where the details available for the alternatives are insufficient and the advantages and disadvantages cannot be fully evaluated, leading to decisions that are somewhat based on assumptions and intuition.

In other cases, the closure planning process has been subdivided for various sub-areas of the mine (such as the tailings facilities, surface soils including open pits, and underground mines), rather than considering the entire mine as an integrated planning exercise. Where this method is necessary, it must be done with caution to avoid conflicts in needed closure plans for certain mine features.

The alternatives analysis tool most frequently used is the Multiple Accounts Analysis (MAA) (Environment Canada, 2011, and others) and has been successfully used for a wide range of mine closure planning cases. In this analysis, a range of evaluation parameters (referred to as accounts and sub-accounts) are established, numerical weights are assigned to each, and numerical scores are created to represent the degree to which one alternative may be preferred over another. MAA seeks to integrate objective measurements with value judgment.

An example of a MAA Analysis is shown in Table 2 below.

Table 2 Examples of multiple accounts ledgers

Account	Sub-account	Indicator	Indicator parameter	Unit	Indicator quantity
Environmental	Effect on traditional land use during construction	Hunting impact	Time	Yr	2 years
		Fishing impact	Value	Factors based on fisheries studies	3
		Berry harvesting impact	Area	ha	400 ha
Mine waste geochemistry	Mine waste geochemistry	ARD potential	Value	#	2
		Metal leaching potential	Value	#	6
	Diversion design	Channel length	Length	km	3.8 km
		Catchment size	Area	ha	134 ha
Project economics	Complete life-cycle cost	Capital cost	Cost	$	10 million
		Operational cost	Cost	$	2 million/yr
		Closure cost	Cost	$	3 million
	Economic risk	Capital	Value	#	2
		Operational	Value	#	3
		Closure	Value	#	5
Socio-economic	Landowner perception	Land owner perception	Value	#	4
	Archaeological sites	Presence of immovable sites	Quantity	#	2
		Presence of mitigatable sites	Quantity	#	33

Generally, the analyst with input from interested parties should set weighting factors that reflect the site-specific conditions and sensitivities. In addition to these weights and within the framework of these guidelines, it is proposed that the “Base Case” of the options assessment use the following weightings for accounts as recommended by Environment Canada.

- Environment – 6
- Technical – 3
- Project Economics – 1.5
- Socio-Economic – 3

The analyst is still encouraged to assign other weightings to accounts and demonstrate their effect on the assessment outcome (sensitivity analysis). The authors are not convinced that these weights universally constitute a valid base case. For sites at which the environmental impacts are minor and localized to within and immediately adjacent to the mine site, these weights result in a disproportionate emphasis on environmental protection versus potential socio-economics effects and cost effectiveness, which may be more important.

It is highly recommended that site-specific rather than these generic weights are established, and that sensitivity analyses are conducted to determine by how much the selection of the preferred alternatives changes with changes in the weight.

In the event the higher scoring alternative remains the same for a wide range of sensitivity cases, the planning decision can be considered resilient and less likely to be changed or challenged in the future. At the other extreme if significantly different alternatives emerge as the highest scoring for a different set of weights, it is important to highlight this and point out which weights result in the highest rankings. This typically arises when higher weights are assigned to costs, say, than environmental effects. In these cases, it is important to understand what the environmental benefits are for the alternatives ranked higher for a higher relative environment weight, versus the additional costs when compared to the cost of the alternatives that score highest with the high cost weight. This allows for a more detailed evaluation of the benefit/cost aspect of the environmentally preferred closure alternative to one, which may reflect a more balanced evaluation with higher weights assigned to costs.

The most important aspect of the decision analysis is to clearly explain to stakeholders how the accounts selected reflect the closure objectives, how the account and sub-account weights reflect their input and local conditions, and finally how the numeric analysis provides for the achievement of a preferred alternative that provides for the best overall plan, considering the multiple, often conflicting, objectives.

Other important aspects of the decision analysis that are not highlighted by Environment Canada's approach, are the impacts caused by the implementation of the alternative being considered, the scale of the impact being remediated by the closure plan, and the effect to which the alternatives comply with existing environmental regulations. For example, where a lengthy haul road through pristine countryside is required to provide equipment access to remediate a relatively small area of spilled tailings may not be warranted. This is particularly relevant if the impact caused by the tailings is minor, the tailings are being gradually, naturally reclaimed and the temporary and permanent disturbance created by the construction of the haul road is more significant than that of the tailings.

In the author's experience, the decision analyses framework established by the U.S. Environmental Protection Agency (EPA) provides a balanced structure and deals with the closure implementation effects described above. It includes a fatal flaw-screening step, followed by what is referred to as a balanced comparative analysis. The screening involves checking whether the proposed alternatives are sufficiently protective of human health and the environment.

The basic framework for the balancing analyses generally includes the parameters described in Figure 2.

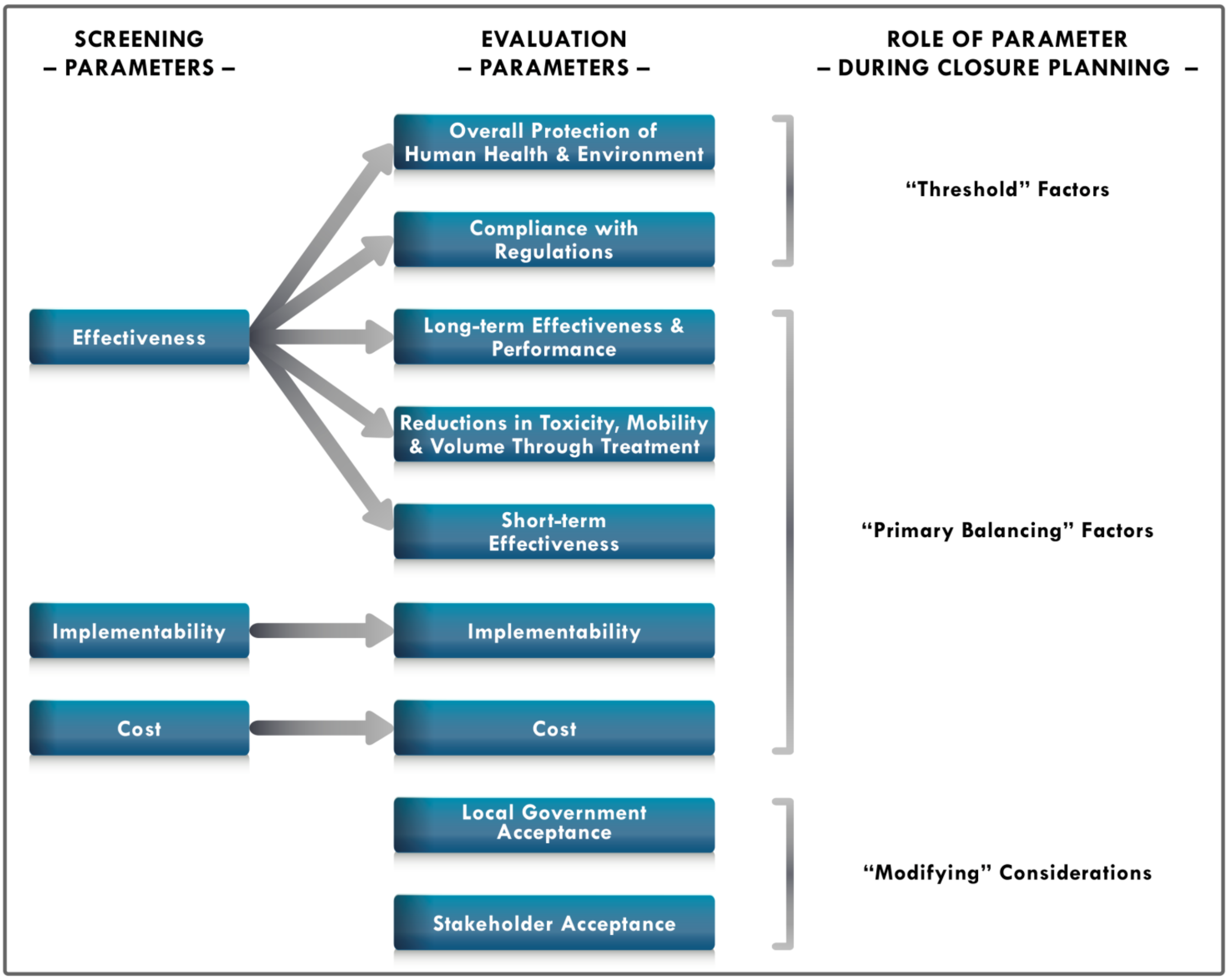

Figure 2 Screening and Evaluation Parameters

As for the MAA, this framework is a starting point and needs to be refined to reflect the specific conditions at each site.

If necessary, the results of the above more formalized analysis provides a rational basis on which to move forward with some sort of dispute resolution process. Since the analysis can readily be used to explain what trade-offs are being made in selecting a particular closure plan, dispute resolution can only focus on the relevant issues. For example, considering the relocation of a TMF in order to eliminate the presence of a local area of impacted streamflow the trade-off is between a reduced area of impact versus human health and environmental impacts during the relocation construction and constitutes a significant increase in costs. In the long term, in both cases it is necessary to maintain a closed TMF with a cap.

Efforts that can be used towards resolving these conflicts highlighted by the above methods can include, but may not be limited to the following:

- More data collection and studies on the disputed aspects; such as more benthic or fisheries studies to determine more precisely what the effects have been and what improvement there will be for traditional knowledge work to more accurately define the importance of the area, etc.;
- Involvement of higher level decision makers in national and local government in focusing on resolving the highlighted issues;
- Legal dispute resolution procedures; and
- As a last resort, litigation.

Finally, it is important to recognize that considering costs and cost effectiveness is not something that should be swept under the carpet as it sometimes is. Governments and proponents do not have unlimited financial resources and it is incumbent on those agencies charged with the responsibility of abandoned mine closure to consider the balance between expenditures and the improvements achieved by these expenditures.

In some countries, where there has been an inordinate amount of pressure on mining companies to achieve as close to pristine conditions as possible, the authors have observed that the closure process deteriorates into protracted legal proceedings and studies with very little site closure work being accomplished. As a result stakeholders become dissatisfied, the unclosed mine site risks persist for longer than is necessary and the costs are further increased by what can be substantial site holding costs that can run into the $10's millions.

7 Advisory Group/Independent Peer Review Panel

The establishment and use of a knowledgeable and experienced technical advisory group should be considered and can be extremely helpful in obtaining stakeholder concurrence on practical closure solutions. This advisory group should have the necessary experience in mine closure and the key technical areas, including geology, geochemistry, geotechnical engineering, surface- and groundwater-hydrology, and risk assessment. The advisory group should review the work being done by the consultants and advise the principal party responsible for the closure. They should prepare written reports on their findings and should be available to make presentations to stakeholder groups if necessary. The authors have found several instances where such a group has supplemented the performing consultant's lack of experience and played a significant role in determining the direction of the closure planning and design process.

8 Levels of Engineering

It is critically important to develop sufficient design details and support analyses to allow complete alternatives analyses to be performed. The authors have seen many cases where an alternative was selected based on insufficient information only to be later proven to be not as effectives as thought or infeasible, impractical, or unnecessarily costly during the more detailed design phases following closure planning.

There is a tendency to want to save on costs during the closure planning process by often using conceptual level engineering and limited analyses of the effects of the alternatives being evaluated. In the authors experience this is definitely a case of "penny wise and pound foolish", particularly on older abandoned mines where scientific data on the location and environmental effects of the mine waste is limited and often costly to obtain.

As a minimum, pre-feasibility level engineering (AACE Class 4) details need to be developed and in some case even feasibility level designs are necessary. Geotechnical and geochemical analyses should be comprehensive enough to make reliable projections of the long-term behaviour of the mine waste and the performance of the closure plans proposed. Assessing what the actual environmental conditions are and performing realistic risk assessments is also critical.

9 Resilient Construction

Resilient design and construction is required to ensure long-term effectiveness. Some of the key problems the authors have encountered include surface drainage ditch slopes that are too flat to prevent ponding and debris accumulation after settlement, resulting in minor erosion and natural re-vegetation. Rill erosion on steeply graded side slopes, blockage of subsurface water drains, either by chemical precipitation or sedimentation, ponding on newly constructed covers due to un-foreseen settlement of the underlying mine waste, gully erosion under hard-scaped (e.g. gunnited) diversion ditches, which couldn't adjust to settlement, etc. Another important consideration arises where it is the intent to construct a zero, or close to zero, infiltration cap using soil materials relying on compaction to achieve the necessary low permeability. This approach has been found to be generally ineffective in the long term as the cover materials gradually "weather" to resemble natural materials. A more realistic approach is to acknowledge natural soil covers can at best reduce but not eliminate infiltration and plan accordingly.

The authors recommend a conservative approach to developing the design details to be adopted to ensure both robust and resilient construction details. For example, robustness can be increased by incorporating smaller channels within larger channels to accommodate flows under ice covers, flatted berm side slopes to reduce the risks of freeze-thaw creep and damage, oversized subsurface drains in covers used for groundwater diversions, and the use of open channels rather than subsurface drains wherever possible, etc. Resilience can be increased by providing for anticipated failure modes; e.g. by thickening certain layers of a cap or rip-rap placed in a ditch, oversizing surface and subsurface drainages, providing cover designs that don't exclusively rely on relatively thin synthetic drainage layers, etc. A Failure Modes Effects Analysis (FMEA) is a useful tool for establishing a basis for selecting which elements need to be designed for increased resilience.

10 Closure Process

Closure of abandoned mine sites has become complex and time consuming. Furthermore, because there often is a concern about extremely high closure construction costs, teams managing closure have fallen into the trap of continually extending the closure plan decision and capital construction costs. The authors have evaluated costs for several mine closures where the major cost component (in some cases over 50%) is the site care and maintenance before closure, since funding the closure plan and performing closure construction has been deferred for ten years or more. These site "holding" costs can become particularly pronounced when water treatment plants need to be operated to manage water quality issues before closure is completed. These cost increases can be considered by a more rigorous and concentrated closure planning process by taking the view that closure is a construction project, just like any other, and not an abandoned mine operations and maintenance project. Closure managers should also be aware of the fact that there is often little merit in lengthy debates, or the need for closure elements that may increase costs by a few $ million, when the resulting annual site management costs are increased by several millions due to delays.

11 Conclusions and Recommendations

Planning and the design for closure of abandoned sites are sometimes unnecessarily cumbersome and do not necessarily lead to resilient solutions. Specific general issues that arise and how they can be dealt with are as follows:

- A large number of stakeholders with varying agenda and objectives requires that a comprehensive and systematic approach be adopted to planning and designing mine closure, including full documentation of all stakeholder comments and concerns and how these have been addressed;
- Closure objectives is one of the primary concerns that demands that issues be much more focused on specifics at the mine site;
- Well conducted consultation will reduce unnecessary challenges at a later stage and therefore need to be thorough and well documented for future reference;
- Well-conceived remedial or closure engineering alternatives are required. A systematic approach to screening of technologies and the selection of closure alternatives using combinations of the remaining technologies will lead to more resilient solutions;
- Improved decision making and approval processes will lead to reduced uncertainties in the appropriateness of the selected closure plan. This issue can be resolved by using detailed and formalized decision analyses that clearly show what trade-offs are made and how the various stakeholder inputs are addressed;
- Devote more effort to evaluating the required level of detail for the comparative analyses that are comprehensive and durable; and

- Improve robustness and resilience by designing more conservative designs where key elements can accommodate anticipated failure modes.

Another key issue that will be increasingly noticed in the future, is the cursory approach used to address post-closure land use issues. It is imperative that these be addressed during the closure planning and design phases to insure that expectations of future potential land uses of the closed facilities are well understood, that the appropriate access controls are included, and that, as necessary, permanent land use restrictions are included in durable legal documents, such as government regional land use plans, deed notices and restrictions, etc.

12 Closing Remarks

Planning of mine closures, whether it be for government or private entities is a complex multidisciplinary exercise involving not only the basic sciences, but also comprehensive decision analyses, risk analyses and risk communication and the politics of dealing with stakeholder groups with varying interests. The risks of having to change plans or re-do closure construction are unnecessarily high. The engineering profession has of yet not provided adequate support or leadership in these areas, so there is plenty of room for improvement. The authors challenge the engineers and scientists involved with closure to expand their horizons and play more of a leadership role in the planning, design and construction for closure.

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Modelling the Reduction of Iron Loads from Lignite Mining Dump Groundwater to the Pleiße River Considering Land Use Changes

H Büttcher *Ingenieurbüro für Grundwasser GmbH, Germany*

H Mansel *Ingenieurbüro für Grundwasser GmbH, Germany*

B Janisch *Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH, Germany*

R Schlottmann *Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH, Germany*

Abstract

The lignite mining dump of Witznitz in Central Germany is characterized by iron concentrations in groundwater up to 4 g/L. The total iron pool of the dump amounts to approx. 5 million tons. Rerising groundwater levels after mine closure in 1993 have resulted in the discharge of consistently high iron loads to the adjacent Pleiße river.

The quantity of groundwater discharge to the river is described by a 3D groundwater flow model using the program PCGEOFIM which is well known in German mine water specialist circles. Model coupling with PHREEQC enables the consideration of hydrogeochemical processes in the dump in order to predict the future development of iron concentrations and loads in the effluent groundwater.

Concerning remediation strategies, land use changes are considered by growing bur clover on the agricultural areas of the mining dump in order to enhance evapotranspiration. This leads to a reduction of groundwater recharge and therefore results in lower discharges and iron loads to the adjacent river. The model enables to quantify the effects of the measure, including different crop rotation scenarios which are demanded by law. The distribution of iron concentrations in the aquifer is calculated as well as the development of concentrations and discharging fluxes to the river. Thereby, the time delay due to the water passage through the unsaturated zone is taken into account.

Iron loads from the Witznitz mining dump to the Pleiße river are calculated in the order of 1 ton/day for the current century followed by a slight decrease, whereas only 3% of the total iron pool of the dump are easily mobilized. However, discharge is slow due to the low hydraulic conductivity of the dump material. Considering land use changes within the agricultural areas of the dump and reducing groundwater recharge by 75%, results in total iron loads to the river of approx. 0.6 ton/day, which is a reduction up to 40%.

In conclusion, specially selected land use changes seem to be a suitable measure in order to reduce highly iron-contaminated widespread dump discharges to surface waters.

Keywords: *reactive solute transport modeling; iron loads; dump aquifer; PcGeofim*

1 Introduction

The surface water quality of the Pleiße river in the lignite mining area south of Leipzig, Germany, shows total iron concentrations of up to 6 mg/L during periods of low water. Besides the visual impact, the high iron concentration results in iron clogging of the river bottom as well as negative effects on the aquatic ecosystem. By this, the achievement of a good ecological potential in accordance to the European Water Framework Directive is hindered.

Iron originates from the lignite mining dumps alongside the river, whose groundwater exfiltrates into the river. Due to iron disulfide oxidation of tertiary sediments, the dumps are often rich in bivalent dissolved iron. During the transition from the anoxic groundwater to the aerated environment of the river, oxidation to trivalent iron takes place as well as further formation of iron(3)-hydroxides or -hydroxysulfates, respectively. The process is accompanied by the formation of acidity.

Different measures are taken into account in order to reduce iron concentrations in the river, whereas a target concentration of 1.8 mg/L has been defined.

2 Study Site

One major source of iron in the Pleiße river is the dump of the former surface mine Witznitz, which was operated between 1946 and 1993. Dump material mainly consists of tertiary marine overburden as well as the adjacent sediments of the removed coal seams and to a lesser extent of quaternary flood sediments and tills. The tertiary marine sediments are rich in pyrite. The total iron pool of the dump was estimated to approx. 5 million tons.

After the devastation of the original river bed, the Pleiße river was relocated directly across the dump during the 1960s. Following the termination of operations, uplift of the groundwater table, which was formerly lowered by mining activities, began. This is connected with a direct discharge of dump groundwater into the river.

Recent mean total iron concentrations measured in dump groundwater are 1050 mg/L, whereas the mean pH is slightly acidic at 5.3. The ionic balance is decisively influenced by the concentrations of both calcium (480 mg/L) and sulfate (3700 mg/L). The spatial variability of iron concentrations is great, ranging from 3 to 4245 mg/L (Figure 1). This is due to a varying geochemical composition of the source material of the dump as well as a differing intensity of oxygen contact and iron disulfide weathering taking place during fore field drainage and dump formation as well as on active mining slopes and exposed dump surfaces. Maximum concentrations are measured along the Pleiße river, as it crosses the dump.

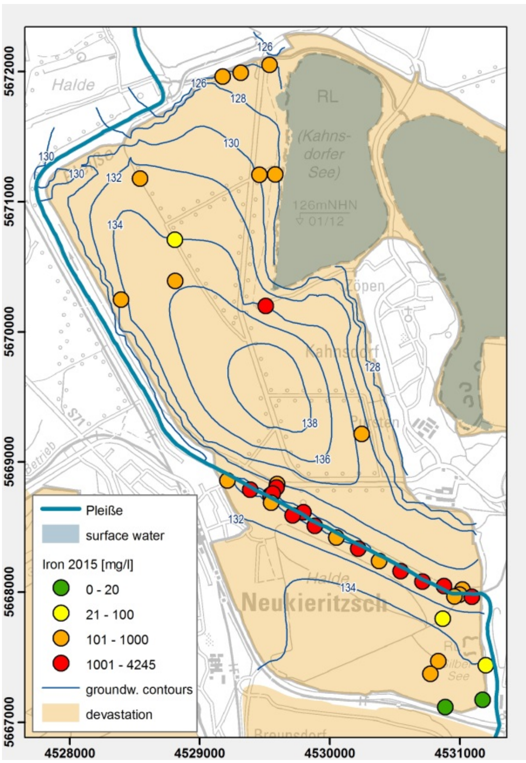

Figure 1 Study Site with measured iron concentrations and current groundwater contours

The area has been subject to an extensive monitoring during the last decades. There is good knowledge on groundwater levels and quality (wells), groundwater recharge (lysimeter data) and the composition of the solid phase. Furthermore, the Pleiße river is well monitored. Thus, data analysis enables to understand and quantify the ongoing processes.

3 Methods

In order to predict future dump-originated solute inputs to the Pleiße river, a reactive solute transport model was developed for the Witznitz dump, which allows a spatially differentiated calculation of groundwater discharge to the river both in quantity and quality.

Reactive solute transport modeling was realized by coupling the groundwater flow and solute transport model PcGeofim (Blankenburg et al., 2013) with the hydrogeochemical simulator model PHREEQC (Parkhurst & Appelo, 1999). By coupling the two models, it is possible to take into account reactions within the liquid phase, interactions between liquid and solid phase, such as iron disulfide weathering, as well as gas exchange processes in combination with transport modeling.

A more detailed description of the modeling approach is given in Büttcher & Mansel (2015).

3.1 Groundwater flow model

The 3D groundwater flow model of the Witznitz dump is part of a large-scale model which comprises the whole lignite mining area south of Leipzig. The surrounding consists of mining dumps as well as active mining areas with a still massive lowering of the groundwater table. PcGeofim calculations are based on the method of finite volumes.

The hydraulic conductivity of the dump aquifer was calculated from the silt and clay content using an empirical relationship according to Kaubisch (1986). Kf-values of the upper dump are in the order of 10^{-6} m/s, whereas the lower dump is characterized by values in the order of 10^{-8} m/s. Groundwater flow therefore takes place primarily in the upper part of the dump aquifer. Surface waters such as the Pleiße river as well as mining lakes are implemented as boundary conditions. Groundwater recharge is derived from the catchment model ArcEGMO (Becker et al., 2002) and amounts to an average of 80 mm/yr considering the whole dump body.

3.2 Hydrogeochemical model

The batch model represents the dump hydrogeochemistry originating from the initial unweathered substrates during dump formation to the recent monitored conditions. The primary minerals of the model are iron disulfide FeS_2, calcite $CaCO_3$, clay minerals (for the sake of simplicity represented by kaolinite $Al_2Si_2O_5(OH)_4$) as well as primary silicates such as feldspars or micas (Figure 2).

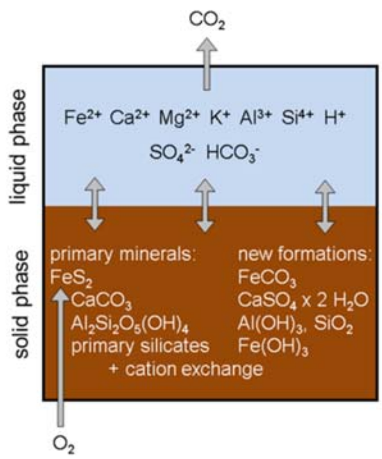

Figure 2 Hydrogeochemical process model

Addition of oxygen during dump formation leads to an oxidation of iron disulfide and a release of iron, sulfate und acidity. Buffering is primarily provided by calcite and after depletion at lower pH values by clay mineral solution. Dissolution of primary silicates is a kinetically slow process which takes place in parallel with the processes mentioned before.

CO_2 originating from calcite weathering degasses in part. Furthermore, new mineral phases such as siderite ($FeCO_3$) and gypsum ($CaSO_4x2H_2O$) can be formed. Solution of silicates and clay minerals can lead to the formation of aluminum hydroxide as well as silicon dioxide. Beyond that, precipitation of a mineral phase of trivalent iron is implemented in the model ($Fe(OH)_3$). Finally, the model takes into account the cation exchange of calcium, manganese, potassium, iron, and aluminum.

4 Results

4.1 Investigated Model Scenarios

The examined remediation strategy focusses on land use changes in order to reduce groundwater recharge and thus discharge and solid fluxes to the river.

It has been found that bur clover is a suitable plant for this purpose (Figure 3). It has a rapid growth, a huge growth height as well as a dense stock. Furthermore, it can be used as energy plant.

Figure 3 Bur clover (Wikipedia; Ivar Leidus)

Extensive experimental investigations using data from field studies as well as from lysimeter experiments have shown that bur clover (instead of traditional land use) is able to reduce groundwater recharge by 75%. Ideal conditions are created by soil loosening, fertilizing and liming.

In the modeling, a baseline scenario with traditional land use is considered and furthermore a second scenario, which takes into account bur clover planting on parts of the Witznitz dump with a reduction of groundwater recharge by 75%. In addition, crop rotation scenarios are included.

4.2 Groundwater flow regime

Groundwater dynamics within the Witznitz dump are essentially determined by surrounding surface waters (Figure 4 left). Due to comparably low hydraulic conductivities a groundwater cap is formed within the northern part of the dump at a level of > +139 m above sea level (a.s.l.).

Groundwater flow from the dump takes place to the Pleiße river, as well as to the mining lakes in the north-eastern part of the dump. The dump body south of the river is characterized by a groundwater flow to the river from southeastern direction at steady-state conditions after the completion of the groundwater table uplift.

Taking into account the growth of bur clover in the area shaded in red color results in a steady state groundwater table of max. +135 m a.s.l., which is 4 m lower (Figure 4 right). Thus, the hydraulic gradient to the Pleiße river is significantly reduced.

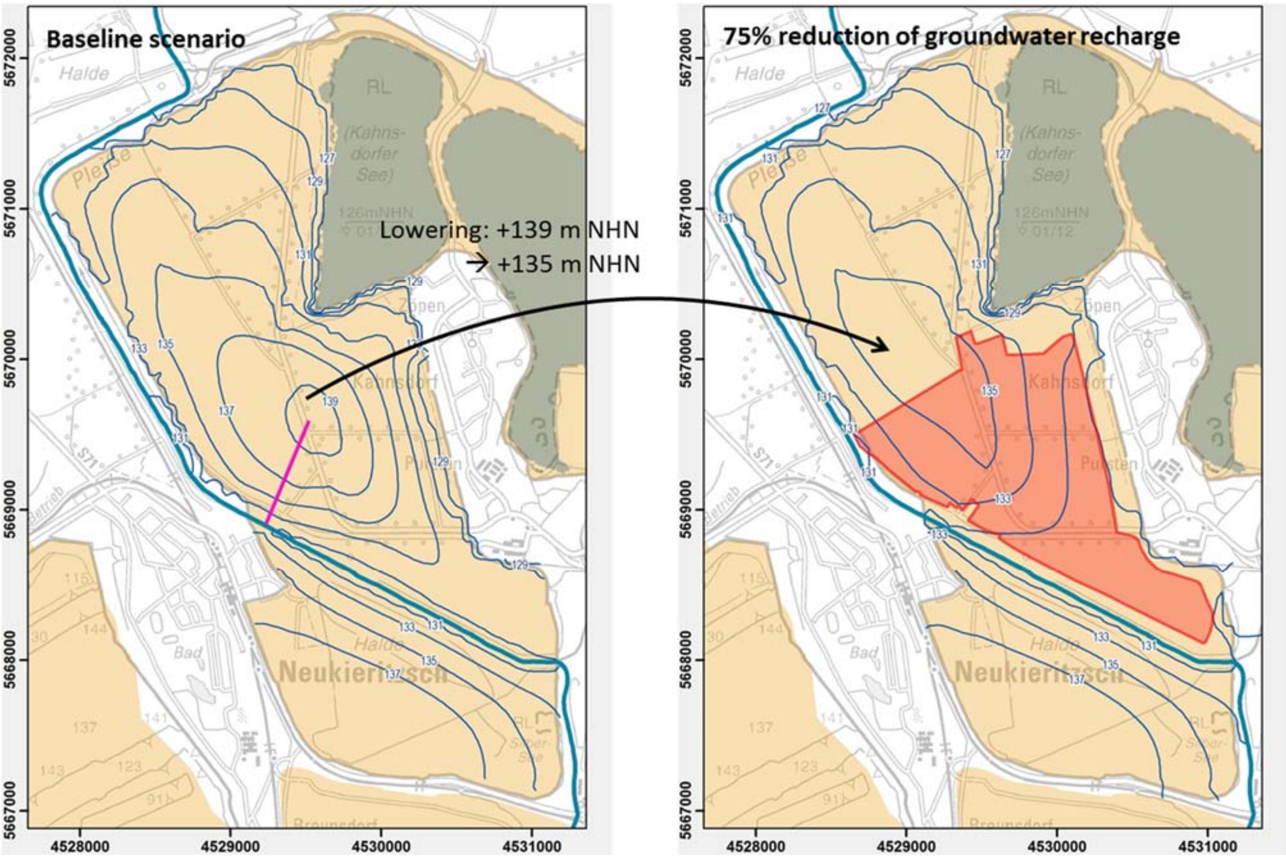

Figure 4 **Steady state groundwater contours (m a.s.l.); baseline and bur clover scenario (bur clover growth is considered in the area shaded in red color); pink line: cut (cp. Figure 6)**

Considering the development of the groundwater table in time, effective lowering is visible (Figure 4 left). However, it takes about 20 to 30 years to reach a new steady state in the dump, as groundwater levels are approx. 10 m below the surface and the seepage passage through the vadose zone causes an extinct delay. This has been investigated by a separate modeling approach using the program HYDRUS (Šimůnek & Šejna, 2011) and taken into account in the groundwater flow model.

Furthermore, two additional crop rotation scenarios have been modeled (Figure 5 right) considering 4 years of bur clover followed by three years or one year respectively of a different crop (scenario A, B). Crop rotation results in a great temporal variability of the groundwater recharge. However, model results show that there is only a strongly attenuated effect on the groundwater level. The effect of the measure is reduced by the proportion of the cultivation time of the different crop.

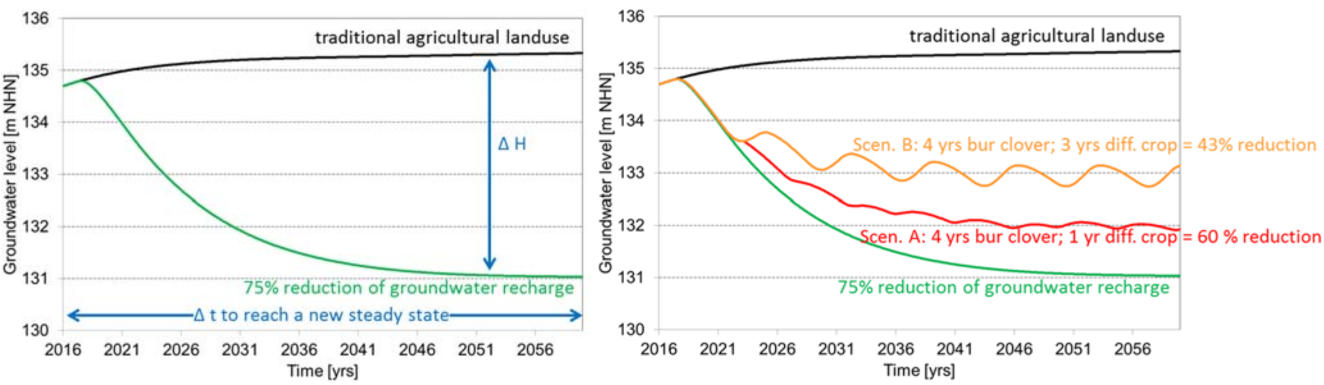

Figure 5 **Development of the groundwater table in time; baseline scenario, bur clover scenario and different crop rotation scenarios**

4.3 Iron concentrations in the aquifer

Exemplary results from the coupled groundwater flow and reactive solute transport model are shown for one cut representing the groundwater flow from northern direction to the Pleiße river (Figure 6).

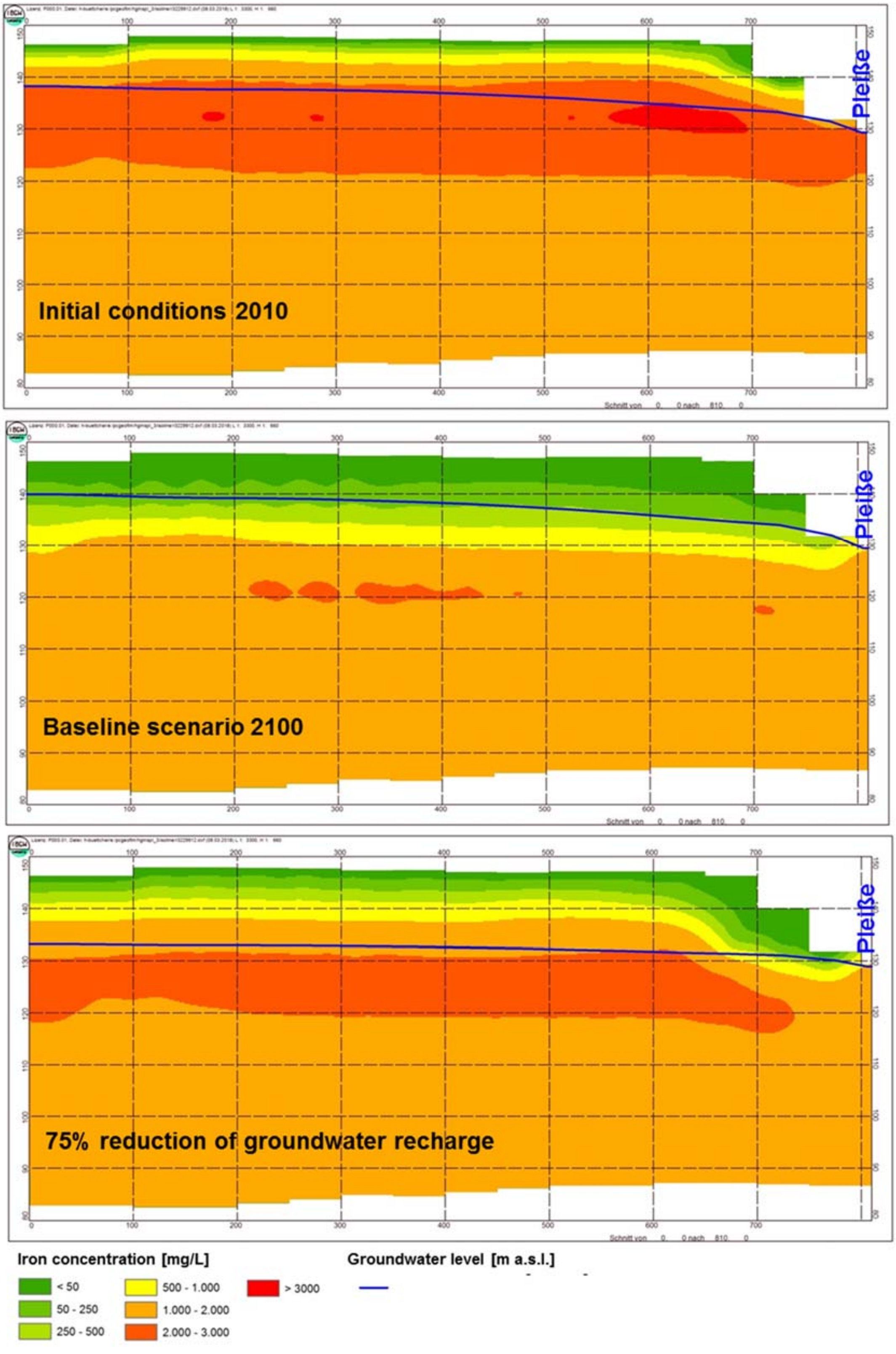

Figure 6 Modeled concentrations of total iron in the aqueous phase along an exemplary cut in the northern part of the dump to the Pleiße river; time slice 2010 (initial conditions) and 2100 (baseline scenario and scenario with 75% reduction of groundwater recharge); cut cp. Figure 4

The model simulates the solute discharge originating from iron disulfide oxidation with the groundwater flow. Iron concentrations in the cut for the year 2010 are between 2000 and 4000 mg/L in the upper part and between 1000 and 2000 mg/L in the lower part of the dump (Figure 6 top). Concentrations are reproduced in the model by considering the iron disulfide turnover during the dump formation and shortly thereafter. Low hydraulic conductivities and slow groundwater flow lead to the preservation of high iron concentrations in the dump body for long time intervals. The vertical concentration gradient is due to the oxygen input via the dump surface leading to a secondary iron disulfide oxidation next to the primary one within the whole dump body.

Considering the baseline scenario with traditional land use (Figure 6 middle), the model predicts a clear reduction of iron concentrations in the upper aquifer for the year 2100 because of diluting effects by groundwater recharge and the solute discharge to the river. Modeled concentrations are below 1000 mg/L in the upper aquifer. This effect continues into the future. In contrast, solute discharge from the lower aquifer is small, as the hydraulic conductivity is comparably low in this part of the dump.

The scenario with reduced groundwater recharge results in still much higher iron concentrations in the aquifer of > 2000 mg/l for the year 2100, as groundwater discharge is smaller and thus fluxes to the river are lower.

4.4 Iron concentrations and fluxes in groundwater discharge

The comparison of iron concentrations in the discharge to the Pleiße river, which result from the calculations in the cut shown above, exhibits iron concentrations of approx. 2500 mg/L in 2010 declining further on to approx. 500 mg/L for the baseline scenario in 2200 (Figure 7 left). For the scenario with a 75% reduction of groundwater recharge the decrease is less. Thus, modeled concentrations in 2200 amount to approx. 1000 mg/L. The faster decline in the baseline scenario is due to a greater solute discharge to the Pleiße river and corresponds with the results from the cut shown above.

Iron fluxes from the whole Witznitz dump to the Pleiße river amount to approx. 1100 kg/d in 2010 according to the model approach (Figure 7 right). In the baseline scenario a slow decline to 1000 kg/d is derived until 2080 followed by a stronger decline to approx. 400 kg/d in 2200. Considering a 75% reduction of groundwater recharge by land use changes, fluxes decline to approx. 600 kg/d by 2050. Thereafter they remain stable until 2080, followed by a slight decrease to 400 kg/d in 2200. The remediation strategy is therefore useful to significantly reduce fluxes during the next decades. Since discharges are smaller than in the baseline scenario, fluxes remain at this level for a long time after.

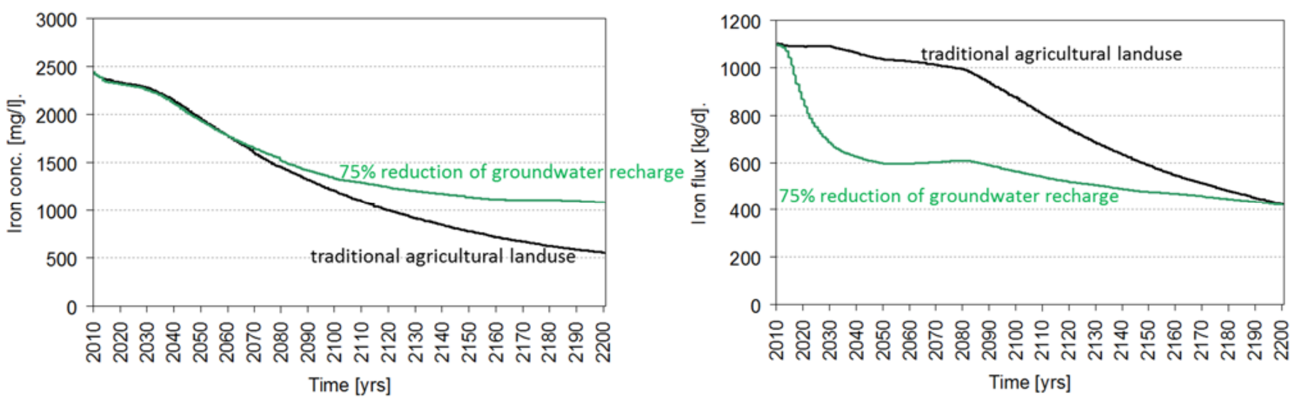

Figure 7 Time series of modeled iron concentrations (for the shown cut in Figure 6) and iron fluxes from the whole dump to the Pleiße river; baseline scenario (traditional agricultural landuse) and scenario with 75% reduction of groundwater recharge

5 Conclusion

The model approach shows that land use changes are able to significantly reduce solute loads the surface waters by reducing groundwater recharge.

The Witznitz dump exhibits ideal conditions for that remediation strategy, as the treated area is a hot spot of iron concentrations. The dump aquifer is fed by groundwater recharge only rather than by inflowing groundwater. Furthermore, evapotranspiration from the groundwater surface is neglectable, as the groundwater table is deep enough. Finally, the area used to be cropland. Thus, realization of land use changes is easy to perform.

Different measures such as collecting ditches or the creation of sedimentation areas are also investigated. The model provides a suitable decision making support by calculating different scenarios and thus quantifying the expected development of groundwater levels, solute concentrations as well as fluxes.

Acknowledgement

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Change Management over the Life of Mine: Challenges and Opportunities for Closure Residual Risks

J Sanders *Klohn Crippen Berger Ltd., Canada*

M Wendtman *Glencore Coal, Australia*

A Sexton *Glencore Copper, Australia*

Abstract

Change within the resources sector is inevitable. Whether change occurs through mine plan optimisation, design updates, regulatory or personnel changes, each type involves managing risk. The lack of change management practices in a constantly changing environment and resulting loss of knowledge is a significant risk that largely remains unmeasured throughout the mining life cycle. Staff turnover, poor documentation, and/or the impact of an experienced workforce transitioning to retirement enhance the challenges of effectively managing change and transferring important knowledge. The effects of poor change management at the end of the mine life are obvious: unfocused closure objectives and performance targets; risks and opportunities not identified and managed; and diminished trust with key stakeholders and future stewards of the land. Yet, change management and mine closure planning are rarely thought of as the same process.

Mine closure and relinquishment of tenure is the ultimate goal; however, only a minority of mine operators achieve this. Active or passive care and maintenance of a facility is a typical outcome with focus on managing long term residual risks and reducing financial assurance carried for the liability. Closure residual risks can be described as either tolerable (i.e., site is safe, stable, non-polluting); intolerable, but can be practically reduced to a tolerable level (i.e., requiring remediation); or intolerable (i.e., not practically reduced resulting in long-term legacy or unsustained costs). Understanding and quantifying residual risk throughout the mine life is critical, particularly with changes to the mine plan.

This paper discusses key practices over the life of mine that may increase a mine operator's resilience during change and reduce the potential for long-term closure liabilities. Application of management practices are discussed, relative to project execution and life of mine planning. A group of mining industry professionals from various countries and technical backgrounds, whom rely on the outcomes of change management, were interviewed to support this study. Various challenges and opportunities are summarized from these interviews.

The motivation for developing this paper is from an observed need to increase dialogue on this topic (i.e., consolidating and transferring implicit knowledge to explicit knowledge), with a goal to improve the mining industry's reputation in closure outcomes and manage legacy risks This paper targets mining industry leaders, specifically those within operational and corporate decision-making roles.

Keywords: *change management, mine closure, residual risk, knowledge transfer, legacy*

1 Introduction

1.1 Overview

The mining industry is defined by complexity, uncertainty, and reliance on short-term decisions that can result in rapid change. The cumulative effect of these decisions can be seen at the end of operations where closure residual risks may persist for hundreds of years (e.g., water treatment of ML/ARD).

There are numerous studies which have focussed on advancements within mine closure technologies for key closure risks (e.g., acid mine drainage/metal leaching, tailings design, final voids, cover designs, etc). Similarly, numerous industry guidelines are available which help define why to implement change management practices, but often lack detail on the processes for how to implement it. Few studies have focused on processes within change management in the mining industry, particularly as it relates to closure residual risk. This paper discusses some of the key practices used in change management over the life of mine that may improve the ability to increase resilience during change and better manage closure residual risk, particularly during operations.

1.2 Business Case

Change management requirements are typically included in mining standards and guidelines, however quantifying and promoting the advantages onsite are difficult as benefits are not always tangible and require financial resources and time (Massingham, 2008). Since the 1980s, the importance of change management and knowledge transfer within the mining industry has increased due to various pressures. These include, but are not limited to: i) mergers acquisitions, and company restructuring with globalization and market fluctuations; ii) increased government regulations which require vast amounts of data to support compliance; iii) increased technological advancements which have created a sea of digital data and an accessible international jobs market; and iv) intense scrutiny from public and political stakeholders in order to maintain “social license” expectations (i.e., long-term trust within a community based on transparent and meaningful engagement).The following summarizes five justifications for establishing good change management practices, specifically as it relates to long-term planning outcomes.

1.2.1 Life of Mine Planning

Change management requires a structured decision analysis approach to systematically address important choices in the context of multiple variables and objectives, especially for changes which influence mine closure outcomes. Our interpretation of facts often shape important strategic decisions for life of mine planning. The “ladder of inference” is a useful model to describe how people give meaning to observations and base life of mine planning decisions on this. The thinking stages can be compared to rungs on a ladder, whereby the reasoning process starts at the bottom of the ladder (Senge 1990). People select facts from data and observations which they translate from prior experiences. These interpreted facts form the basis for beliefs and assumptions, which in turn lead to decisions. Once beliefs are formed, a reclusive loop can either lead to new conclusions or re-enforcing existing beliefs through selection of similar information (e.g., “*at this mine site we don’t have a water quality issue as our current sampling plan hasn’t shown any issues*”).

A structured decision-making process involving multi-disciplinary teams is required at this reclusive loop stage to question existing assumptions and seek contrary data or sensitivities. Timely access to the right explicit knowledge (i.e., information which can be physically captured and documented) and tacit knowledge (i.e., information extracted from personal experience), for decision makers creates the platform for good life of mine planning outcomes.

Management of tailings and mine waste storage facilities is a relevant example for the minerals industry relating to life of mine risks and opportunities. On one hand, robust and resilient designs present an opportunity to incorporate knowledge gained through an adaptive observational method approach (Patel et. al. 2007), however significant closure and operational risks can develop if life of mine change is not managed and acted on. The transfer or retention of critical information is integral to the long-term strategic management and execution of dam construction. These facilities contribute to a significant portion of legacy risk at the end of mine life, which is made more complex by annual design changes from initial construction to closure as they are raised in height over the mine life. Recent evidence of poor life of mine change management has been observed with extreme tailings dam failures in Canada (Mount Polley) and Brazil (Fundão). Independent investigations highlighted that poor change management in either design, mine plan, and/or key personnel were contributing causes to each dam break (see MEM 2015 and Morgenstern et al. 2016). While these events occurred during operations, the same failure mode hazard and residual risk may persist into closure. The objective of eliminating these failure modes and delicensing a tailings facility at closure is often unrealistic, as annual life of mine planning is often not aligned with creating a safe, stable, and non-polluting final landform.

1.2.2 Market Fluctuations and Unplanned Closure

Laurence 2006 reviewed 800 closed mines to retrospectively help inform rehabilitation and closure risk management. Approximately 75 percent of observed mine closures were unplanned and were due to economic factors, predominately from fluctuating commodity prices and industry cost cycles leading to voluntary administration or receivership (Laurence 2006). Each cycle fluctuation places tangible pressures on costs, budgets, schedules and operating performance (Table 1). These pressures can influence often intangible outcomes regarding the ability to transfer critical knowledge to key personnel or depleted workforces, typically resulting in inefficient rework and prioritisation of short-term compliance and production risks. Decision making which is influenced by short-term planning key performance indicators (KPI) (e.g., safety, production targets, and compliance with permit conditions), while important, sometimes overshadow more strategic decision making such as managing risk closure related design. Furthermore, as this mine lifecycle extends, the opportunities to manage long-term residual risks through higher order critical controls (e.g., elimination, substitution, engineered) is reduced.

Table 1 Market fluctuation pressures

Market Pressure	Site Reaction	Observed Outcomes
Price decrease	Deferring CAPEX spend reducing C1 cash costs	Delaying projects and CAPEX, staff layoffs, reducing C1 cash costs (e.g., focus on daily overheads and compliance of exiting permit conditions rather than long-term planning)
Price increase	Increasing mill throughput, fast-tracking projects aimed at resource/reserve definition	Increased mine expansion/production related projects, short-term operational KPIs focussed on increasing tonnes and mill throughput resources spread thin, reduced ability to attract and retain good staff due to undersupply of experienced and qualified people, increased burnout of key staff due to increased demand, systems not fully developed and implemented.

1.2.3 Retiring Experienced Workforce

Canada has more people over the age of 65 than under 15 (StatCan, 2016). The age group that now encompasses the baby boomers (50-69 years old) makes up 27 percent of the population, compared with 18 percent in that age group two decades ago (StatCan, 2016). This is a similar story for similar developed countries, where an increased number of industry specialists from the baby boomer generation will retire, leaving a reflective skills shortage. This population shift from the knowledge keeper "guru" to the next generation may represent a failure point for an organization. A wider gap between workforce experience and availability may impact project outcomes due to over demand for expert opinion, increasing costs and affecting critical review for technical risks (Chand and Tung, 2014).

De Long 2004, describes knowledge as the *"capacity for effective actions or decision-making in the context of organizational activity."* Prusak 2015 also notes that organizations that are most effective at knowledge transfer improve project outcomes by nearly 35 percent. Lost knowledge undermines the capacity to innovate and make informed decision, ability to adequately assess risks which may affect long-term performance outcomes, and results in more costly errors, additional time, unplanned OPEX/CAPEX costs due to rework and inefficiencies. Transferring this experienced workforce tacit knowledge now as part of change is critical to remain competitive and influence long term legacy outcomes.

1.2.4 *Increased Regulatory Enforcement and Reclamation Provisions*

Regulatory enforcement and legislative change involving mine closure outcomes and increased financial assurance liabilities has recently been observed in numerous mining jurisdictions.

Within Canada, examples of policy review have been observed in British Columbia (e.g., BC financial assurance report by Ernst and Young 2017) and other jurisdictions. Within Australia, a recent senate inquiry was initiated on rehabilitation of mining and resources projects as it relates to Commonwealth responsibilities. Furthermore, Queensland (Qld) and New South Wales (NSW) have both seen an increased legislative focus on rehabilitation requirements and financial assurance liabilities due to financial assurance deposits are not likely to be sufficient to cover the full costs of each mine's rehabilitation (e.g., NSW Government 2017 "Improving Mine Rehabilitation in NSW"; Qld Government's 2017 Financial Assurance Reform). An updated bonding scheme is proposed in Qld and NSW during 2018 which will include some form of company financial default risk.

As such, the mining industry should acknowledge that fundamental change is required to address poor closure and rehabilitation outcomes. These outcomes are often the result of a lack of closure objectives engagement and closure alternatives decision analysis, couple with poor change management throughout the mine life. The alternative is a stringent and rigid regulatory framework with hampered opportunity for industry leading practice, and potential for legal proceedings against companies.

1.2.5 *Due diligence: Mergers and Acquisitions*

A data room is an online depository of key documents on a company or site which is used during mergers and acquisitions due diligence. Due diligence investigations by investors frequently find gaps in the seller's quality of historical documentation, whereby deficiencies may lead to an investor applying remedy conditions negatively impacting the assets value. Evidence of good documentation, accurate closure design and financial assurance throughout the life of mine improves investor confidence, and perceived asset value.

2 Background

The following section summarizes the two main themes of this paper which are closely linked; change management practices and residual closure risk. A study-specific industry survey was facilitated to help support observed challenges and opportunities.

2.1 Change Management Practices

The Association of Change Management Professionals (ACMP) defines change management as "t*he practice of applying a structured approach to transition an organization from a current state to a future state to achieve expected benefits*" (ACMP 2014).

Closure planning shares a similar definition. Relating to mine closure, "*achieving expected benefits"* is typically promoted as the conceptual ideal (i.e., smooth mine relinquishment of post-mined landforms which has an economic and/or social beneficial use). Pearman's 2009 book on "101 things to do with a hole in the ground" is a light hearted read about good news stories on mine closure and reclamation. These examples however are few and far between, and typically can be observed in smaller non-complex mines and environments. A more common scenario is that residual risks remain, resulting in active care and maintenance by the Owner with financial assurance maintained to reflect the long-term liability.

Key to change management is securing buy-in to the change, and aligning design and people with this vision. Change management practices are closely linked with strategic planning, risk management, and project lifecycle practices. Change management has various models and theories for implementation (CMI, 2017), however it typically requires implementation of various success factors (see figure 1).

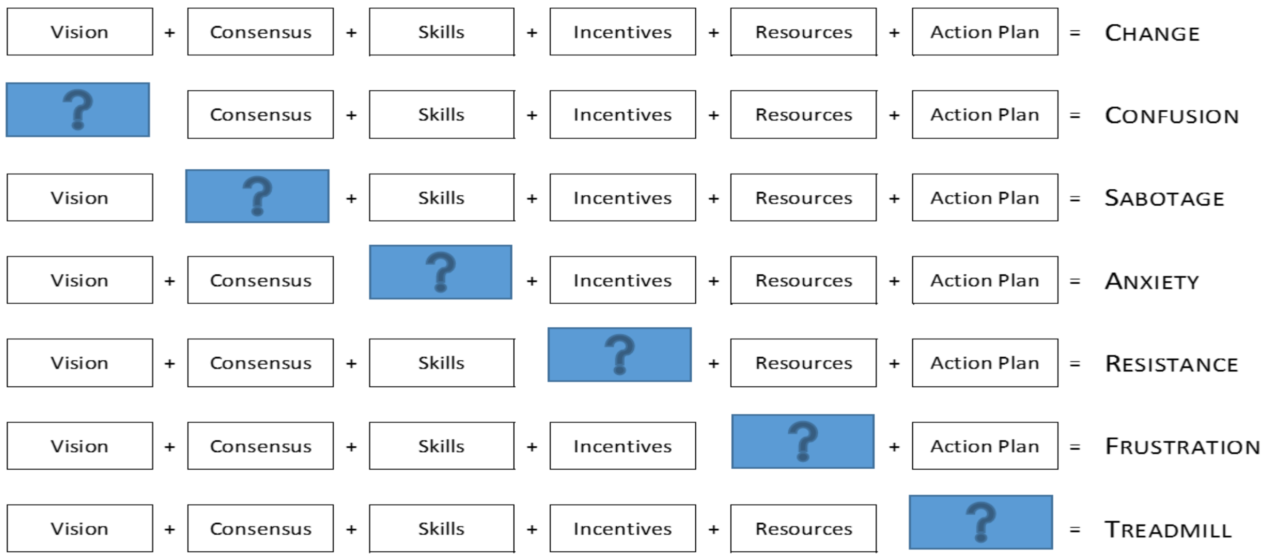


Figure 1 Managing complex change (adapted from Knoster 1991)

Like most systems based and planning approaches, change management can be compared to a "PLAN-DO-CHECK-ACT" framework which captures implementation of the above success factors, summarized below.

- **PLAN**: establish a sense of urgency, define vision and objectives, gain consensus/buy-in and evaluate change impact/operational readiness, commit governance structure, resources and define roles/responsibilities, assess risks and opportunities through structure decision analysis.
- **DO**: execute plan with required skills/incentives/resources/etc, while removing inefficiencies.
- **CHECK**: review implementation/effectiveness with project and review teams, inform and align stakeholders, generate and communicate short term wins and lessons learned.
- **ACT**: review vision, objectives, and action plans as part of annual and long-term business planning cycles. Sustain change as part of corporate culture.

The above PLAN-DO-CHECK-ACT change management framework can be applied to various levels of closure planning:

1. Business as usual: change is captured within business planning cycles to review objectives, assess short and long-term risks, and implement management programs to manage those risks. Significant level risks are typically reviewed by corporate governance or independent review panel function.
2. Unplanned changes: material changes and major projects (e.g., CAPEX >1M, extension of life of mine, complex in nature with high degree of technical uncertainty, involves high hazard activities, etc). Standards which involve risk management and structured decision analysis help maintain focus and continuity in assessing the effects of the change on the business and integrating these into the annual business planning cycle.
3. Formal closure plan updates: typically involves clarification and buy-in with internal/external stakeholder on closure objectives (including desired end land uses), reviewing risks and opportunities, development of closure alternatives and prescriptions for implementing those objectives, and establishing programs with performance and success criteria for demonstrating objectives are met to reduce closure residual risks.

2.2 Mine Closure Residual Risk

Residual risk is defined as the "*risk remaining after risk treatment*" (ISO 31000:2009). Specific to mine closure, residual risk is considered as the treated inherent risk (i.e., physical stability, chemical stability, end landuse, socio-economic factors) after measures have been implemented and monitored for effectiveness. Closure residual risks can be categorized as either tolerable (e.g., site is safe, stable, non-polluting landforms); intolerable, but can be practically reduced to a tolerable level (e.g., requiring minor remediation); or intolerable (e.g., effects not practically reduced resulting in long-term legacy or active management).

A standard closure plan should be risk-based to identify and assess residual risk. Identified gaps can be then captured in a forward works program, supported by design/technical assessments, with uncertainties suitably reflected in financial provisioning. As stated in International Accounting Standard 37 Provisions, Contingent Liabilities and Contingent Assets "*risks and uncertainties that inevitably surround many events and circumstances shall be taken into account in reaching the best estimate of a provision*" (IFRS 2018).

After fully assessing the closure risks and opportunities, a closure plan (to achieve closure objectives and agreed end land use/s) can be developed to manage risks to an acceptable level, while maximising strategic opportunities. Assessing potential residual risk may include any number of risk assessment tools at various stage of planning, with some examples provided in the ICMM Closure Toolkit (ICMM, 2008). For assessing process and business risks, HAZOP studies and bow-ties are often used to assess fatal flaws and high consequences/critical controls. For assessing technical risks, a failure mode effects assessment (FMEA) in combination with an ecological risk assessment (using a source-pathway-receptor model approach) are useful tools. On its own, risk assessments do not provide strategic decision-making around end landuse planning and assessing cost-benefits for closure alternatives in meeting identified end landuse/s. Meaningful collaboration with internal and external stakeholders in identifying a positive end land use legacy is critical and complimentary to the risk assessment.

2.3 Industry Feedback

An industry survey was developed (see Sanders and Wendtman 2016) and built on to support the main themes of this study. The survey was conducted using a combination of targeted interviews and an online tool using "EsurveysPro". Survey recipients were pre-selected through industry contacts of the authors, and chosen to capture a range of mining disciplines. Survey questions included:

- What do you see as the key challenges/barriers to change management (i.e., related to long-term decision making such as closure planning)?
- What opportunities are there to address these observed challenges?
- How often are closure objectives revised and updated (i.e., as required by permit conditions, determined by corporate standards, formally every 5 years, etc)?
- When is feasibility level design detail of mine closure typically integrated into business plans (i.e., prior to construction, during operations, < 2 years from closure, after operations, etc)?
- Does your company/site have long-term KPIs which are linked to closure planning?

Approximately 90 mining professionals responded ranging from a variety of demographics, experience levels, technical disciplines, and countries (e.g., Canada, Australia, Peru, Chile, the United States, Mongolia, Indonesia, Democratic Republic of Congo, and the U.K). An even distribution of experience levels ranging from 5 years to 40+ years was obtained. Figure shows the range of technical backgrounds of survey respondents.

Professionals within the environmental management discipline were specifically targeted, as their roles typically involve mine closure planning and managing multi-disciplinary tasks covering a range of onsite and offsite responsibilities.

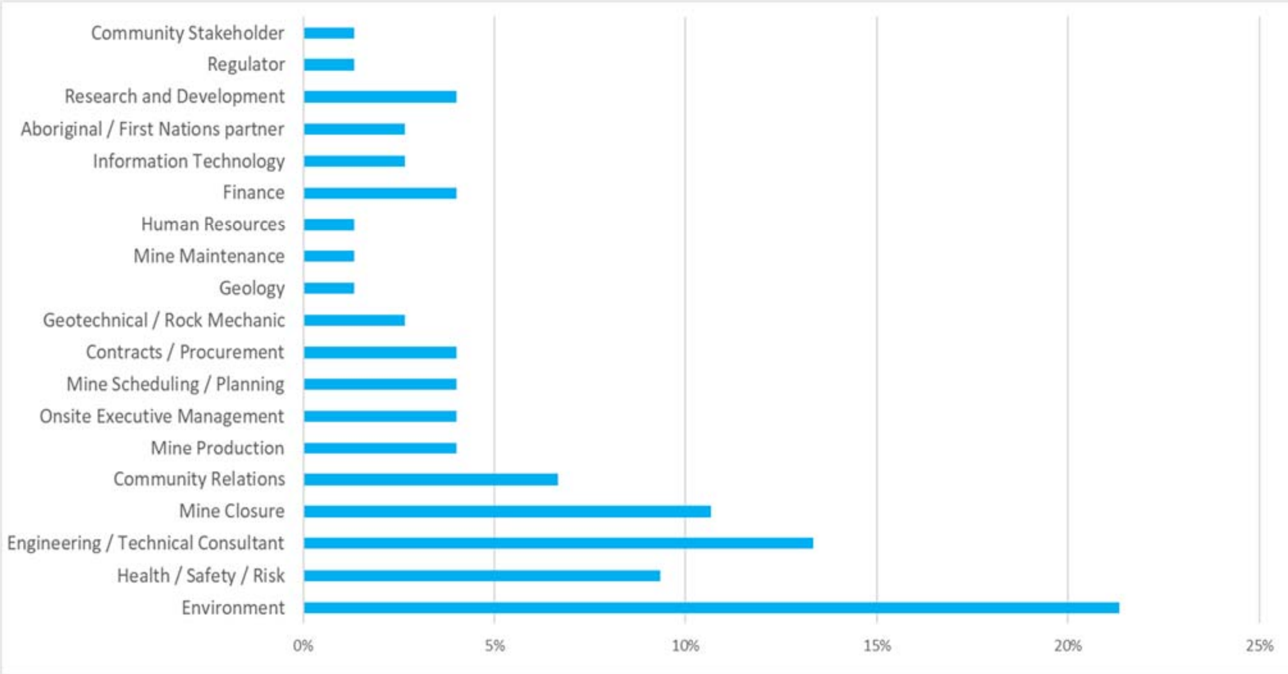


Figure 2 Mining background / discipline of survey respondents

3 Challenges and Opportunities

An overarching challenge observed through review of literature and engagement with survey respondents was that mine closure planning is not thought of synonymously with change management.

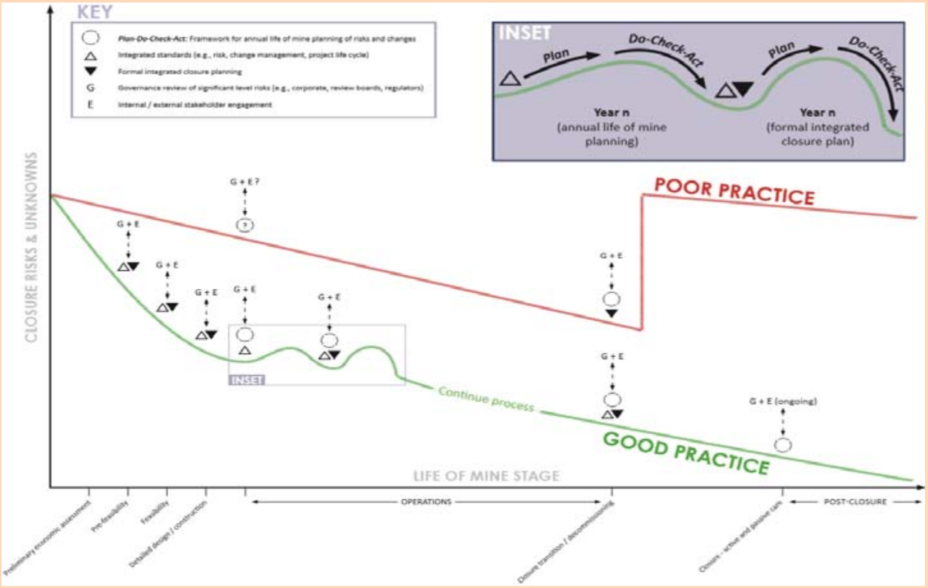
The industry survey also identified the following additional key challenges to change management and knowledge transfer as it relates to the effects on long-term closure planning outcomes. In order of significance:

1. Lack of time, which is typically driven by other high operational priorities.
2. Silos created between departments.
3. Lack of team continuity resulting from staff turnover.
4. Lack of effective systems.
5. Change management and knowledge transfer is not identified as a major risk / opportunity.
6. Poor strategic planning and execution.
7. Leaders don’t recognize the value of knowledge transfer.
8. A disconnect between corporate expectations and site performance.

The following section builds on the survey respondent’s feedback and summarizes some of typical challenges and opportunities relative to long-term closure planning outcomes (Table 2).

Challenges and opportunities have been categorized under “governance and systems”, “risk management”, “tools/technology”, and “people”. Opportunities are focussed primarily for mine operations and are assumed to build on an existing robust mine plan and closure design developed prior to construction.

Table 2 Challenges and Opportunities

Challenge	Opportunity	Lead
Governance and Systems		
Lack of life of mine planning which incorporates change management and closure risk	• Life of mine closure planning relies on a change management frameork. Significant operational and closure risks (e.g., identified by operational risk registers/bow-tie risk assessment, etc) should include mine closure and be closely linked to annual life of mine planning. The below figure (adapted from ICMM 2008) provides a useful framework for managing life of mine closure residual risk through life of mine change management.  	Owner
Absent or ineffective standards which define change management	• Change management standards should under the definition of "change" include mine closure risks in additional to operational change (e.g., method of operation, change in design/specification, regulatory/permit conditions, new plant/equipment, etc). • Project lifecycle standards should detail closure requirements to be assessed at each study phases based on project definition. Include 'tollgate reviews' and project close out requirements which assess lessons learned and details transition plans to the next mine life stage.	Owner

Challenge	Opportunity	Lead
Poorly managed decision making around closure vision, objectives, and design alternatives	• As part of change management and project execution, conduct decision analysis approach to define objectives and assess design/mine plan alternatives. Gregory et.al 2012 and http://www.structureddecisionmaking.org/ outlines a useful process as below. Hockley and Coulter (2010) provides an example of how decision analysis can be implemented as part of the Red Dog mine closure plan. Decision analysis steps include: 1. Clarify decision context: Identify the problem, identify who needs to be involved, process for decision making, and clarify roles and responsibilities of the decision/review teams. 2. Define objectives and evaluation criteria: scope definition, issue raising and classification, decision classification and strategic alternatives. 3. Develop alternatives and estimate risks/opportunities. 4. Evaluate trade-offs and select preferred alternative (e.g., using a multi-accounts analysis process). 5. Implement and monitor: Ramp up level of design accuracy and account for material changes.	Owner
Lack of closure design definition prior to mine closure	• Approximately 15% of respondents from the industry survey said that a feasibility level detail of mine closure estimate occurs too late in the mine life, typically within two years prior to the end of mine operations when opportunities have long passed. • Support closure plans and design with a Class 3 estimate during permitting prior to construction (i.e., AACE classification Class 3 is a semi-detailed costing for budget authorization (typically +/- 30 % design accuracy). The closure design should then be optimized during operations with updates every five years as a minimum for a life of mine with 20 years of ore reserve, and more frequent for a shorter mine life.	Owner, Regulator, Consultant
	• Establish an experienced and multi-disciplinary mine closure committee to help identify the broad closure risks and opportunities (i.e., representing Senior Management, Engineering, Health/Safety, Environment, Community Relations, Human Resources, Finance, key Partners/Stakeholders including Aboriginal persons). This team should form the basis for ongoing alignment between stakeholder interests and alignment on closure objectives and implementation plans.	Owner
Permit conditions not aligned with closure objectives	• 25% of industry survey respondents stated that closure planning objectives were revised as required by permit conditions. Owners must spend effort to refine these with stakeholders in meaningful engagement. See references by Hockey and Coulter 2010, Anderson et. al 2015, Unger 2017, and McKenna, et al. 2016 for further discussion.	Owner, Regulator

Challenge	Opportunity	Lead
Closure risks, changes, and assumptions are not adequately reflected in closure cost estimates.	• NI 43-101 was created after the Bre-X scandal to protect investors from unsubstantiated mineral project disclosures and optimism of a resource. Similarly, closure asset retirement obligation estimates should include enough detail that over-optimism in liability costs are managed on the balance sheet and reflect the intent of IAS 37 'Provisions, Contingent Liabilities and Contingent Assets'. Assumptions should be revised with closure risk assessments and technical studies by an experienced professional and reflected as part of the company's asset retirement obligation. Formal annual reviews by corporate technical and finance leads should be undertaken to reflect changing conditions and improved information. • For Net Present Value (NPV) calculations devalue closure liability making closure costs irrelevant to project financials, apply an annual risk-adjusted discount rate for discounted cash flow (DCF) models. For long-time periods (e.g., water treatment or uncertainty in meeting closure objectives), a higher risk-free discount rate (i.e., > 4%) can be factored. • Probabilistic costing models can be useful to help define the expected range of closure costs (e.g., variability in technical costs, unit rates, escalation factors, IAS risk factors, etc). Accurately identifying the components and probabilities that contribute to high-end costs of a cumulative cost exceedance probability curve improves focus on identifying the major cost risks early on in a mine's life cycle (see Hutchinson and Dettore 2011). Annual business planning of net direct (C1) cash cost (i.e., onsite costs of mining/processing/smelting excluding company overheads) can then be reflected to capitalize on progressive reclamation and and align studies to minimize high risk costs and/or probabilities. Financial modelling via the risk identification and strategy using Quantitative Evaluation (RISQUE) method can assist managers integrate triple bottom line considerations into planning processes (Bowben et al., 2001).	Owner, Regulator, Consultant
Risk Management		
Poor quality closure risk assessment	• Assessing closure residual risk is unique and should be assessed independent of day-to-day operational risks for the following reasons: i) probabilities for closure have longer return periods (e.g., flood), and ii) closure risks require a greater level of community interaction to determine the range of tolerable and intolerable residual risk.	Owner
	• Ensure risk assessments are conducted by an experienced facilitator. Ensure risk assessment team is engaged in the process and is multi-disciplinary (e.g., safety, environment, human resources, finance, legal, engineering, Aboriginal, Community). • Select the best risk assessment tool and scoping for the right purpose (e.g., Failure Modes Effects Assessment in combination with a source-pathway-receptor model is a useful tool at assessing failure modes and technical risks). • The hierarchy of controls should be applied to control measures (i.e., more effort should be spent on elimination/engineering design mitigation of closure failure modes compared to management/systems based). Apply confidence factors for each risk based on the depth of knowledge (e.g., studies, expert opinion, etc) to reduce bias and overconfidence.	Owner

<table>
<tr><th>Challenge</th><th>Opportunity</th><th>Lead</th></tr>
<tr><td>Lack of buy-in for the ranges of tolerable and intolerable risk with internal and external stakeholders</td><td>

- A consultative approach undertaken with the future stewards of the land needs to help define where the range of tolerable and intolerable risk lies. Planned strategies can then be developed with future stewards (e.g., pastoralists/First Nations/Council) and administrators (e.g., regulators).
- Typically, three types of residual closure risks: i) risk is tolerable; ii) risk is intolerable, but can be practically reduced to a tolerable level and; iii) risk is intolerable. The below figure summarizes this relative to a standard 5 x 5 risk matrix score.

<table>
<tr><td></td><td colspan="5">Typical range of tolerablility (sliding scale depending on stakeholders/partners)</td></tr>
<tr><td>Risk Matrix Score</td><td>Class 1</td><td>Class 2</td><td>Class 3</td><td>Class 4</td><td>Class 5</td></tr>
<tr><td>Residual risk tolerability level</td><td>Tolerable (i.e., site is safe, stable, non-polluting)</td><td colspan="2">Intolerable, but can be practically reduced to a tolerable level (i.e., requiring remediation)</td><td colspan="2">Intolerable (i.e., not practically reduced resulting in long-term legacy).</td></tr>
<tr><td>Mine Closure Phase</td><td>Discussion about relinquishment</td><td colspan="2">Passive care and maintenance. Potential relinquishment with conditions.</td><td colspan="2">Active care and maintenance</td></tr>
</table>
</td><td>Owner</td></tr>
<tr><td>Risk assessments lack a forward works program</td><td>

- Closure risks and opportunities should be adequately assessed, and a forward works program implemented to improve certainty in "known unknown" risks and reduce the overall residual risk profile at end of operations. A program with quantitative performance metrics with clear responsibilities and timelines should be developed with the risk assessment team to gain buy-in and drive the quality of future risk assessments.
</td><td>Owner</td></tr>
<tr><td>"Adaptive management" either not understood or poorly implemented</td><td>

- The Observational Method is an essential element in the overall site monitoring and surveillance program. At the center of the Observational Method is the identification of plausible failure modes to select performance parameters that can be effectively monitored in the field against predefined trigger (alert) levels. The method was never intended to "rescue" a sub-standard design that was based on inadequate site investigation, insufficient details and less than acceptable design practices.
- The Observational Method focuses on "unusual conditions" whereby there is sufficient time to collect data, monitor the performance of a system, and implement contingencies as appropriate. Closure risks typically include many developing hazards that are either not identified (i.e., unknown unknows) or their potential to materialize isn't understood (i.e., known unknowns), therefore not given higher priority. Conditions that are "rapidly developing" or "urgent" are not amenable to the effective implementation. See Patel et, al 2007 for further reading.
</td><td>Owner, Consultant, Regulator</td></tr>
</table>

Tools and Technology		
Poor historic record keeping and factual data (e.g., monitoring data)	• "Digital effectiveness" (i.e., the need to use digital data to solve urgent business problems and improve productivity) is named as the leading global resource risk for 2017/2018 (Ernst and Young 2018). As technology shifts, companies jeopardize falling behind unless they adapt to technological change and evaluate information to assess alternatives and make good decisions. • Establish I.T. systems that capture, institutionalize, and deliver knowledge to operations at the point of need. A simple project management I.T. platform (e.g., SharePoint) allows knowledge transfer among a range of users. Establish a simple network interface which has access to key information, including project lessons-learned. Key common data management systems should be as far as practice, integrated consistently across the site to reduce the risk of management 'silos', and duplicating information.	Owner, Consultant
	• Establish document control platforms for managing current/historic technical studies, procedures, and lessons-learned through a digital library. Use available industry guidelines and tools to help guide long-term knowledge transfer (e.g., Section 6 of the ICMM guideline for planning integrated mine closure, and the Anglo-American Mine Closure Toolbox).	Owner, Consultant
Poor documentation of operational monitoring data used to support closure planning	• Data management platforms should be integrated early in the mine life, transitioned between projects and operations, and be user-friendly (e.g., GIS based, SCADA, etc.). For significant level closure risks, a real-time, easily accessible and understood factual data record should be maintained, to inform design, monitoring, external dam safety reviews/boards, and surveillance Trigger Action Response Plans (TARPs) for use as part of an observational approach. Regulators should set minimum standards for closure documentation if a company become insolvent. Information should be easily accessible to the public (i.e., GIS based platforms).	All
Lack of information sharing on mine closure lessons learned	• For various reasons (e.g., different technical focus with different interests, company commercial advantage and competition for knowledge, etc), there remains limited user-friendly platforms for sharing lessons learned. Mine operators should benchmark closure planning performance against other industry leaders to reduce the risk of complacency and conventionalism. Some publicly available platforms exist (e.g., "Mine Closure WIKI", "GARD GUIDE", "CLOSEDURE", "HUMAN RIGHTS WIKI"), however these are often limited to who contributes. Regulators have a role within the industry to set the tone and direction for helping connect this information to the public domain. A recent push by regulators have been observed by some regulators (see NSW Government, 2017) to improve the level of publicly available regional information.	All

People		
Lack of knowledge transfer practices	• See Sanders and Wendtman 2016 for potential opportunities for knowledge transfer which includes opportunities for the following barriers: o Retiring and semi-retiring baby boomers (i.e., lack of availability to contribute additional time) o Movement of key staff o Quality of Project Managers involved in closure planning o Loss of site knowledge at end of operations o Lack of integration between mine planners and operations team o Lack of organization structure and external review boards	All
Over-optimism	• Design: Implement external assessment with experienced industry professionals through practices such as peer review, review boards, external audits, and project third-party assessment. • Risk: Ensure technical risk assessments (e.g., failure modes effects assessment) or critical controls risk assessments (e.g., bow-ties) include the ability to weight each risk based on the level of certainty. Information used to support the assessment of risk for high-hazard conditions and subsequent mitigating controls should reflect confidence factors based on the depth of knowledge and expert opinion. See McLeod & Plewes, 1999 for further reading.	All
No long-term planning KPIs for senior operational staff	• Nearly half of survey respondents commented that no formal long-term KPIs are developed within the organization. There is an opportunity for industry leaders to reshape performance reviews and bonus structures based on a balance between operational KPIs (e.g., production, safety, compliance, etc) with targets for progressive reclamation and management of long-term risks/opportunities. Include into operational KPIs the requirement for long-term mine planning and closure planning objectives. For example, KPIs for mine planners and geologists may include KPIs to manage mine waste to prevent onset of Acid Rock Drainage/Metal Leaching and protection of growth medium required for reclamation.	Owner
Technical bias of the closure planning lead based on background or experience	• A multi-disciplinary team is critical within project execution and review teams. Engineers and scientist often show technical bias (i.e., biologist typically focus on revegetation, hydrotech/geotechnical engineers will typically focus on physical stability of structures, etc). These people are critical in reclamation planning, however closure leads involved in strategic decisions (e.g., end landuse planning, alternatives assessment, risk management, etc) need to have a broad skillset, ideally with operational experience to understand the complexities and constraints involved.	Owner
Poor succession planning and transfer of tacit knowledge	• Change management processes should include succession planning or terms of reference for key roles which may be tied to mine closure risk assessment critical controls (e.g., tailings Engineer of Record, Independent Reviewer(s), closure lead, etc) • Establish early the use of multi-disciplinary closure working groups involving engineering, environment, human resources, finance, safety, Aboriginal/First Nations, etc, and external/internal review boards.	Owner

4 Conclusions

The business case for systematic management of change to improve mine closure outcomes is clear; however, implementation is always easier said than done. Opportunities to identified change management challenges are presented in this paper to help improve dialogue with industry leaders.

Key conclusions include:

- Mine closure planning relies on a change management framework. A key challenge is that change management is either considered to be a separate process to closure planning, or there are no formal processes in place to manage the change. Change management should be integrated into the annual life of mine planning process.
- Change management processes and risk assessments supported by a body of technical work and effective consultation are often underutilized and are carried out to a sub-quality level. Understanding and quantifying residual risk throughout operations is critical, particularly with changes to mine plan optimsation and design.
- The perception of mine closure design prior to construction should be changed from 'conceptual' to at least 'pre-feasibility' level which is supported with design and costs accuracy. Closure Plans and life of mine closure cash-flows should then be optimized during future mine life stages through change management, control checks and best available technology and practices.
- Mine closure knowledge is costly to acquire and is quickly lost if not managed effectively. Decision analysis is an important process in change management to align on objectives, identify risks/ opportunities, and assess alternatives. Involving potential mine closure stewards (i.e., corporate, local community, Aboriginal/First Nations, regulators) into this planning process is important.

The aim of this paper is to increase industry conversation around operational change management as part of life of mine planning. We hope these practices and feedback from industry professionals can be applied to other practitioners, with provision to local issues and life of mine stage.

Acknowledgement

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Landscape Evolution Modelling of Large Sand Tailings Dams

N Slingerland *University of Alberta, Canada*

NA Beier *University of Alberta, Canada*

GW Wilson *University of Alberta, Canada*

Abstract

Tailings dams are permanent features in the landscape; however they are rarely designed as such. Data on their long-term post-closure behaviour, failure mechanisms, and environmental risk is critical to the design of a responsible and holistic closure plan. This information is frequently not evaluated, forcing an elongated process of trial and error at closure. This paper explains how the CAESAR-Lisflood Landscape Evolution Model (LEM) was used to simulate and assess geomorphic changes on a tailings dam in northern Alberta thereby enhancing our understanding of associated long-term risk.

Northern Alberta is home to some of the largest tailings dams in the world, constructed predominantly of highly erosive sand tailings. Erosion has been noted as a potential post-closure failure mechanism for these "sand dams" since the 1970's; however, to date no long-term studies have taken place to investigate the extent of this threat. Extreme erosion of a tailings dam may lead to exposure and release of the contained mine waste. Eroded tailings may be transported and deposited downstream on land or in waterways where they can increase sediment load and negatively impact the environment.

Modified precipitation data for the oil sands region, average grain size distribution of sand tailings, and a digital elevation model (DEM) of the proposed post-mining tailings landform were input to CAESAR-Lisflood along with several parameters used to describe the environment. Outputs of the model were validated through a spatial comparison with existing geomorphology of erosional features identified in the field and via aerial imagery.

This paper describes the morphology of an oil sands tailings dam after 200 years of simulated precipitation, and discusses the role that vegetation plays in stabilization. The similarity of outputs to landform characteristics seen in the field builds confidence in CAESAR-Lisflood's predictions for sand dams in the region. Landscape evolution modelling highlights the risk of large-scale erosional features at selected locations, although not always in the form anticipated. Results provide critical information on the long-term behaviour of sand dams which is necessary for closure design, regulation, and calls into question the prospect of a "walk away" post-closure landscape.

Keywords: *Sand dam; oil sands; mining; reclamation; CAESAR-Lisflood; Landscape evolution modelling*

1 Introduction

International best practices in the regulation of mining and the environmental have evolved over the last 50 years. Historically mass dumping of waste into watercourses was customary during operation and mine sites were abandoned once mineral extraction ceased. 'Best practices' now entail minimization of off-site impacts such that all waste is contained on-site and all disturbed areas are progressively reclaimed until a new landscape has been constructed: Many regulators call for this new landscape to be monitored until such a time that it is considered to be self-sustaining, posing no significant threat to human or environmental health.

The rapid development of oil sands mines from 2000-2010 has been reflected by government and regulatory agencies through additional mine closure regulation: particularly via the mine financial security program (MFSP), and the need for mine owners to demonstrate work towards recreation of post-mining landscapes with equivalent land capability, minimization of off-site impacts, and the reclamation of waste storage facilities. Due to the long 50+ year extractive/operational life of oil sands mines, the regulator will have time to refine their planning requirements through trial and error. However, the opportunity to define what is acceptable at closure comes only once per site. There is a need to identify how these waste-constructed landscapes may behave in the future, what is acceptable, and what is unacceptable so that undesirable occurrences may be guarded against and monitored.

Surface mining and processing of oil sands in northern Alberta, has evolved through nearly 100 years of innovation. Between the year 2000 and 2017 bitumen production increased nearly 350%: over 200,000 cubic meters (approximately 1,300,000 barrels) of crude bitumen were produced per day through surface mining in 2017 (AER 2017). This has logically coincided with an increase in waste products: As a rule of thumb, for every 1 m^3 of crude bitumen produced, roughly 3-4 m^3 of dry (overburden) waste and 8.5 m^3 of wet waste (tailings) are produced (Sego and Wilson 2011). Waste management is therefore of utmost importance in oil sands mining.

The large quantities of wet waste ("tailings") are stored in above-grade ring-dykes (or "external tailings facilities", ETF's) until space can be generated in-pit to backfill. These ring dykes can be up to 100 m in height, several kilometres in diameter, and over 20 km in circumference; at present 14 ETF's exist across the various mines. The ring dykes themselves are predominantly constructed of coarse sand tailings (CST) using an upstream method shown in Figure 1. Fluid fine tailings are placed behind the dykes for future treatment or transfer in-pit.

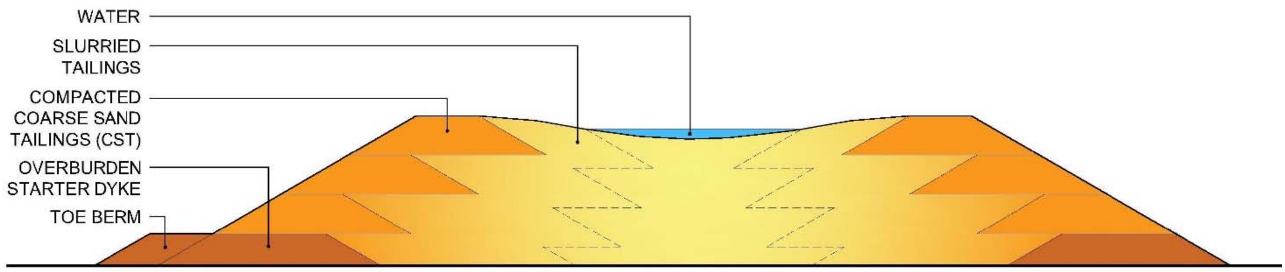

Figure 1 Ring dyke constructed using the upstream method. Drawing is not to scale.

Tailings dams are necessary for oil sands mines to operate. They are rigorously designed for safety and stability throughout their active life and monitored 24 hours a day. The stability of these dykes is critical; the release of tailings would result in substantial physical alteration to the surrounding landscape, accompanied by increased salt concentrations and other geochemical changes to a previously balanced, healthy ecosystem. Design requirements with respect to long term safety and stability of dykes post-closure is understood to a lesser degree, in part because it is not known how these structures will degrade. Additionally, the operational design life for a tailings dam is 8 - 15 years, whereas for a post-mining landscape the design life is increasingly considered to be "forever". How does one design a landscape to be stable and to minimize its impact on the surrounding environment "forever"?

Due to the physical properties of CST, 2-3 m deep gullies occasionally form on dyke slopes by concentrated overland water flow. These erosion features are readily visible at many active ETF's and would be an undesirable occurrence post-closure once maintenance and monitoring is reduced. Erosion of tailings dams can have direct and cumulative negative consequences both on-site and off-site; Land degradation through reduced vegetation productivity, inability of stabilizing vegetation to grow, and deposition of sediment and contaminants to adjacent environments are a few possibilities. It is therefore of interest to gain knowledge surrounding the long-term erosion potential on ETF's in order to identify if massive release (structural dyke failure) is possible by this mechanism, and what, if any, downstream impact exists due to dyke erosion over long time frames.

Rather than designing for stability "forever", the Australian government recommends a more tangible minimum design life of 200 years for the cover systems used at uranium mines, while MEND recommends 100 years for covers used in cold regions. Other studies have been completed looking at erosion on tailings dams: Sawatsky, Dick, Ekanayake, and Cooper (1996) conducted rainfall and runoff simulations on an oil sands tailings dyke using multiple rainfall intensities (including simulated real storm events) less than 2 hours in duration. Hancock and Willgoose (2004) used SIBERIA computer simulations to predict how erosion would impact a tailings dam in Northern Territory, Australia. This paper uses the CAESAR-Lisflood landscape evolution model (LEM) to simulate rainfall on an oil sands tailings dyke for a long time frame (200 years) in an effort to better understand long-term behaviour, potential consequences, and whether these consequences are acceptable based on current regulatory guidelines.

2 Methodology and data

The study area modelled is a ring dyke - ETF structure approximately 65 km north of Fort McMurray, Alberta. The ETF covers 13 km^2 with a maximum height of 70 m including post-closure topography. The plateau-like surface of the structure within the boundary of the ring dyke acts as an isolated watershed with ridges and swales at a maximum slope of 10%. The dyke itself ranges in slope and drains in an undirected fashion to a perimeter channel at its base.

The ETF is located in the boreal forest which consists predominantly of low, undulating muskeg and fen wetlands. The ETF itself is in stark contrast to this: poised as an un-vegetated upland 60+ meters above the surrounding terrain. Sub-zero temperatures exist for over 5 months of the year, and evaporation exceeds precipitation annually.

A number of inputs and parameters are used by CAESAR-Lisflood in order to simulate geomorphic changes to terrain over time and space. The model itself has been previously verified using known historic topography and climate in order to recreate the present landscape (Welsh et al. 2009; Coulthard et al. 2002), and evaluations have also taken place by comparing CAESAR-Lisflood outputs to those of LEMs calibrated with different parameters, mainly SIBERIA (Hancock et al. 2010; Hancock et al. 2011; Hancock et al. 2015;).

CAESAR-Lisflood is a cell-based model that functions by reading a digital elevation model and routing water (precipitation and watercourse inputs and calculated runoff) through it. As this occurs, each cell (elevation) is evaluated for flow velocity, erosion, deposition, roughness, etc. and the cell is altered accordingly. Rainfall inputs are used to generate surface water runoff using a modification of TOPMODEL (Bevan & Kirkby 1979): TOPMODEL calculates soil moisture deficit using rainfall inputs and a calculated soil moisture in order to determine when precipitation will remain on the surface. Code from Lisflood-FP (Bates et al 2010) is used to distribute this surface water as runoff to any of the 8 surrounding cells with lower elevations: this is known as D∞ flow routing, and is particularly important for the development of braided channels and deltas. Flow depth and velocity are used to determine shear stress, which, in combination with the creep rate, dictate the extent of erosion or deposition occurring during one iteration for each cell. CAESAR-Lisflood can be run in three modes: Reach, tidal, and/or catchment. Reach mode requires additional input with respect to watercourse (reach) flow inputs over time, while catchment mode uses only the precipitation file inputs to calculate runoff. The landscape modelled comprises two isolated watersheds, therefore catchment mode within CAESAR-Lisflood version 1.9b has been used.

Parameters for use in the landscape evolution simulation were identified through sensitivity testing, a literature review on reclamation in the Fort McMurray region, and calculation. In addition to parameterization basic inputs include a regular grid DEM of the landscape topography, particle size distribution of the surficial soil, and rainfall quantities taken at a regular intervals. Additionally, a DEM for bedrock can be included, as can a spatially variable grid of m-values, which is an adaptation on the m-value used in TOPMODEL (Bevan & Kirkby 1979).

The surface topography DEM was generated from 2016 LiDAR data of the project site provided by the mine owner/operator, with horizontal accuracy of 40 cm and fundamental vertical accuracy of 25 cm. The DEM was then edited to remove surface features that cause unnecessary calculations or inaccurate flow routes, such as minor peripheral topography or culvert overpasses for ETF access. In order to identify the extent of impact, the cells surrounding the ETF perimeter channel were flattened to a 0 degree slope such that no existing surface topography or surrounding infrastructure was available to alter model outputs. The final surface topography was represented with a 425 x 467 DEM resampled to a resolution of 12 x 12 m cells: this resolution provided optimal functionality and modelling speed for the 200 year simulation.

A “bedrock” DEM was generated based on pre-mining surface topography to the same size and resolution as the DEM representing the post-mining surface topography. Pre-mining surface soils (brunisols and luvisols) remain beneath the ETF, and while not bedrock, they are likely more erosion-resistant and less permeable than that of the dykes. The “bedrock” DEM therefore acts as a limit to the depth erosion may occur.

One of the benefits of using CAESAR-Lisflood is that it allows for precipitation data inputs over small time scales, capturing the intensity and duration of extreme storm events that cause the majority of erosion in northern Alberta. Fifteen years of hourly rainfall data were acquired from the Regional Aquatics Monitoring Program (RAMP) Aurora C1 monitoring station. This station was the closest to the study site and also comprised the longest available hourly record of all climate stations in the region. Rainfall data was quality controlled and cross referenced with nearby stations to ensure accuracy, and any periods of missing data were filled in with data from these stations. This 15 year precipitation data set was then looped to run for 200 years, with statistical 24-hour extreme (1:25 year, 1:50-year, and 1:100-year) storm events input regularly starting at year 16, 50, and 80, respectively, using a triple-peak design storm typical of large rainfall events in the Fort McMurray area (Dick & Ghavasieh 2015).

Freezing temperatures typically occur at the study site from the end of October until early April each year. The precipitation record does not distinguish between rain and snowfall, however this significantly impacts the soil moisture and erosion rates, particularly during periods of spring snow melt. In order to account for this temperature data was acquired from the Aurora C1 and Mildred Lake climate stations, and precipitation was set to zero once daily temperature averages were consistently -1°C or less until daily averages were greater than -1°C. Snow melt begins to melt in the Fort McMurray region at -1°C. Snow depth and density measurements from RAMP were used to calculate the snow water equivalent once melting began each spring. The difference in snow depth each day (as snow water equivalent) was then applied as a single hour of precipitation for that day.

CST samples were attained from 20 different locations around the ETF ring dyke in the spring of 2017. Grain size distributions of the samples were determined using sieve analysis, a mean distribution was calculated, and this mean was then fractionated into nine classes for input and use in CAESAR-Lisflood (Figure 2). The finest class acted as suspended sediment when flow velocities exceeded the minimum fall velocity.

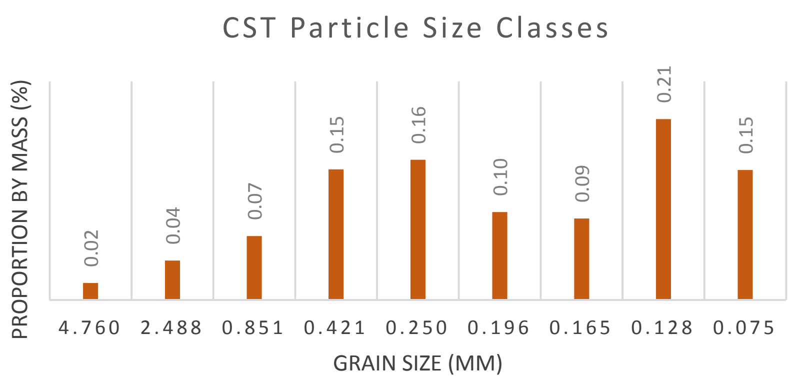

Figure 2 Mean CST particle size (by percent mass) obtained from the ETF perimeter dyke, as input into CAESAR-Lisflood.

The 200-year simulation was completed with vegetation developing linearly over a period of 24 years. Erosion resistance correspondingly increases from none at t = 0 when no vegetation is present at closure, to 85% when vegetation is fully established, mimicking a nearly erosion-resistant surface as documented previously

(Sawatsky et al 1996). Figure 3 shows these relationships graphically. If flow velocity leads to exceedance of the vegetation critical shear (force required to remove vegetation), vegetation is removed and erosion returns to full strength, linearly decreasing to 15% over 24 years or until the critical shear is exceeded. This two-part process attempts to replicate the mitigation provided by strongly rooted vegetation and the accumulated organic debris dropped to the soil surface over time.

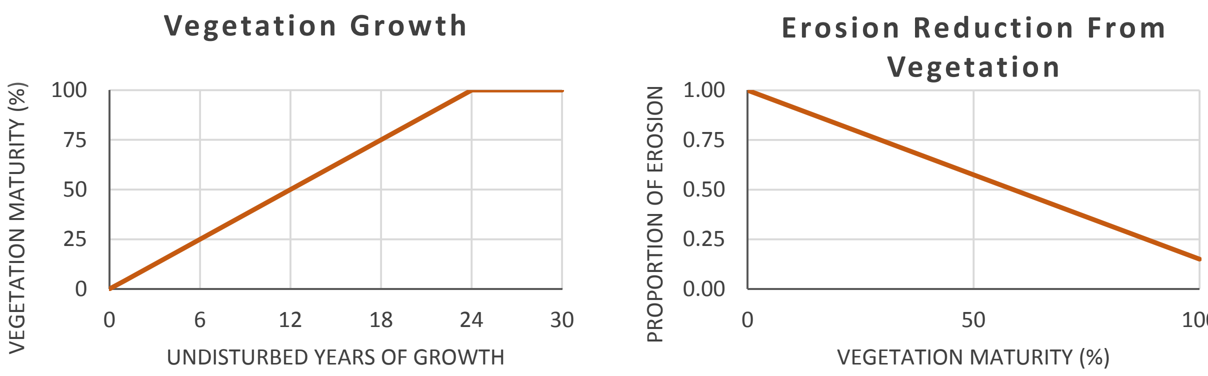

Figure 3 Relationship between vegetation maturity and corresponding proportion of erosion permitted to occur.

Due to the narrow particle size distribution, uniform distribution across the entire ETF, and limitations of CAESAR-Lisflood to vary particle size distribution spatially, the same distribution was used for the entire surface. No maintenance was incorporated during the 200 year simulation in order to determine cumulative effects over time. Throughout the model cumulative water discharge and sediment discharge was recorded for each simulated day, and yearly plan view imagery was taken. Surface elevations, median surficial grain size, and water depth were also recorded for each cell on the DEM each year simulated.

3 Results and discussion

ETF morphology was evaluated using erosion and deposition quantities and rates, cross-sections, and sediment discharge over time. In terms of geomorphology, the majority of changes along the external dykes occur in the first 60 years as large gullies develop and progress retrogressively inward through the dyke. The sediment eroded via these gullies was then deposited at the bottom of the slope, blocking off perimeter drainage routes and sediment transport out of the model due to suspension. Gullies along the dyke were 20 meters deep in some locations and gullies were more prevalent in areas where flow was concentrated. Changes to the plateau were minimal after approximately 30 years; incision of the main drainage channels were observed nearly to their entire length and to a depth of over 10 m in some locations.

An analysis of erosion rates summarized in Figure 4 shows how the removal of sediment reduces over time, eventually reaching an equilibrium around year 42. Some portion of this would typically be attributed to initial preferential removal of fines by the model; however there is negligible change in the surficial D_{50} that would indicate surface armouring. Simulation of landscape evolution on a natural landscape would typically require a “spin-up” period in order to achieve natural armouring of the surface; however, in the case of this sand dam the entire surface is newly constructed over the last 10 years and minimal armouring has occurred on the ring dyke to date, eliminating the need for spin-up. The initially high erosion rates seen in Figure 4 are more likely due to the narrow grain size distribution and fine texture of surficial sediments that makes them highly erodible. Occasional spikes in sediment discharge can be seen at year 16, 41, 50, 66, 80, 91 and 100 where statistical precipitation events were applied to the DEM. These statistical events produce greater erosion than we see when unamended historic precipitation is applied due to the additional water depth, velocity, and erosivity of larger storm events.

Vegetation plays a significant role in reducing erosion and mass wasting (landslides) in natural environments, and the CAESAR-Lisflood model does a good job of mimicking that through the functions illustrated in Figure

4 and other parameters. The reclaimed landscape behaves differently from the natural environment, and long-term erosion measurement on fully vegetated reclaimed sand dykes will need to continue in order to gain more certainty with respect to future estimation. Parameterization of vegetation components drew from available research that was predominantly short term in nature, and the simulations completed indicate very little erosion once vegetation is established. Major gullies are initiated prior to vegetation reaching full maturity and none establish after this point within the simulation.

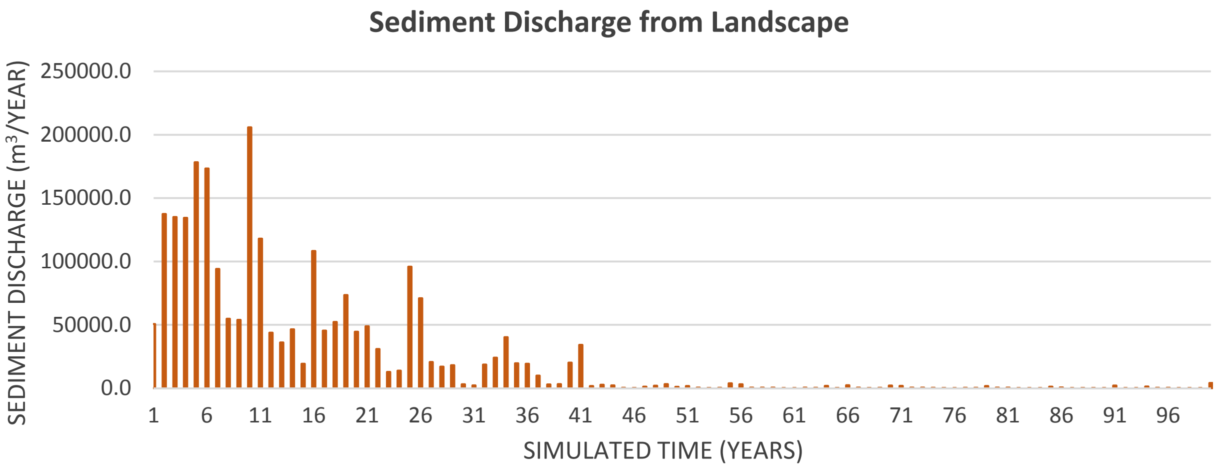

Figure 4 Annual sediment discharge from broader ETF landscape over the first 100 years of simulated landscape evolution.

Diffusive erosion, or "creep", is typical of upper slopes resulting in incremental changes over long time periods. While non-linear transport equations more accurately approximate creep, transport rates even on steeply sloping terrain over 10,000+ years are low in comparison to other erosion modes, such as landslides or gullying; a linear approximation is therefore often sufficient over short and long time frames (Martin, 2000). Creep rate was calculated using the DEM cell size and mean hillslope gradient for use in simulation. As expected, after 200 years of landscape evolution modelling minimal evidence of degradation due to creep processes exists. Smoothing of contours and of the remnant angular topography generated by gullies are the dominant contributions of diffusive erosion processes to this simulated landscape.

The initial formation of gullies on the ETF dyke was observed to begin near the bottom of the dyke in most cases: the bottom half of a slope typically has higher moisture content in the soil and overland flow transitions from dispersive flow in favour of more centralized, efficient flow paths. As concentrated flow progresses down a slope it gains speed and erosive power. Development of gullies following this process occurred on dyke slopes without topography that would lead to significant pooling or concentration.

The other observed method of gully development arises from surface water being directed and concentrated in one location, eventually finding the downward path of least resistance and eroding the surface as the previously dammed water flows. In nearly all locations with laterally concave slopes (where overland flow is directed perpendicular to topographic contours down a central valley), large gullies were formed. In contrast, on laterally convex corners of the perimeter dyke (where overland flow is directed divergently) there are few indications of gully formation even after 200 years of simulated evolution.

In total, nearly 40 gullies developed that were at least 100 m in length and 24 m in width. All of these were initiated in the first 30 years of simulated time. The longest gully was over 1250 m long reaching well into the central tailings storage area and had 8 dendritic-patterned branches feeding into the main corridor. This gully, and other larger gullies, were deep: this gully in particular eroded sediment to a maximum depth of 19.90 m which would certainly have penetrated the tailings contained by the CST cap and dyke. Correspondingly, deposition of sediment extended in some instances well over one kilometre beyond the perimeter channel wall.

Figure 5 illustrates the development of a gully along the eastern downstream slope of the ETF dyke. The initial profile at t=0 years has an overall gradient of 14%. At t=50 years a gully has already been initiated in the lower reach and developed in the upstream direction about 275 m. By year 100 the gully has further developed 80 m and sediment is being deposited at the toe of the slope. The gully continues to expand over the next 50 years, continuing to deposit sediment at the bottom of the slope. Stabilization of the slope is evident in the 200 year profile, as it deviates only slightly from that of the profile generated in year 150. This process of eroding upper reaches and depositing in lower reaches has the effect of reducing the slope to less than 8% in the lower half, creating an elongated lower concave slope and a short, steep convex slope at the top. This is in line with theories of hillslope evolution which define mature hillslopes (previously eroded slopes that are presently in equilibrium) as having an 'S'-curve in which the lower concave portion is heavily elongated (Toy & Hadley 1987). This mature profile provides an alternate design option for long-term stability of sand dykes.

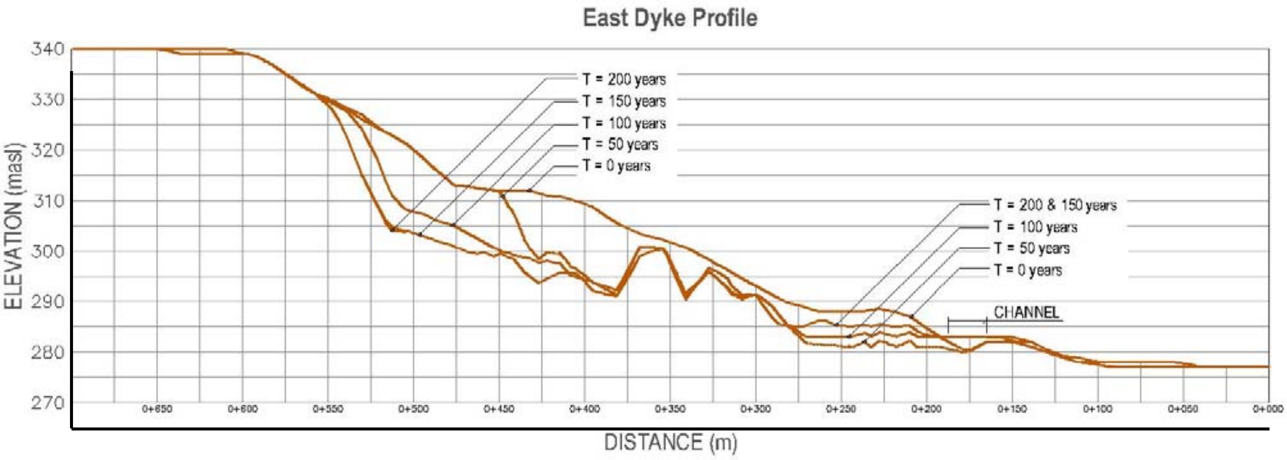

Figure 5 **Surface profile of an eastern (downstream) portion of a sand dyke prior to landscape evolution modelling (time = 0 years), and after 50, 100, 150, and 200 years of simulation. 3x Vertical exaggeration, profile is not to scale.**

Of particular interest in the evolution of these anthropogenic landforms is the point at which they no longer function and will require outside intervention. Intervention is necessary when the landscape fails to function as intended and poses a threat to either environmental or human health, or to the economy of a region or entity. At the base of the east dyke in Figure 5, deposition of soil eroded from the upper reaches occurs due to gully formation. The perimeter channel installed around the dyke is evident at T=0 years, the fictional "end of construction date", spanning just less than 30 m in width. As simulated time progresses through the first 50 years, the channel width expands, and sediment is washed downstream within the channel by fluvial processes. Over the next 50 years, from t=50 to t=100 years, soil removed by the retrogressive gully formation is deposited in the channel to the point where the channel is completely filled. This continues as an alluvial fan develops at the base of the gully, moving outward. The result of this channel blockage is that overland flow from the dyke that is captured by the channel backs up until it overtops the channel banks. When flow is high this subsequently erodes the outside channel wall and drainage water is diverted onto the surrounding landscape. This phenomena occurred at several locations within the modelled landscape after being subjected to small rainfall events that were less than a statistical 1-in-25 year storm.

4 Conclusion

The simulation and study discussed herein sought to identify how anthropogenic CST landforms may evolve and morph over a 200 year time period using the CAESAR-Lisflood LEM. The model has been widely evaluated, and parameterization was conducted with field data, local climate data, and recent literature. Future work in this area should consider the evaluation of longer time frames, eolian processes, and the direct measurement of vegetation-erosion relationships on reclaimed CST hillslopes. Additionally, coarse

DEM cell sizes lead to similarly coarse outputs: finer DEM modelling will give finer detail regarding landscape changes and their dimensions.

The research has indicated that erosion poses a threat to the stability of the structure, the ability of the structure to contain tailings, and the surrounding environment when not maintained. Nearly forty large gullies (> 100 m long and 12 m wide) and many more small to medium-sized gullies were generated on the downstream dyke when subjected to historic and statistical precipitation events. Sediment tended to fill the perimeter channels, produce altered flow routes surrounding the ETF, as well as deposition of tailings at distances over 1 km from the ETF base. Note that CAESAR-Lisflood assumes a consistent grain size distribution across the landform/ DEM. As a result, modelling cannot account for erosion mitigation measures such as rip rap, but can inform and optimize its use and placement.

The model indicates that without ongoing maintenance (particularly prior to establishment of mature vegetation), the landscape will not function as designed and has the potential to negatively impact the surrounding landscape and watercourses. This has critical implications for the region, and the regulator in terms of the present timeline and conceptual pathway towards delicensing.

The findings of this study suggest two main conclusions: Firstly, that the design of sand dykes should be reconsidered to take into consideration the forces present at and after reclamation; and secondly, that the integration of ETF's into the broader environment and spatial context requires further attention.

Acknowledgement

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A Model to Reduce the Probability Mine Closure in Iran

E Pouresmaeili *Department of Mining Engineering, Islamic Azad University, Qaemshahr, Iran*

A Ebrahimabadi *Department of Mining Engineering, Islamic Azad University, Qaemshahr, Iran*

S Nouri *Department of Geology, Islamic Azad University, Maragheh, Iran*

M Pouresmaieli *Mining engineering department, Engineering Faculty, University of Zanjan, Iran*

Abstract

Mining activities play a major role in economy of each society so that any interruption in extraction flow of ore minerals could affect the amount of planned income anticipated from this sector. Therefore, mining and excavation operations should be continued and needs to be appropriately managed throughout the mine's life. Normally, a mine closes when its deposit is totally mined but there are some reasons could lead to pre-mature mine closure such as environmental, social, economic and technical issues. Risk-based approaches are considered powerful management tools to deal with such problems. The main objective of this research work is to develop a model to assess the mine closure risk as well as providing a safety factor for investment feasibility in mining projects. With this respect, a risk matrix is proposed and the probability and intensity of activities are determined using statistical analyses and multiple-criteria decision-making (MCDM) techniques. Through the analyses, the type of minerals is also take into account (as divided into 6 groups). Afterwards, the risk matrix as well as risks of pre-mature closure of mines in each mineral category were calculated. The safety factor stems from the model is viewed as a proper measure to clarify the investment feasibility of the projects. This factor may impose extra investment but it is able to reduce the risk of pre-mature mine closure. 2298 pre-mature mine closure throughout Iran were investigated and closure factor for each mine were calculated to verify the model. The risk factor of unplanned mine closure in Iranian building stone mines and safety factor of investment were found to be 4.06% and 1.0406, respectively. Ultimately, achieved results from analysis of 1005 mines data showed that for more than 66 percent of the beneficiaries, the current sales and market condition is regarded as the major reason affecting mine closures.

Keywords: *Pre-mature mine closure, Risk-based model, Risk factor, MCDM, Iran*

1 Introduction

Mining has always been the keystone of human civilization (Ghose 2009) which has a long history and it is considered to be the second important activity in the world after agriculture (Blinker 1999). Based on the World Bank reports, mining plays a special role in the economy of countries in which a huge share of gross domestic production (GDP) of some countries is linked to mineral production, for instance this amount for Chile is 14.7%, Ghana 12.7%, Peru 12% (ICMM 2012) and Iran 0.6% (Mansouri et al. 2012). Also, with urbanization of world population (1.4 billion) the demands for metals and minerals will probably be in rise and can be doubled in years 2010 to 2025 (Albanese et al. 2011). Due to the important role of mining on the economy of countries, the negative effects of mine closure would be undeniable and if this event occurs in an unexpected way, the consequences would be even worse. As defined previously and by other sources, the unplanned mine closure occurs when the ore resources are not exhausted yet. Several factors can cause mine closure including: economic, geological, geotechnical, regulatory, community, and so on. Osanloo has suggested the following factors as the main causes of mine closure which includes: environmental pollutions, incorrect estimations of grades and reserve, equipment changes, governmental and legislation problems, and so on (Osanloo et al. 2007).

David Lurance was the first person who started to use risk management techniques to reduce the risks caused by mine closure. He could calculate the risk of mine closure for some cases in Australia by the use of risk management matrix (Laurence 2006). Osanloo could develop a risk model for calculating the risk of mine closure in Irankosh Zn-Pb mine (Osanloo et al. 2007). In such cases, researchers use the conventional formula for measuring the risk and compare the mine closure risk among other cases. What is needed for reducing the risk of mine closure is a general model which can associate the conventional approach of risk measurement with a combination of other methods. For an instance, an amalgamation of MADM methods with risk management approach is done with the purpose of tunneling projects in which the traditional risk matrix is approved by MADM methods (Sayadi 2011).

In the present study, a general and new model is designed to calculate the risk of unplanned mine closure. In accordance with the previous research, a risk breakdown structure (RBS) is defined and the main risks caused by unplanned mine closure are also determined. By adding and taking the type of minerals into consideration, the risk of unplanned mine closure related to each type is calculated. After measuring the risk factor, a safety factor is defined to reduce the probable effect of risks. Finally, for proving the validity of mentioned model, 2298 unplanned Iranian mine closures and the risk of closing those mines are investigated.

2 Model Creation

Traditional methods use two main parameters in calculating the risk: risk probability and intensity of consequences. It is shown in equation 1.

$$R= P*I \tag{1}$$

Where P stands for probability of risk and I stand for intensity of risk.

Although this method is simple and easy to use, but its results are not satisfying in terms of validity since it is focusing all the attention on parameters P and I and as a consequence other parameter are neglected (Chapman et al. 2003). Another problem which is noticeable is that the high probability risks with low intensity are equal with low probability risk with high intensity that will make some systematic errors (Pipattanapiwong 20014). As the weight of criteria is not considered in this method, so it needs to be amalgamated with other methods to create valid results. In this way, multi attribute decision making (MADM) methods which are being used by experts are trustworthy solutions (Saaty et al. 2006).

In mining industry, the use of risk management is a usual technique for determining the risk as some researchers use it for calculating the risk of mine closure. But as it is mentioned before, it does not demonstrate trustworthy results and as a remedy it has to be amalgamated with MADM methods. In this study, a general model is designed which can recognize effective parameters in risk of mine closure and also consider the weight of these risks.

For developing this model, three steps should be taken: 1. Model input, 2. Process, 3. Model output. Firstly, the input of model which includes risk breakdown structure (RBS) and a historical database should be prepared. A RBS system which is in accordance with the previous researches is used and main and sub-main risks are also defined. This system needs to access a database of mine closure cases in the region that is under investigation. Secondly, by using the MADM and risk matrix method the second step of this model which is labeled as process will be completed. The final step of this model is dedicated to determining useful information about risk management. Risk factor and safety factor (investment safety factor) are two main outputs of this model. The purpose for using safety factor is to reduce the risk of mine closure in a project. The safety factor is multiplied at initial investment and then added to an additional investment to form the total investment of mining project with the purpose of reducing the probable risk of unexpected mine closure. A general view of model is shown in Figure1.

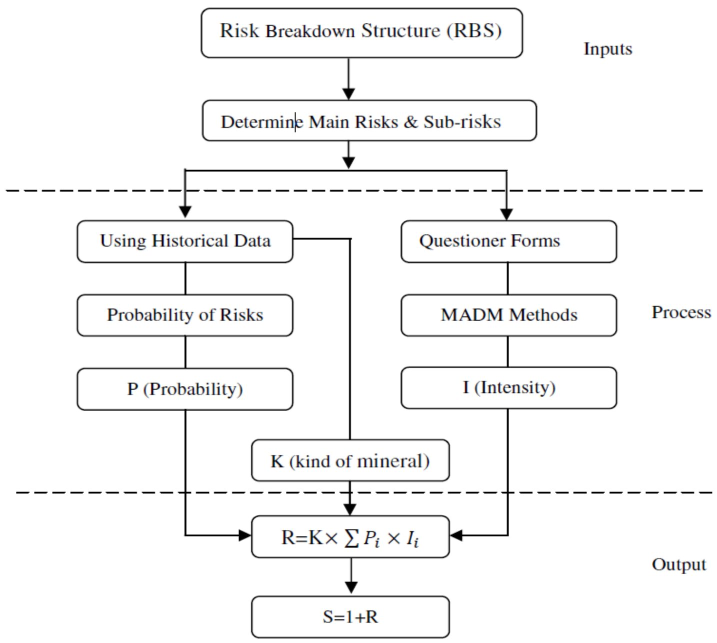

Figure 1 General View of model (P: probability of each risk, I: intensity of each risk, K: kind of mineral, R: risk of unplanned mine closure, S; safety factor)

2.1 Model Inputs

Risk breakdown structure (RBS) - which forms the main inputs of the model- is used for determining the risk of unplanned mine closure Table 1. RBS is a hierarchical representation of risks which starts from higher levels and goes down to finer levels of risks. Figure 2 demonstrates a general view of RBS model.

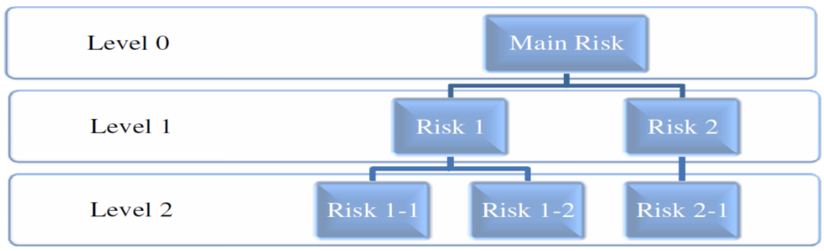

Figure 2 General View of RBS (Mansouri et al. 2013)

Table 1 Risk breakdown structure (Albanese et al. 2011

Level 0	Level 1	Level 2
Unplanned mine closure	Economic	Decreasing the commodity prices
		Lack of sufficient investment
		Loss of markets
		Increasing of costs
	Efficiency and Technical	Resources depleted
		Geology or geotechnical problems
		Low ore grades
		Production difficulties
		Equipment/technical problems
		Lack of explorations
		Industrial relations
	Environmental and community	Regulatory or government intervention
		Safety
		Pollution (water, air, surrounding)

Besides the above-mentioned structure, there should be a database filled with historical data about mine closure events related to the region which is under investigation. This database includes useful information about mine closure reasons, but the data must be further analysed based on the RBS system framework. Risks which are taken in levels 1 and 2 are already determined and the cause of mine closure for each item is also known.

2.2 Model Process

Model processing is formed of three steps as follows: measuring the probability of each risk, measuring the intensity, and adding the type of mineral. Mine closure is subject to some risks such as economic, environmental and community risks. As a result, when calculating the risk of mine closure a researcher should keep an eye on all of these risks and their related sub-risks and furthermore consider the weight of each risk and the type of minerals which are added to the model.

2.2.1 Probability of Risks

Probability of risk equals the extent to which a risk can occur. The probability is usually determined by historical data, mathematical relations or other kind of studies, but in this model the historical database method is used. When using the database method, mine closure cases and their reasons must also be analyzed. For accessing such a database, there should be an organization in each country which is responsible for preparing and storing such information. For instance, in Iran the ministry of Industry, Mining and Trade is responsible for storing mining projects and related statistics. When the databases get ready, then by doing a careful investigation the reasons behind mine closure in the region will be found. According to RBS system, the main risks of mine closure are already known. After determining the main risk, sub-risks must be recognized, too. By using statistical analysis, probability of each risk will be calculated and as it is already clarified the number of the mine closure events related to a risk compared to all closure cases is the probability of that risk.

2.2.2 Intensity of Risk

Calculating the intensity of each risk is done by applying MADM methods. Intensity shows the direct effect of each risk on the mine closure. In this model, two types of methods are utilized that one of them is MADM method and the other one AHP. Analytic Hierarchy Process (AHP) is one of the multi criteria decision making methods that was originally developed by Saaty and is used to drive ratio scales from paired comparisons. When using the AHP method, the determined risks will be ranked according to their effect on the mine closure. The intensity of each risk equates its effect determined by AHP ranking system on mine closure.

2.2.3 Kind of Minerals

As it is clarified before, one of the purposes of this model is to determine the risk of mine closure based on the type of mineral. For determining the type of mineral, we have to conduct a thorough research on the database. This indicator is known with % and it is multiplied at the risk factor and will determine the risk factor based on the type of mineral.

2.3 Model Output

According to general view of model, the risk of mine closure is measured by the following formula.

$$R = K * \Sigma Pi * Ii \tag{2}$$

Where P stands for the probability of each sub-risk, I stand for the intensity of each sub-risk, K is the representative for kind of mineral and R is risk of unplanned mine closure (%).

And the safety factor (investment safety factor) is calculated by the following formula,

$$S = 1 + R \tag{3}$$

Where S stands for safety factor.

3 Case Study

For validating the model, real data of Iran's unplanned mine closure is used which is gathered from 2000 to 2017 based on annual report published by Iranian mining engineering organization (NGDIR 2017). The prepared database gives information about the causes of mine closure (level 1 and level 2 risks) and the type of minerals are also determined.

3.1 Probability of Risks of Mine Closure

The most important task of model input is determining the causes of mine closure. According to the mentioned requirements of model, a database of unplanned mine closures is needed and by using the information stored in the database related to 2298 mine closure cases of Iran and the RBS system, the probability of each risk is calculated and shown in table 2. Note that the table is based on previous studies (Mansouri et al. 2013) and is modified in efficiency risk for production rate less than 10,000 tons per year. Statistics showed that more than 70 percent of closed mines have production rate below 10,000 ton per year. This is why this issue is taken into account through the analysis (http://www.ime.org).

Table 3 Probability of risks based on RBS

Main risk (Level0)	Risks (Level 1)	Sub-Risk (Level 2)	Probability (%)
Unplanned mine closure	Economic	Marketing	25.3
		Lack of investment	18.7
		Decrease of price	15.9
	Efficiency	Insufficient of exploration studies	9.3
		Production rate (less than 10,000 tons per year)	7.1
	Community	Licensing problem	5.9
		Official bureaucracy	5.5
	Uncertain		12.3

According to (tab.2), important causes of mine closure respectively are: marketing (25.3%), lack of sufficient investment (18.7%), decline in commodity price (15.9%), insufficient exploration studies (9.3%), production rate (less than 10,000 tons per year) (7.1%) and revocation of government licenses (5.9%), official bureaucracy (5.5%), and uncertain causes (12.3%). The general view believes that 63% of premature mine closure is due to economic reasons and by taking other researches into account it is proved that economic aspect is the most important risk of mine closure.

Also, by designing the questionnaire and contacting all the legal and natural beneficiaries licensed by the ministry of commerce and Trade, information about the status of mines, whether active or inactive, reasons for inactivity were inquired and in this regard, information was gathered. received data from 1005 mines show that in the follow up the reason underlying the inactivity of mines was inquired, 51% of the beneficiaries due to the market downturn and 15% due to the lack of customer have stopped working. In total, more than 66 percent of the beneficiaries has announced the current terms of sale as the reason for not being active. The results of this questionnaire are presented in Table 3 and Figure 3.

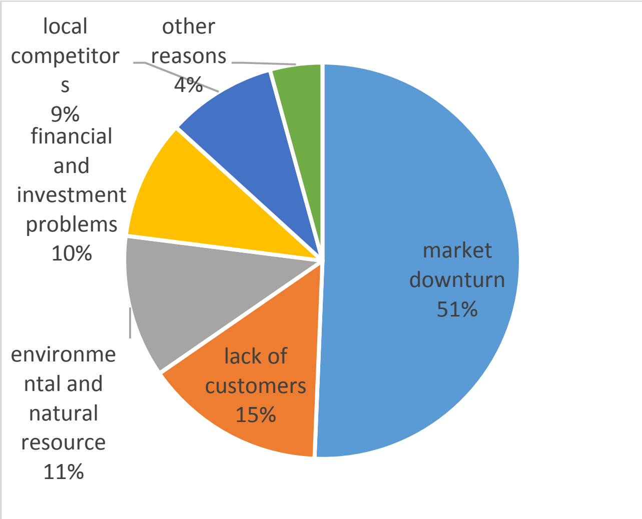

Figure 3 reasons of pre-mature mine closure

Table 3 reasons of pre-mature mine closure

reasons of pre-mature mine closure	quantity
market downturn	509
lack of customers	148
environmental and natural resource	117
financial and investment problems	98
local competitors	90
other reasons	43

3.2 Intensity of Risk Using AHP Method

AHP method is applied for measuring the intensity of the risk. By using experts' opinions, questioners are prepared and the risks are ranked based on three important criteria which are economic, environmental and social consequences. Finally, the results are calculated based on the same mentioned criteria table 4.

Table 4 Intensity of each risk

Risks (Level 2)	I (%)
Marketing	26
Lack of investment	21
Decrease of price	15
Insufficient of exploration studies	11
Production rate (less than 10,000 tons per year)	7
Licensing problem	12
Official bureaucracy	8

3.3 Kind of minerals

The gathered data cover a wide range of materials, from non-metallic to industrial rocks, not allowing to assess the risk for a specified material. It should be stated that all materials are grouped into 4 categories according to Iran mine law as fallow: Group one such as clay, lane, plaster, pumice, salt, etc. Group two such as gold, copper, lead, zinc, mica, alkaline-salt, sulphates, phosphates, talc, graphite, bauxite, some precious minerals, some kinds of ornamental rocks, bitumen and etc. Group three such as all hydrocarbons except coal. Group four consists of hazardous materials (http://www.mimt.gov.ir).

Since the first two groups mentioned above are mainly produced from mines, the materials in these groups classified into 6 subgroups again in accordance with Iran mine law. In order to incorporating the kinds of minerals (based on subgroups) through the risk assessment, we introduced "K factor" which allocates to each category to represent the proportion (in percent) of the category over 2298 pre-mature mine closure cited in database. Table 5 shows the K factor for each subgroup (http://www.mimt.gov.ir).

Table 5 Pre-mature closed mine based on kind of minerals

Mineral	K factor (%)
Building stones	26.11
Decorative stones	24.06
Industrial Rocks	15.84
Industrial minerals	12.26
Building materials	11.72
Metals	10.01
Total	100

26.11 % of these mines are in Building stones. The rest of minerals are ranked as follows: decorative stones 24.06%, industrial Rocks 15.84%, industrial minerals 12.26%, building materials 11.72% and metals 10.01%.

Using the analysed historical data and AHP method, the risk factor and safety factor are measured based on the kind of mineral. According to Eq.2 and 3, risk factor is calculated for quarry mines in table 6 and risk factor and safety factor are calculated for all minerals in table 7.

Table 6 Risk Factor of building stones

No	Risk	P (%)	I (%)	R (%)	R*K (%)
1	Marketing	25.3	26	6.578	1.72
2	Lack of investment	18.7	21	3.927	1.03
3	Decrease of price	15.9	15	2.385	0.62
4	Insufficient of exploration studies	9.3	11	1.023	0.27
5	Production rate (less than 10,000 tons per	7.1	7	0.497	0.13
6	Licensing problem	5.9	12	0.708	0.18
7	Official bureaucracy	5.5	8	0.44	0.11
	Building stone's risk factor				4.06

Table 7 Risk and Safety factor of all kind of minerals

Mineral	Risk (%)	S
Building stones	4.06	1.0406
Decorative stones	3.74	1.0374
Industrial Rocks	2.46	1.0246
Industrial minerals	1.92	1.0192
Building materials	1.82	1.0182
Metals	1.55	1.0155

4 Conclusions

In this study, a general and new model is presented to calculate the risk of unplanned mine closure. The probability of mine closure is calculated by using risk breakdown structure (RBS) and historical databases of unplanned mine closures. In the next step, by the use of MADM methods the intensity of each risk is determined and by adding the type of mineral the risk of unplanned mine closure is calculated for each of them. The final output of model is defined as safety factor (1 + risk factor) which reduces the effect of mine closure risks on mining projects and predicts the additional amount of investment. This amount of investment is helpful in preventing the risks of mine closure at the beginning of a mining project. According to the probability of each risk, additional amount of investment is divided among the total number of risks. For validating the model, 2298 unplanned mine closures in Iran and risks of closing are investigated and by putting the results in the model, it is found that the risk of mine closure for quarries in Iran is 4.06 % and the safety factor of this kind of minerals is 1.0406. The results of this study indicated that 51% of the closure of these mines is due to the market downturn and price drop, 15% lack of customers, 11% environmental and natural resource constraints, 9% local competitors, 10% financial and investment problems and so on. In summary, more than 66% of the reasons for closing these mines are related to market conditions.

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http://www.ime.org

http://www.mimt.gov.ir

Advangeo® - Machine Learning for Geological Process Modelling: Background, Software, Application Cases

M Schipek *Beak Consultants GmbH, Germany*

P Hielscher *Beak Consultants GmbH, Germany*

E Kallmeier *Beak Consultants GmbH, Germany*

A Knobloch *Beak Consultants GmbH, Germany*

A Brosig *Beak Consultants GmbH, Germany*

A Barth *Beak Consultants GmbH, Germany*

C Drebenstedt *TU Bergakademie Freiberg, Germany*

M Steffen *Beak Consultants GmbH, Germany*

G Volkmer *Beak Consultants GmbH, Germany*

Abstract

In geosciences machine learning approaches like Artificial Neural Networks, Random Forests or Support Vector Machines can be used to deal with huge amounts of data gained from field work, analytical investigations and remote sensing. Since 2007, Beak has invested considerable efforts to develop a stable and user-friendly software with comprehensive data pre- and post-processing and model reliability evaluation tools. Today, the developed advangeo® Prediction Software offers full integration of Artificial Neural Network (ANN) into 2D and 3D data processing procedures, making the method available for daily use by non-mathematicians within their standard ESRI ArcGIS software respectively Paradigm GOCAD® software environment. Artificial neural networks are a powerful data-driven modelling approach for the creation of prediction maps based on existing raster and vector data. ANNs analyze complex, non-linear relationships of potential controlling parameters on the probability of any spatially distributed, geo-related event or phenomena. Advangeo® has shown its capabilities in the prediction of a wide variety of phenomena from which selected issues will be illustrated: temporal and spatial prediction of lignite mining waste rock pile stability, geo-hazard maps for slope instabilities and landslides along transport infrastructure as well as the qualitative and quantitative prediction of mineral occurrences.

Keywords: *advangeo®, machine learning, Artificial Neural Networks, temporal and spatial prediction, geo-hazards, mineral resources*

1 Introduction

Natural phenomena and events are usually caused by various interacting factors. An exact mathematical formulation of a geo-scientific task, however, with equations describing the dependence of a phenomenon on several main influencing factors, is rarely feasible (Barth et al. 2014). Due to the lack of data and knowledge of details of many geo-processes, mathematical models cannot be successfully defined and applied with reasonable certainty. This paper explores machine learning, in particular Artificial Neural Networks (ANN), as a means to provide a reliable tool to analyse causal relationships and to make the knowledge available for predictive processes. This approach differs from traditional methods in that viable results may be obtained with reasonable efforts invested in data processing, model design and computational time.

Results for three different application cases are discussed in this paper, following an introduction on the theoretical background about machine learning and the neural network approach. The outcomes are predictive maps, which illustrate the probability of occurrence for a given phenomenon. This forms an important basis for the planning of further economic activities. The three application cases deal with various tasks in applied earth sciences and demonstrate the applicability of ANN/GIS approach. In particular, the following objectives applied to the case studies presented are:

1. Temporal and Spatial Prediction of Lignite Mining Waste Rock Pile Stability,
2. Compilation of a geo-hazard map for slope instabilities and landslides along the German railway infrastructure,
3. Prediction of the potential of tin occurrences in the Mid-Saxonian Erzgebirge.

2 Methodology

2.1 Background

The location of a spatial event both naturally or human induced is determined by a complex network of influential causes and subsequent effects. To address the complexity of some geo-scientific modelling, methods and practices are becoming more reliant on large, interdisciplinary data repositories (Willcock et al. 2017). Recent developments in software technology have expanded modelling capabilities, allowing geoscientists to maximise the utility of the great data amounts, so-called ‘big data’ (Lokers et al. 2016). Machine learning (ML) approaches like Artificial Neural Networks (ANN), Random Forests (RF) or Support Vector Machines (SVM) can be used to deal with huge amounts of data gained from field work, analytical investigations and remote sensing.

In general, ML algorithms can be divided into two main groups: supervised- and unsupervised learning. Within the supervised- and unsupervised-learning categories, there are several different varieties of machine learning algorithms, including: neural networks, decision trees, decision rules and Bayesian networks. A ML algorithm is a process that is used to fit a model to a dataset, through training or learning. The learned model is subsequently used against an independent dataset, in order to determine how well the learned model can generalise against the unseen data, a process called testing.

ANNs have been described in detail by different authors, e.g. Bishop (2008), Hassoun (2003), Haykins (2008), Kotsiantis (2007), Kasabov (1996). The main principle of the ANN approach is built on the concept of how networks of biological neurons are organized and function by imitating the properties of a real nervous system (Negnevitsky 2002). These systems are composed of many chemically interconnected neurons (nerve cells), which receive and process signals from other neurons. When these signals reach a certain threshold, sets of nerve cells (closest to the originating signals) are activated and forward the information to other connected neurons. Learning processes result from the constant adaptation of the interconnections amongst neurons, where the growth and strength of connections are directly related to their frequency of use and degenerate when rarely accessed (Olden & Jackson 2002, Olden et al.2004). It is a supervised classification, during which the software caries out an independent (from expert knowledge) weighting and combination of the different influencing parameters (model input data). This model calibration is done by iterative ‘training’ of the ANN, during which the weighting of the parameters is adapted until the prediction error at the known locations reaches a minimum. Artificial neurons are usually organised in layers (see Figure 1). The most commonly used network paradigm is the multi-layer perceptron. It consists of an input layer V_0 which contains n + 1 neurons, where n is the dimensionality of the input space. Input values will be derived from the different independent variables and determining factors. Within the hidden layer V_1, the input information of the upstream neurons is processed and an output value is calculated by transformation with an activation function. Here, very often, sigmoid functions are used. In the output layer V_t, the to-be-predicted, dependent variable is then generated.

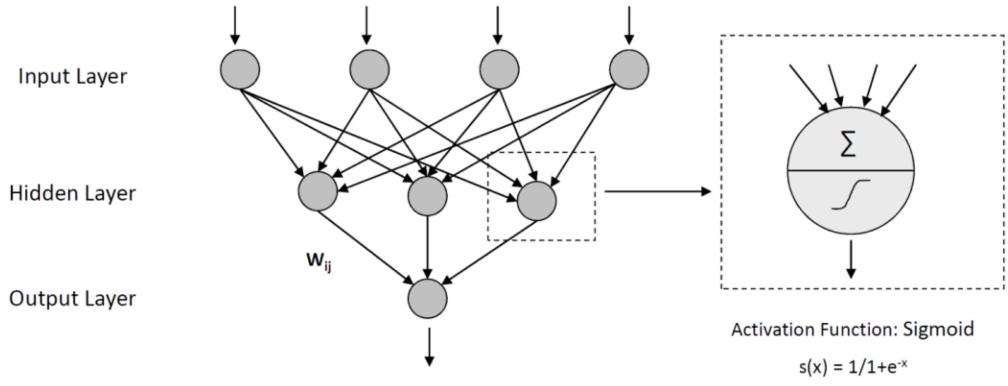

Figure 1 Principle Setup of Artificial Neural Networks

Although the value of the application of neural network technologies in GIS environments was recognized in the past, up to now, there was no wide use of ANNs in geosciences due to the lack of user-friendly software within a GIS environment (Brown et al. 2003, Pradhan & Lee 2008, Yilmaz 2009, Knobloch et al. 2017).

2.2 Software

The advangeo® Prediction Software was developed to enable GIS users to apply neural network methods on geodata. It uses the learning ability of Artificial Neural Networks and combines them with the strengths of modern databases and geographic information systems (see Figure 2). The software assists the user in the different steps of data preparation, network training and application. It records the metadata of all working steps, what makes the calculations repeatable and helps to visualise the results. Many useful features, such as automatic mapping of vector and raster data to base grids, calculation of derivatives and generation of Euclidian distances are included.

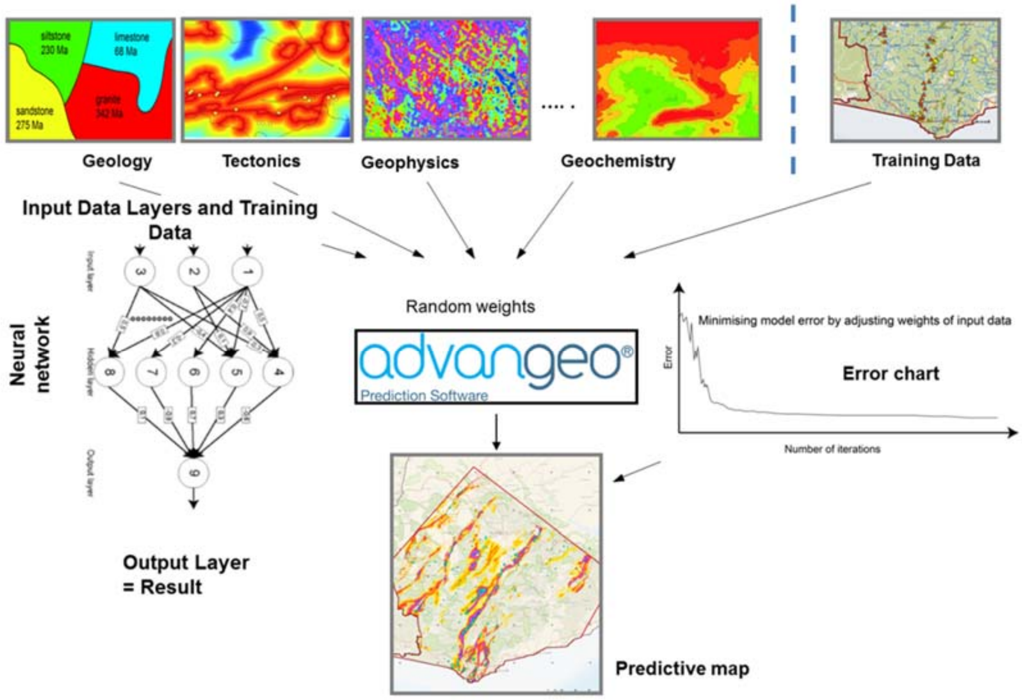

Figure 2 advangeo® as a tool for the analysis of complex non-linear relationships

The advangeo® 3D Prediction Software creates Artificial Neural Networks based predictive models for 3D voxets utilizing geological, geochemical and geophysical data. It is ideal for the solution of innovative tasks like 3D exploration targeting and 3D geohazard prediction.

3 Application Cases

3.1 Application Case 1: Temporal and Spatial Prediction of Lignite Mining Waste Rock Pile Instability

3.1.1 General

Due to rising ground water after the abandonment of the old lignite open pit mines in the Lusatian region, the stability of the waste dumps in the pits changed dramatically. Liquefaction of sandy waste backfill led to huge surface deformations. Advangeo® prediction software was applied to establish and predict the time-related dependencies between the surface deformations and their controlling parameters, such as the rising ground water table, the lithological composition of the mining waste, the thickness of the waste and the morphology of the pit footwall.

3.1.2 Source Data and Data Pre-Processing

Base data included the surface morphology, footwall elevation, groundwater level as well as lithological information of the waste piles. Geotechnical events were used as training areas. Groundwater and surface elevation data was available as annual information (2009, 2010, 2011, 2012, 2013). 64 independent parameters had been derived from the base data: slope, aspects, depth to groundwater, thickness of saturated waste rock material, lithology of the waste rock pile (content of gravel, coarse sand, medium sand, fine sand, silt, clay, lignite and carbonate). Further parameters were calculated: degree of uniformity (U), d_{10}, d_{60}, kf-value. The influence of the parameters and their combination on the hazard potential was investigated within 132 scenarios.

The ANN have been used to establish the time dependency of the parameter “ground instability” and the variety of time depending variables (groundwater levels, surface morphology, depth to groundwater, thickness of saturated dump) and not time depending variables (e.g. waste pile lithology, pit footwall).

3.1.3 Results

Terrain deformation, due to soil liquefaction, has been modelled as time series for the years 2009 to 2013 (see Figure 3). The model has clearly recognized the influences of various lithological and non-lithological controlled parameters on the occurrence of geotechnical events, and these have been quantified and weighted in terms of their importance. The model is able to predict the temporal evolution and the exact spatial location of the event occurring in the dumps as a function of changing groundwater levels and surface morphology. The predictive success of the model was demonstrated through forecasting of events for the years 2014 and 2015 and their comparison with the observed events of those years (Figure 4).

The following risk factors were identified: (1) Important destabilizing factors are: (a) a monotonous lithology with the following composition: 96% sand, 3% silt, <1% gravel, lime, clay, coal; (b) kf-values between 10^{-4} and $10^{-4.5}$ m/s; (c) a surface to groundwater distance of 3.45 meters; (d) high gradients of non-lithological controlled parameters: waste dump surface, groundwater level, depth to groundwater and thickness of saturated dump. (2) Important stabilizing factors are: (a) a high heterogeneity of lithology; (b) a low proportion of sand; (c) high proportions of gravel, silt, clay, lime, or coal; (d) a high depth to groundwater; (e) low gradients of non-lithological controlled parameters: open pit surface, groundwater surface, depth to groundwater, thickness of saturated dump; (f) strongly changing kf values between 10^{-7} and 10^{-2} m/s.

The model can be used as a dynamic tool for risk management before and during the rehabilitation of lignite waste dumps, and for constructing stable waste dumps. By means of varying the model parameters, the geotechnical effects of dump design and remediation scenarios can be predicted (Roscher et al. 2013, Kallmeier et al. 2016).

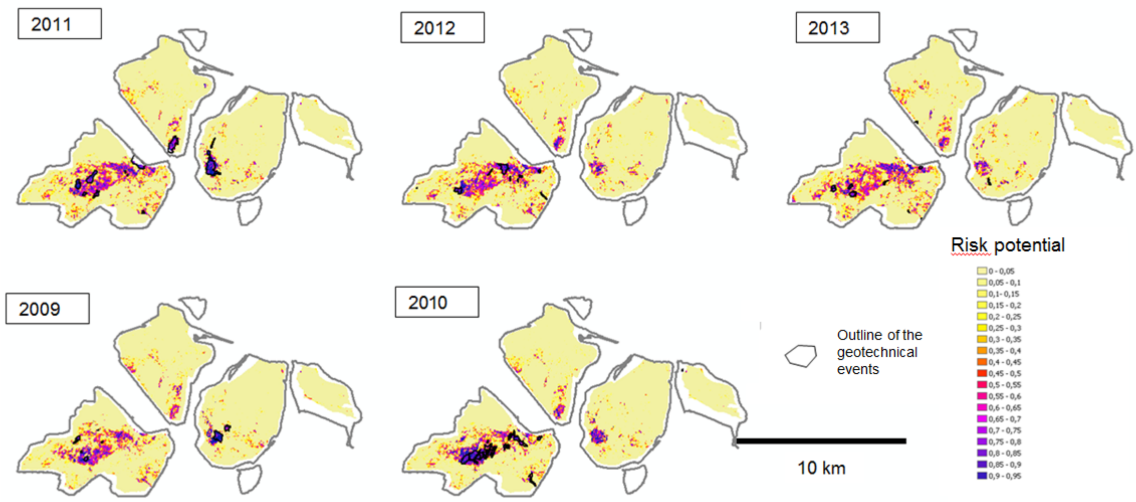

Figure 3 Development of the instability potential over time (2009 – 2013)

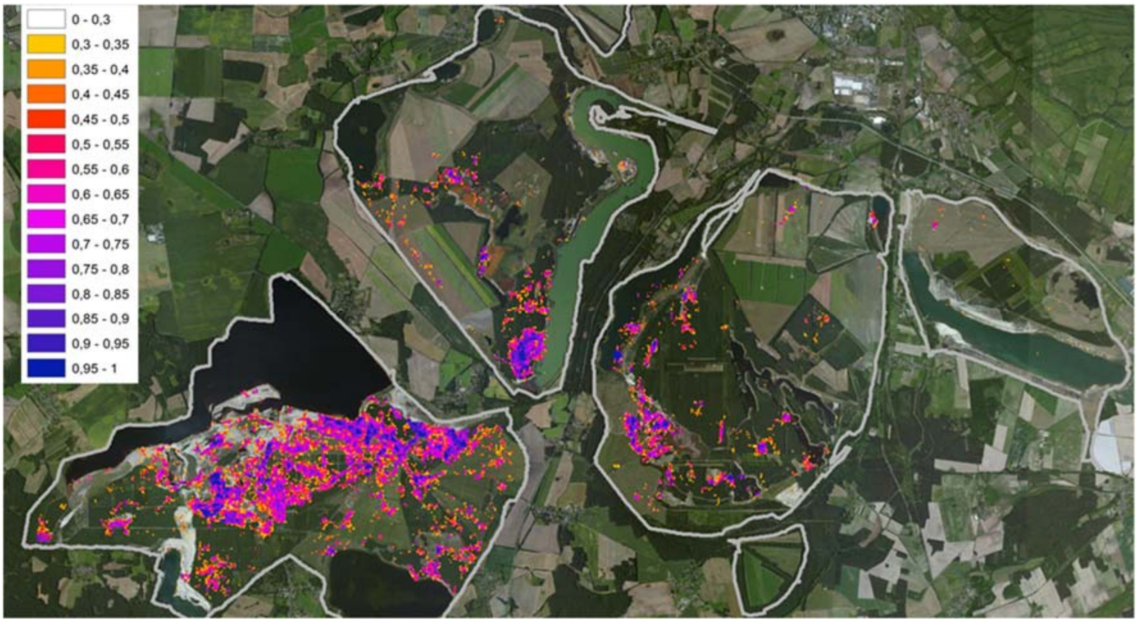

Figure 4 Predicted instability potential map for 2014 using the neural network trained with 2009-2013 data

3.2 Application Case 2: Compilation of a geo-hazard map for slope instabilities and landslides along the German railway infrastructure

3.2.1 General

The aim of the project was to create a geo-hazard map for slope instabilities and landslides along the German railway system based on a Germany-wide engineering-geological model, which shall incorporate landslide-related geological, morphological and land use information (Knobloch et al 2018). Two approaches have been applied: a knowledge-driven approach (based on a classification schema defined by slope classes and geotechnical rock classes) and a data-driven approach based on the application of self-learning Artificial

Neural Networks. Due to the limited availability of training data sets (i.e. observations points), the model was only trained and applied along the railway network of Saxony.

3.2.2 Source Data and Data Pre-Processing

The following base data, partly free, was available within the frame of the project:

- tracks of the German railway network,
- geological overview map 1:200,000 (GÜK200),
- digital landscape model 1:250,000 (DLM250),
- digital terrain model with a raster cell size of 25 m or 10 m (DGM25 and DGM10),
- data from the cadastre of observed geo-hazards from the DB Netz AG and the Saxon State Office of Environment, Agriculture and Geology (LfULG).

All available data were combined into a unified dataset throughout Germany and stored with a uniform reference system (ETRS89 UTM32N). The following project-relevant model input data were derived from the above-mentioned base data:

- geotechnical properties of the rocks (non-cohesive/cohesive/mixed-grained, unconsolidated/consolidated, fracture-favorable/non-fracture-favorable, deformation-resistant/non-deformation-resistant, with divisional surfaces parallel to layering/without divisional surfaces parallel to layering, etc.),
- properties of the hillsides/slopes (slope angle, horizontal and vertical curvature),
- characteristics of the catchment areas (flow accumulation),
- land use (density of vegetation cover, degree of soil sealing).

3.2.3 Calculation of Geo-hazard Potential

In general, the geo-hazard potential was calculated within a buffer area of 1 km on both sides of the railway track. The data-driven approach using multivariate statistics and Artificial Neural Networks (ANN) was applied for the areas of the Free State of Saxony due to the limited availability of the required training data.

The final model was created with the following 12 model input data:

- DGM20 – negative horizontal curvature,
- DGM20 – positive horizontal curvature,
- DGM20 – negative vertical curvature,
- DGM20 – positive vertical curvature,
- DGM20 – flow accumulation,
- DGM20 – slope angle,
- DLM250 – density of vegetation cover,
- DLM250 – degree of soil sealing,
- GÜK200 – rock class 1: hard rocks,
- GÜK200 – rock fracturing class 1: fracture-favourable,
- GÜK200 – rock surface class 2: with divisional surfaces parallel to layering,
- GÜK200 – rock deformation sensitivity class 2: distinctive deformation sensitivity.

3.2.4 Results

The result of the ANN model is a raster map with continuous values between 0 (no geo-hazard potential) and 1 (very high geo-hazard potential), which was divided into discrete classes for better graphical output. In this regards, it was distinguished between endangered (geo-hazard potential ≥ 0.75) and non-endangered areas (geo-hazard potential < 0.75). As before, endangered areas were additionally buffered with 50 m, 100 m and 200 m and then intersected with the railway tracks to outline sections, which are endangered by geo-hazards that may occur in the vicinity of the railways itself. All results were printed on maps and made available for further use as spatial datasets. The compiled maps are so-called geo-hazard maps that show potentially endangered areas, but without stating the height of the risk itself (Figure 5).

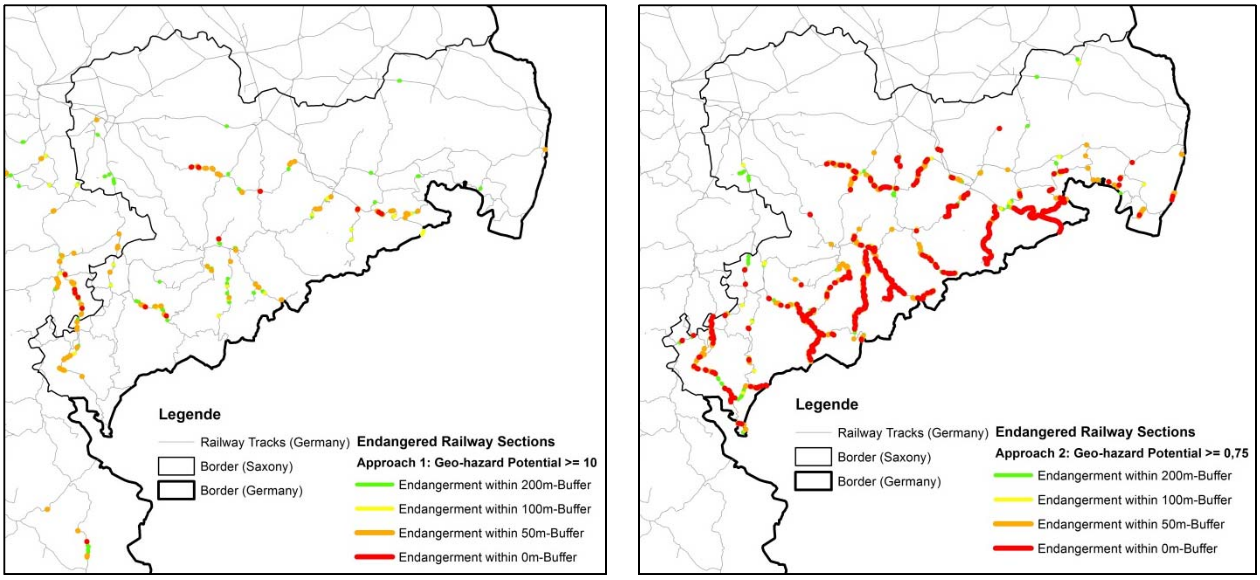

Figure 5 Saxony-wide map showing railway sections that are located directly at or within a buffer of 50, 100 or 200 m away from an area with a calculated geo-hazard potential class of ≥ 10 (knowledge-based approach) or ≥ 0.75 (75%) (data-driven approach) (Knobloch et al. 2018)

3.3 Application Case 3: Prediction of the potential of tin occurrences in the Mid-Saxonian Erzgebirge

3.3.1 General

Tin mining in the Erzgebirge (Saxony, Germany) has a history going back at least to the 14^{th} century. Recently, exploration activities in the vicinity of historical mining areas have resumed (Barth et al. 2018). Due to the long mining history and the related amount of geological, geochemical, geophysical and mineral data, the Erzgebirge were selected as test case for developing advanced mineral predictive mapping approaches in brownfields.

3.3.2 Source Data and Pre-Processing

For 3D predictive modelling, a new 3D model of the Erzgebirge was constructed (9500 km^2) in Paradigm Gocad® considering tectonics, stratigraphy and lithologies with special focus on the various types of granites. Along the NW-rim of the Erzgebirge, the so-called Central Saxon Lineament, a deeply concealed granite intrusion was constrained using 3D inverse gravimetry modelling. Geological primary (bore holes) and derived (maps, sections) datasets, as well as geophysical and geochemical data were used for geological modelling. Enveloping bodies of known Sn-W occurrences were modelled using data either from literature or provided by exploration companies. They are classified according to commodity content and genetic type for later use as training data in the neural network. The individual voxels (100x100x50 m, corresponding to

12.8 Mio. voxels in the 80x20x4 km model space) were attributed with geological unit, lithology, geochemical and geophysical properties, tendency to form joints, existence of calcareous layers and other properties (see Figure 6). True 3D distances to the different categories of faults and to the granite surfaces were calculated with the tools available in Gocad®. The advangeo® 3D Prediction Software was used to generate 3D favorability models for Sn mineralisation of skarn and vein type.

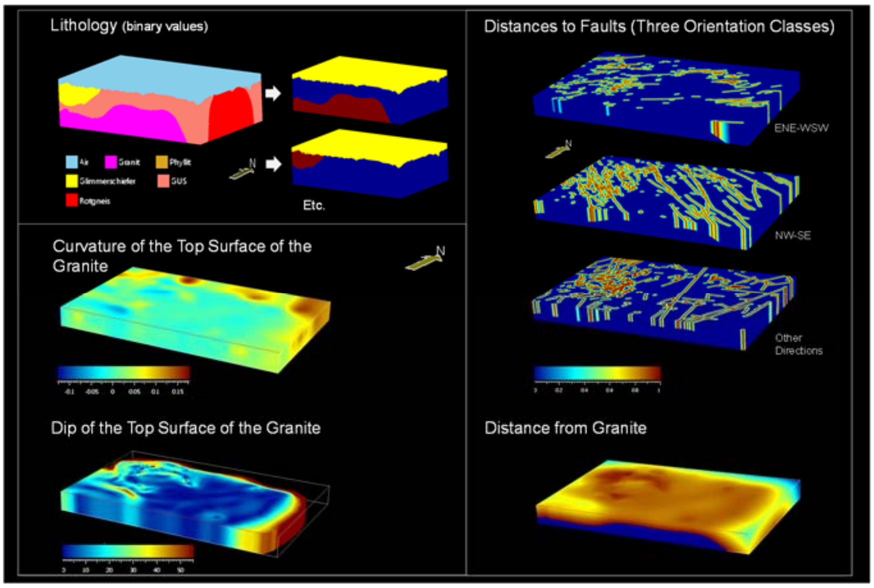

Figure 6 Examples of Model Input Data of the advangeo® 3D Prediction Software

3.3.3 Results

Key to predictive modelling was the creation of separate models according to the genetic types of deposits (e.g. Sn in skarns or pneumatolytic veins) to fully account for the different geological factors controlling different types of ore genesis.

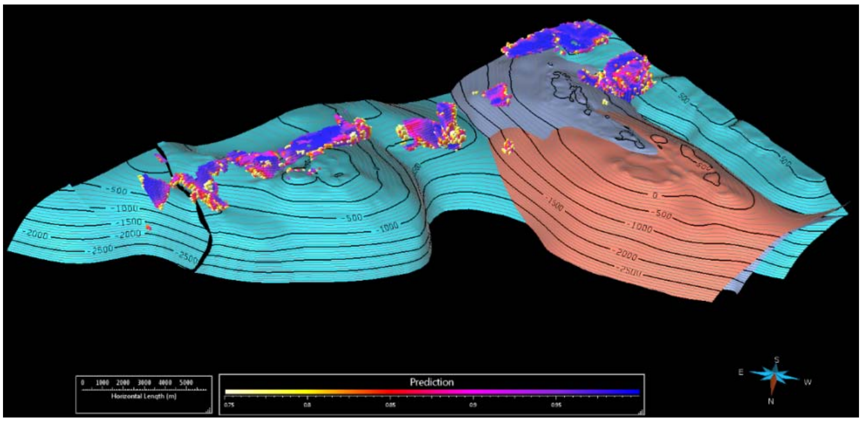

Figure 7 Sn potential in skarns modelled by using advangeo® 3D Prediction Software

Figure 7 shows the Sn skarn potential modelled by using advangeo® 3D Prediction Software. The advantage compared two 2D prediction maps is that the volume and the depth of the predicted resource are determined. Consequently, predicted volumes can be ranked for potential economic viability and further exploration activities can be allocated accordingly.

4 Conclusion

The case studies demonstrated that the machine learning is suitable for the analysis and prediction of various applications of spatially-dependent natural and human induced phenomenon, including the temporal and spatial prediction of waste rock pile stability, the prediction of the geo-hazard potential along infrastructure as well as the identification of potential mineral resources.

The stepwise generation of model scenarios with advangeo® supported the derivation of information while taking the sensitivity of controlling factors into consideration. However, one disadvantage to this approach is its inadequate ability to explain results where the specific influences of single parameters cannot be directly retraced. All interrelations amongst factors of influence and the final result were revealed through the course of the training process. With this process, 'erroneous learning' cannot be excluded. As a result, it remains a challenge to define the boundaries of neural network applications.

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Supervision of Tailings - EIT Project STINGS

K Zimmermann *DMT GmbH & Co. KG, Germany*

Š Bavec *Slovenia*

GZ Slovenije *Slovenia*

S Fingerhuth *Pontificia Universidad Católica de Valparaíso, Chile EIT STINGS Project Consortium Partners*

Abstract

STINGS is an innovation project funded by EIT RawMaterial. It aims to establish an integrated monitoring service for observation and analysis of tailing operations. By integrating remote sensing data, ground-based sensor information and modelling, safety-relevant information on the stability, material discharge and contents of tailings are derived and converted into decision-relevant criteria for safe operation. The following paper gives a brief project overview concerning scope, monitoring approach and partner network.

Keywords: *integrated monitoring service, tailings*

1 Introduction

STINGS is an innovation project funded by EIT Raw Materials to establish a ground- and space borne remote sensing and analysis system to effectively and cost-efficiently monitor critical ground infrastructure stability and content, primarily focusing on mining tailing dams (Fig. 1). It is dedicated to increase the safety standards related to tailing operations and to deliver the related mining sector, government, citizens and all stakeholders affected by previous and current activities with an extended monitoring and early warning system for identification of operational impact and environmental risk.

Figure 1 Mining related tailing operations

Global data on failures of both operated and closed tailing dams are extremely scarce and incomplete, much of this due to differences in legislative reporting requirements and to some degree as a reflection of willingness of failure reporting. Nevertheless, available data shows that there has been a significant amount of tailing dam failures during the last decades (Fig. 2). Data shows that the number of very serious and serious (both including loss of life) failures are increasing. This is mainly driven by larger tailings becoming necessary to allow economic extraction of lower grades of ore. This tendency is predicted to continue at a rate of at least 1 - 2 major failures every year from 2017 - 2020. Increasing global mining operations need the availability of new technologies to monitor tailings safety effectively and cost-efficient. Here, a key value STINGS will provide is the intersection between the increasing risks of tailing management and the improved technologies of monitoring.

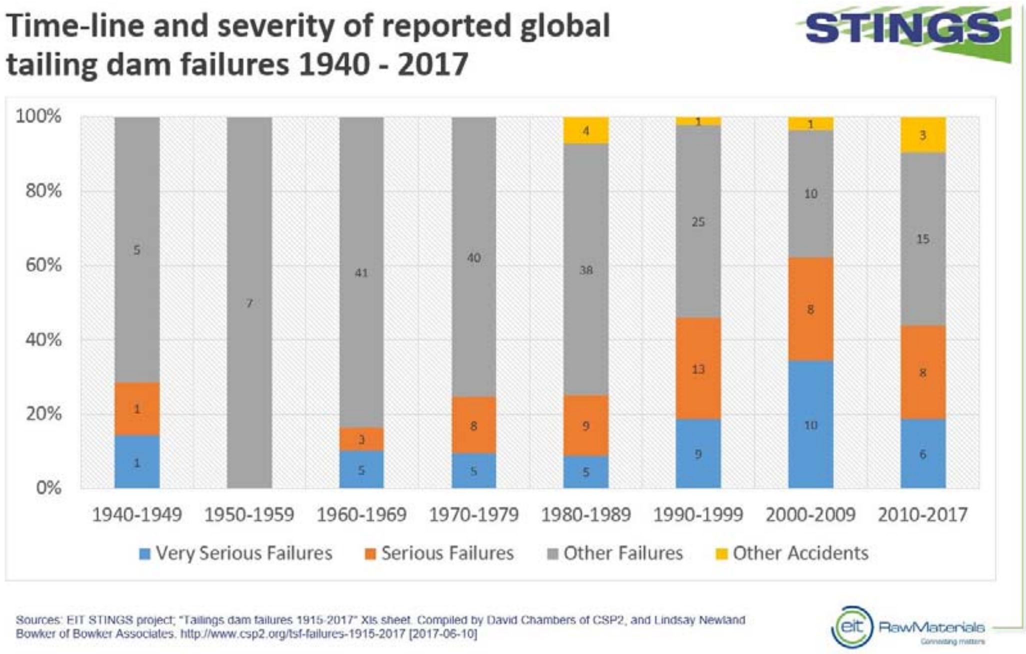


Figure 2 **Reported global tailing dam failures and severity over time**

2 Integrated Monitoring Approach

By integrating and analyzing a broad range of complementary ground and space borne sensor data STINGS offers a unique information service to identified risks, prevent disasters and to capture previously undetected secondary values. The monitoring system will focus on different information types, different sensors and combines them in order to generate the most reliable information related to tailings stability, chemical and mineralogical content (Fig. 3). It will implement satellite radar information as well as ground based sensor data to detect mechanical movements. An additional integration of optical remote sensing information enables to detect observable exits of substances from tailings. By using these different kinds of sensor information, data analysis and modelling the system will create safety information relevant for early warning. STINGS will offer cost efficient performance improving automation for monitoring of both active and closed tailings sites while providing a holistic risk management tool helping monitoring operations to ensure both measuring as well as analyses and reporting.

Figure 3 Integrated monitoring approach of STINGS

The technical feasibility of STINGS developments strongly depends on the underlying technical components. Satellite radar interferometry is a cornerstone of remote sensing. The European Union (ERS 1, ERS 2, ENVISAT, and now Sentinel 1A and B) and Germany (SRTM, TerraSAR-X, TanDEM-X mission) are leading players in this field of technology. In this project, in particular differential interferometry (dInSAR) is of interest in order to detect and monitor surface deformation occurring at tailings. For this application, the capabilities of the current operational European and German radar satellites are complementing quite well. Furthermore, radar absorption methods are investigated by STINGS to identify soil moisture changes by multi-temporal analysis of SAR-Data from Sentinel 1 as an indicator for the potential dry out of tailings. The results can be used as an early warning signal for particle emissions by wind from the tailing pond. In addition, the same methodology is foreseen to be applied for the detection of ground moisture changes due to leakages of liquids from the tailings pond. Optical Remote Sensing with data namely from the Copernicus Sentinel 2 mission (Fig. 4) and hyperspectral missions (e.g. Hyperion, EnMap) represents a keystone of the planned system.

Figure 4 Sentinel-2 image of Mina La Africana, Cía Minera Pudahuel (ESA)

Optical remote sensing is already applied for exploration and monitoring tasks in the mining sector. Recent results from R&D-projects clearly demonstrated the potential of new optical space-borne data from missions like Hyperion and Sentinel 2 e.g. for change detection of water bodies and soil moisture due to mining-related ground movement.

In-Situ sensor development and sensor application to detect movements and instabilities at tailing sites is another major task in STINGS. While various sensors (GNSS) and data logging technology are available on the market - within the project we focus on the development of low cost equipment with automated communication technology (ICT) for automated sensor data transfer.

System and data integration is a main challenge of the digital edge and specifically for what is called “Industry 4.0“ - a collective term embracing a number of contemporary automation, automatic and intelligent data exchange and fully digitized manufacturing technologies. STINGS will provide an important part corresponding to the integration of the various systems for the proposed interdisciplinary monitoring of tailings. The data management and early warning system developed during the project will accumulate all information and create safety information about the supervised tailings (Fig. 5). The system is based on DMT’s monitoring system SAFEGUARD that provides a technical foundation and proofs the technical feasibility.

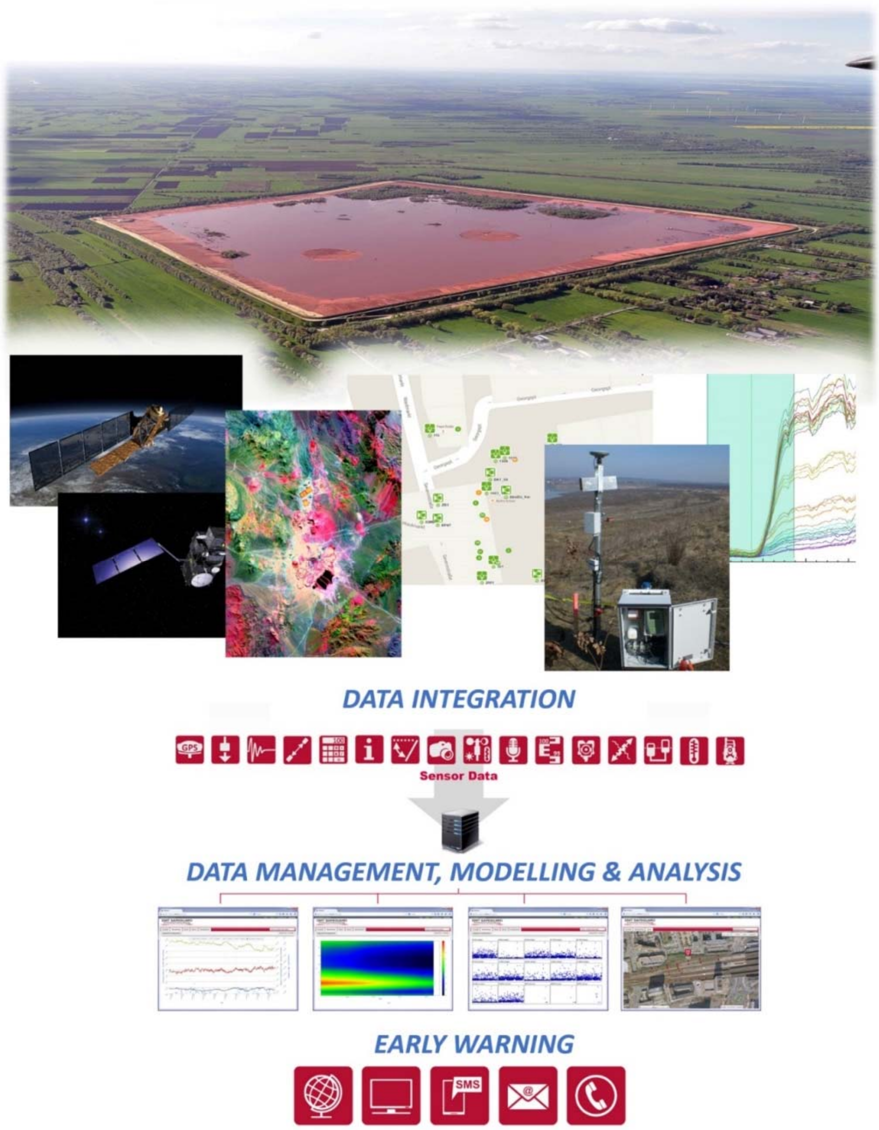


Figure 5 STINGS service illustration

3 Partner Network

The partner composition of STINGS combines user partners to determine market requirements, industrial partners for commercialization and the thematic expertise of scientific institutions. The partner consortium is show in Fig. 6.

Figure 6 STINGS project partners

The main regions for system development within the project are South America and Eastern Europe. To improve tailing monitoring specifically in Latin America one of the core project partners is PUCV (Pontificia Universidad Católica de Valparaíso) from Chile. PUCV has already conducted intense research focusing on improving operational controls and generate technologies for recovering areas occupied by tailings deposits. Within STINGS, the university will give valuable technological input, enables to select a suitable site for the system developments at large local tailing operations and will evaluate the results of the system for use in Chile. Fig. 7 shows the number of tailing operations in Chile and underlines the market size for tailing monitoring.

In Europe STINGS partner Ovidius (University of Constanta) will specifically contribute to the technology development for observation of chemical content of tailings, emission of particles by air (dust), moisture of the tailings inside the tailing basin, chemical content of liquids inside the tailing and detection of potential leakages. The activity will be carried out mainly on the Moldova Noua site in selected tailings and other relevant geological spots.

Figure 7 Tailing facilities in Chile (PUCV)

3. Case studies for mine closure

Gillervattnet and Gamla Dagbrottet Masterplan: Creating Social Relevance

MJ Baida *Cedervall Arkitekter, Sweden*

Abstract

Mine closure goals have evolved over the past 20 years with not only the strengthening of environmental and technical goals but also an increased emphasis on socio-economic goals. Such new goals include regional sustainability, community resilience, community driven development, cultural, and land-use planning components. This has resulted from an increased social awareness about the mining industry's' potential to contribute to the sustainable development of a region long after mining ceases. Globally, it is evident that mining companies are placing a greater emphasis on integrating these new mine closure goals within their overall closure plans. However, the question continues to be raised by mining companies 'what, if any, socio-economic closure goals should we have?' and 'how do we plan post-mining landscapes to successfully achieve socio-economic goals?'.

This paper presents a case study in response to the above questions from a project in Boliden, Northern Sweden. Resulting from the finalization and completion of the technical works associated with the closure of the Gillervattnet tailings management facility and an abandoned open pit, a legacy from the company's original operation, New Boliden viewed this as an opportunity to explore potential future social land-uses. They understood that mine closure today is a multifaceted combination of not only technical and environmental components but social and financial factors also that must be holistically addressed if post-mining land-uses are to be implemented successfully. However, beyond the technical and environmental closure goals developed to achieve regulatory compliance there existed no socio-economic closure goals for the site. Therefore, important to the project was the development of an inter-disciplinary design team bringing new knowledge, thinking and skills outside solely scientific and engineering solutions. Also, critical for the development of socio-economic goals was the planning and successful implementation of the community and stakeholder engagement process. These key components were integral to driving long term ecological and cultural decision making for the landscape masterplan.

Keywords: *socio-economic closure goals, case study, open pit*

1 Introduction

There are many great examples of successful post-mining projects with socio-economic outcomes. However, many have resulted from negative mining legacies where no socio-economic closure goals were developed by the mining company. This is despite best practice stating that mine closure planning including, socio-economic considerations, should begin during the application stage of the mining process. In an ideal world socio-economic closure goals would be planned pre-mining, however, in reality early planning for future socio-economic land uses post-mining are often not achieved.

Early planning for socio-economic closure is important for reasons including long-term financial benefit helping to reduce closure cost and obtaining approvals, leases and social licence to operate from authorities and community's. While important, it is also very difficult for mining companies to achieve for reasons that may include:

- Lack of resources within a mining company – small companies may not have the financial capacity to develop or implement socio-economic closure goals;

- Lack of adequate skills and knowledge – to meet society's social and environmental expectations today, new knowledge, thinking, and skills are required within the mining industry;
- Older operating mines may have been operational before the evolution of socio-economic closure goals – companies are being asked to retro-fit socio-economic goals into operational mining projects which can impact legally and financially on existing approved technical and environmental closure goals;
- Short term thinking – this is considered a difficulty from both within the mining industry and humans in general. Within an industry focused on quarterly earning cycles it has not establish a culture of long-term planning and thinking. Within humans our brains have evolved to deal with short term problems, those that are directly in front of us. Case in point; decades of inaction now sees us reactively dealing with the increasingly frequent impacts of climate change. How do we then ask a community to think about the long-term future for their small part of the world if the industry which it depends on does not.
- Changing society – 30 years ago we lived without internet, 20 years ago the social licence to operate did not exist, the world is changing at a rapid pace. It was a dramatically different place 20 years ago and will be a dramatically different place in 20 years from now. When gold was discovered in 1927 in northern Sweden the town known as Boliden and its community did not exist, there was no environmental legislation and society had vastly different ethics, living needs and expectations of mining companies. The natural progression and evolution of society is a challenging reality.

How does one plan and develop socio-economic goals based on the above? This is a question the authors do not seek to definitively answer, nor can, but through this paper dissect a project that has begun to deal with several of the challenges listed above. Through the dissection of the 'Gillervattnet and Gamla Dagbrottet (The Old Pit) Masterplan' project this paper is not intended as academic but offer a precedent and methodology developed from a working process. It can be referenced but current operational mines wanting to determine socio-economic closure goals in collaboration with the local community thus exploring possible post-mining land-uses with social relevance. It is set out in three parts:

- **Project Background**
- **Project Methodology**
- **Project Outcomes**

If applying 'best practice' theory of early planning and setting of socio-economic goals this project would not be considered best practice. Beyond technical and environmental closure goals developed to achieve regulatory compliance no socio-economic closure goals had been developed for the sites of community.

However, such a situation is perhaps a more realistic situation facing mining companies and communities today. One where a mining company would like to explore potential future social land-uses for their site and in doing so develop socio-economic closure goals.

2 Project Background

In Boliden, Northern Sweden, the completion of the technical works associated with the closure of the Gillervattnet Tailings Facility and Gamla Dagbrottet (the Old Pit) prompted New Boliden to explore potential future land uses for the sites. Cedervall Arkitekter and its landscape architect team were engaged to explore future land use options with a focus on long-term socio-economic benefits. Community engagement was recognized as a key driver to ensure successful project outcomes.

2.1 Project Objectives

The project aimed to deliver a Landscape Master Plan, designed in collaboration with the local community, with the following key objectives:

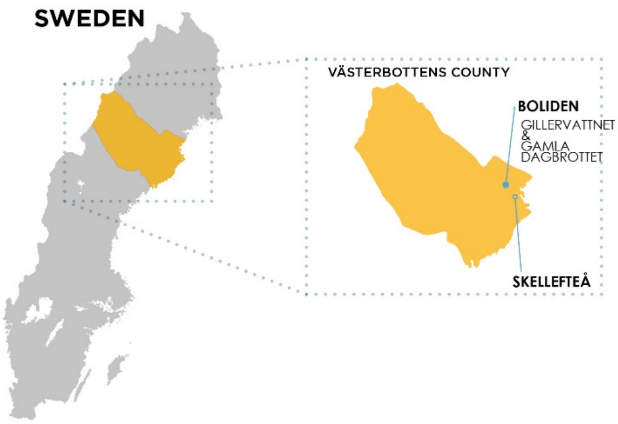
- Determine long-term social visions developed in collaboration with the community;
- Develop a strategy for the design and implementation of the community visions;
- Create a new identity for the town;
- Attract tourists and visitors to drive local economic growth and new opportunities independent of the mining economy;
- Build on local culture and provide increased recreational opportunities;
- Develop an ecological strategy to reintegrate the site with the surrounding ecosystem;
- Create a platform for community driven development.

2.2 Project Context

In 1927 mining began 30km north west of Skellefteå at what was known as the Boliden mine. This developed into one of Europe’s biggest and richest gold mines. The Boliden town and community developed around the mine with its population peaking at the beginning of the 1960’s. Until 1965 the town was owned and managed entirely by the mining company, then Boliden now New Boliden, after which the local municipality took responsibility for the operation and administration of the town. Two years later the mine closed leaving what is known today as Gamla Dagbrottet or The Old Pit. However, the processing plant and industrial area remained in operation servicing surrounding mines and providing employment.

Today, the processing plant and industrial area continues its operations and New Boliden remain independent from the ownership and management of the town. However, subconsciously there still exists a sense of reliance and dependence on New Boliden from the 1700 local inhabitants. This has resulted from a combination of the historical connection between community and company and the lack of business development and opportunity outside the mining sector. While not aiming to create a sense of further reliance and dependence on itself New Boliden recognized they are saddled with a responsibility for the community and can contribute to long-term diversified economic growth and resilience of the community.

2.3 Project Location



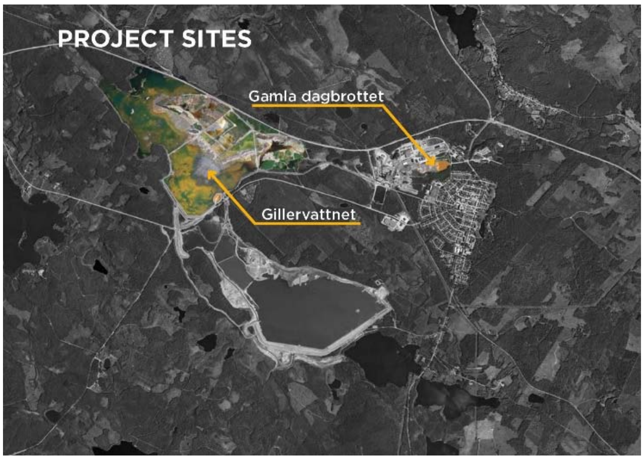


Figure 1 Project location

Figure 2 Project sites

3 Project Methodology

To achieve the specific project objectives the following methodology was developed and implemented by the project team. The intention is it can be used as a template by mining companies in a similar situation.

Figure 3 Project Methodology

3.1 Project Kick-Off

A kick-off workshop between Cedervall Arkitekter (design team) and New Boliden (project team) was undertaken to fully understand the project and set objectives.

Table 1 Tasks and objectives in the project kick off

Tasks	Objective/s
Understanding the Project - New Boliden presented the company's history, overview of current mining operations, technical aspects of the project sites including regulatory requirements, company environmental standards and policy, social license to operate measures and relationship with the community.	To 'meet and greet' the New Boliden project team and develop a common understanding of the project and expectations.
Understanding the Site - An extensive round table analysis mapping was undertaken along with a site of the sites.	Develop a detailed understanding of the sites and their surrounding context. Assess the issues and opportunities that exist in relation to the existing function and character of the sites.
Community Consultation Framework Development - A draft community consultation framework was outlined. It was developed based on the following questions; ○ What is the purpose and scope? ○ What level of participation is it hoped will be achieved? ○ Who are the stakeholders? ○ What are the barriers to overcome? ○ What resources are available? ○ Are there any limitations?	○ Develop an agreed consultation approach and methods ○ Determine stakeholders and their impacts and influences on the project.
Develop Project Objectives - A workshop focused on the development of objectives from a cultural, social and community and ecological perspective.	Define project objectives.

3.2 Project Development

The project development phase aims to develop a thorough understanding of the project and its context on a national, regional and local level. This ensures the correct decisions are made regarding the development of the design team, consultation methods and project objectives. Based on the Project Kick-Off phase the following tasks were undertaken to drive the project forward.

Table 2 Tasks and objectives in the project development

Tasks	Objective/s
Build the Design Team – Identification and selection of an inter-disciplinary team with the skills and knowledge required to achieve the project outcomes.	Form a design team with the required expertise to achieve the project objectives.
Understanding the Sites - GIS data analysis.	Develop a greater understanding of the project sites and their context. Can any issues/opportunities be foreseen?
Finalise Community Consultation Framework - Finalise community engagement framework including details of the when, where, who, why and how.	To design and plan a consultation process that will be receptive, stimulating, inclusive and diverse.
Understanding the Project Preliminary Investigations - Detailed desktop review and gap analysis of reports, papers, studies, existing plans, strategies and policy documents within environmental, social, economic, cultural and political context at EU, national, regional and municipality level.	○ Develop an understanding of the emerging issues and trends that will impact on the project and considering to how these will change in the future. ○ Determine what information exists and what additional information, data or investigations are required.
Finalise Project Objectives - Finalized project objectives with knowledge gained through the preliminary investigations and with consideration to the skills of the design team.	Finalise project objectives based on a greater understanding of the project.

3.3 Community Consultation

The consultation approach focused on engaging the community early in the project process, with the strong intent of building community ownership in the project, and ensuring that the strategic directions of the master plan are directly linked to the unique needs of Boliden's community. The consultation was designed as an intensive 5-day planning for real consultation, which enable the design team to develop a detailed understanding of Boliden as a place and community. The focus was to identify the community's identity and values, the challenges and opportunities for the town, the existing cultural and environmental values associated with the project sites and surrounding landscape and future visions of the project sites to assist guide the directions of the masterplan. A planning for real consultation approach is where a design team will literally plan for real. A design studio is setup in a community and over several days they are invited to share their local knowledge and participate in the consultation. The design team listens and learns from them and as ideas and opportunities are identified they develop them into sketches and plans showing how the community's ideas can be translated into physical realities. It is a collaborative and transparent process as the community can provide immediate feedback on the plans and sketches. It is this two-way conversation which is a critical component of the planning for real. These sketches and plans then form the basis for an ongoing conversation with the community.

3.3.1 Consultation Methods

Several consultation methods were employed ensuring the design team developed a strong and balanced sense of what has shaped the community and where they see their future to inform their decision making. These included:

Table 3 Tasks and objectives in the consultation methods

Tasks	Objective/s
Lead-in activities - Several lead-in activities were undertaken approximately one month before the consultation event. These included; ○ Promotion of the consultation (Facebook event, consultation event posters with QR codes (linked to Facebook event) were displayed around town and flyers sent out to all local homes) ○ Meeting locally identified stakeholders to introduce and talk to them about the consultation method and project objectives.	○ Create interest in the community and provide an online forum for the community to discuss the event. ○ As a means for people to get to know the design team and feel comfortable and encouraged to attend the consultation. It also allows the design team to identify crucial issues early in the process.
Drop-In Sessions - A design studio was established in the town hall where the design team had its work base. Here the community were welcomed to participate in various cogitative mapping exercises, one-on-one meetings and simply to come and see the process and share their thoughts.	○ The cognitive mapping was used to map qualities and values that exist in the town and surrounding landscape with a focus to determine opportunities and challenges that influence the project sites ○ Understand the less tangible assets to help determine what shapes the community.
Primary School Consultation: Wish Tree - Before the consultation the school teachers were introduced to the project and asked to discuss it with their students. Several questions were raised with the students such as, 'what is the best thing about living in Boliden?', who were then asked to build a message tree where they could hang their answers. During the consultation the design team spent a day with the students discussing their answers.	To understand the context of the community from a youth's perspective
Online Survey - An online survey was translated into 6 languages and distributed via the facebook event, emailed to school parents and linked to QR codes on consultation promotional.	Reach a broad cross-section of the community. The survey was intended for those who did not have time to visit the drop-in sessions and the immigrant population whose native language is not Swedish
Individual meetings - Individual meetings were arranged with groups who desired them. These could either be at the design studio or at a location that suits the stakeholder.	Create an exclusion consultation. Not all people of groups feel comfortable talking in front of others so this allows for the design team to meet with those who feel more comfortable speaking one on one or those that don't have time to get to the consultation but still would like to talk.

3.3.2 Community Sign-off

The design team worked constantly across the 5 days evaluating and understanding the community's input. This resulted with a presentation back to the community where the design team presented a summary of what they had heard and learnt from the community during the 5 days and what the key issues and opportunities were to conclude the consultation. The basis for the concluding presentation is to inform the community what directions will be taken to move the project forward. This was achieved by presenting initial ideas, concept sketches and planning principles. This gave the community the opportunity to comment on these and agree or disagree with the direction and ideas from the design team. This enables a two-way conversation about the direction of the project allowing the design team to progress the project with acceptance from the community.

3.3.3 Consultation Schedule

The consultation was planned across 5-days and included two community presentations, individual meetings, open house drop-in sessions and consultation sessions with the local school and Boliden staff. In total across all the methods used 482 community members participated in the consultation representing almost 30% of the population.

Schedule| Community Consultation

Day 1	08.00-15.00	Boliden School	Drop-In Session/Wishing Tree	Students
	18.30-19.30	Community Hall	Presentation	Open House
Day 2	11.00-15.00	Boliden Office	Drop-In Session	Boliden staff
	18.30-19.30	Processing Plant	Drop-In Session	Boliden staff
Day 3	11.00-19.00	Community Hall	Drop-In Session	Open House
Day 4	10.00-17.00	Community Hall	Drop-In Session	Open House
Day 5	16.00-18.00	Community Hall	Presentation	Open House

Figure 4 Consultation Schedule

3.4 Landscape Masterplan

The next stage of the project was developing the landscape masterplan. A landscape masterplan reacts to the immediate site and explores and considers the past but its primary objective is outlining a road map for the future. It is a plan that is not static but used as a foundation and to build upon, test against and change. It allows and invites a rapid changing world and will evolve to meet new challenges defying age. If used correctly a masterplan should evolve with the community and their changing expectations and needs. This phase included the development of a Landscape Masterplan Report. The Masterplan Report is used to communicate the knowledge, thinking and decision making behind the development of the landscape masterplan. It creates a document that outlines a company's socio-economic goals. It includes the following:

- Project Background and Context;
- Consultation Summary and Key Findings;
- Site Analysis;
- Planning Principles;
- Landscape Masterplan.

Before developing the landscape masterplan, to ensure successful project outcomes and a strong foundation for the development of ideas and concepts, work undertaken and knowledge gained in the previous phases of the project was further analyzed, refined, evaluated and investigated. The community consultation data was further analyzed, in collaboration with a social sustainability expert, to ensure the project team had thoroughly understood the communities needs and the issues and opportunities surrounding the project sites. The in-depth site analysis was continued to investigate and understand various quantitative and qualitative landscape and social factors affecting the sites. Through a thorough understanding of the community and project sites the planning principles presented to the community at the end of the consultation were further developed. These can be considered as socio-economic closure goals. They are used to guide the design and thinking for the landscape masterplan.

Figure 5 Design Principles

4 Outcomes

The Masterplan Report and Landscape Masterplan outlines a holistic and long-term approach for developing Gillervattnet and Gamla dagbrottet into landscapes that again benefit society and the environment. The landscape masterplan provides an exciting opportunity to develop the sites into community spaces with social and cultural value and commercial opportunities. Increasing recreation activities, retaining cultural heritage, creating new social locations and re- establishing destroyed ecosystems form part of the Master Plan's objectives. In addition, it sets the foundation for diversified growth and new business opportunities that focus on the long-term development of Boliden and the region. Within the report a 5-year strategy outlines the design development and construction stages of the landscape masterplan's key projects. This provided the community and the mining company a document and mechanism to begin the implementation of the socio-economic goals. It must be understood that the landscape masterplan and strategy is a long-term approach and cannot be implemented over night. They are not seen as linear but will evolve and be subject to change as relationships develop, projects begin and feedback occurs. Its intention is to provide a foundation for the development of community resilience and achievement of socio-economic closure goals.

5 Conclusion

While the guidance available on good mine closure practice suggests early decision making and planning for socio-economic closure goals is desired it is never too late for a company to make meaningful investments and contributions to the long-term future of the community that they rely on. This paper does not intend to contradict best practice guidance as it agrees that early planning and development of socio-economic closure goals along with their progressive implementation will reduce cost, assist obtaining approvals from authorities and communities and reduce the social risks associated with the transition between mining and post-mining. But it offers a precedent to determine socio-economic closure goals during the operational phase of a mine in collaboration with a community to explore post-mining land uses that have social, economic and environmental value. The landscape masterplan, thinking and outcomes discussed in this paper are specific to the current and future needs of the Boliden community. However, the methodology used is adaptable and can be applied to other projects to achieve similar outcomes. The development of a landscape masterplan begins a process that stretches beyond the boundaries of project sites but starts a process with the community that begins to ask them how they see their future and how can this be achieved? It assists a mining company and community develop socio-economic closure goals with relevance and benefit to both parties albeit after mining has begun.

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https://wspsweden.maps.arcgis.com/apps/Cascade/index.html?appid=8f98b76d9d1a41078170959357dacd82
All images are from the masterplan report.

Coal and Gold – How to Rehabilitate Historic Mines for Urban Development

S Longo *Golder Associates Ltd, Canada*

C Crossley *Golder Associates Ltd, Canada*

Abstract

As more orphaned and abandoned mines are becoming challenges or even impediments to urban or recreational development, new rehabilitation technologies must be implemented. The technical challenges of historic mines cannot be underestimated - early 20th century mine plans, no underground access, logistics and proximity to local communities all make solutions more complex and potentially more expensive. This paper will present two different case studies of different mine sites which all applied the novel concept of paste technology for rehabilitation. In one case, the rehabilitation was such a success that a resort community has been developed on the land including wildlife corridors, hiking trails, schools, condos and golf courses.

Keywords: *historic mines, urban development*

1 Introduction

Properly closing or rehabilitating abandoned or orphaned mine sites can be complex, expensive and occur over a long duration, often due to location (remote or adjacent a community), era of mining (type of mining and when mining occurred), and availability of reliable information. These historic mines often have several types of physical hazards, such as mine openings to surface, near surface mine workings, unreclaimed waste rock piles, and uncovered tailings storage facilities. These physical hazards can be problematic as they can present risks to the environment and the general public if left un-rehabilitated. The successful rehabilitation of historic mines therefore requires both a strategy that will work for the local conditions (including economics), and a team that can integrate expertise from multiple disciplines to apply innovative solutions.

When considering the rehabilitation of a mine site, typically issues arise around unmitigated hazards that can present themselves in two ways: gradually or as a sudden event. These hazards can include openings to surface, land subsidence, and/or sinkholes. The problem associated with these hazards is they can be complex and difficult to manage from a technical, environmental and especially economic perspective. The causes of surface impacts can be difficult to understand, making the assessment of hazards and the development of suitable mitigation efforts complicated. In some cases, there is considerable uncertainty around the accuracy/availability of both the geometry and associated geology of the mine site in question. Challenges such as potentially incomplete or inaccurate historical mine plans, physical constraints like limited safe underground access and limited access for equipment and logistics, as well as proximity to local communities, all combined with the overarching umbrella of potential adverse environmental impacts are common.

Over the last decade robust approaches have been developed to cut through the complexity and develop solutions to manage or remove these hazards while optimizing costs and timelines. In particular, paste technology was introduced to the mining industry over 30 years ago as an alternative underground backfill method, and is widely utilized in active mining applications. Paste can generally be defined as a dense, viscous mixture of tailings and water, which unlike slurries, does not segregate when not being transported (Rens B.M Verburg IMWA Symposium 2001). Paste has a working consistency similar to wet concrete, with minimal or no permeability, and no critical flow velocity. The ability to control slump and flow makes paste backfill an extremely flexible solution for filling voids and adapting to changes in geometry. In addition, paste can be made from surplus material available on site, such as tailings and overburden, and the ability to mix and change the properties allows for paste to be used for different applications.

This paper highlights the process of investigating, assessing, mitigating and rehabilitating hazards associated with abandoned, orphaned, or historic mines. In addition, two case studies are presented, where developing a holistic site wide investigation and rehabilitation approach, combined with the application of paste technology resulted in benefits to both the mineral rights holder, government, and/or the general public/landowners in terms of cost savings and environmental impacts.

2 Stability Assessment, Hazard Mitigation and Rehabilitation Strategies

2.1 Overview

In the past, typical risk mitigation measures for abandoned or orphaned mine sites have included fencing off affected areas to restrict access, excavation of the area to expose the voids and emergency filling programs. However, as the public risk and safety issues associated with these sites are receiving increased attention, the need for a proper rehabilitation strategy and alternative remediation solutions has also increased. The approach for rehabilitation is shifting from reactive programs such as "emergency" filling of voids, to pre-emptively identifying and fixing the problem in a planned way. The most popular way to do this has been through backfilling, however the complexity and cost of this method for some sites has made it impractical to actually execute. One issue with backfilling as a solution is inaccurate or absent stability assessments and incomplete mine plans or lack of understanding of mine plans. This can increase project costs as more drilling is required to identify and determine the extent of voids. This section of the paper will discuss the general stages for the effective development of a rehabilitation strategy and backfilling system. The two case studies discussed later in this paper underwent a similar staged approach for the development of their rehabilitation strategies.

2.2 Stability Assessment of Underground Mine Openings

The first step to developing a rehabilitation strategy for a historic mine is to cultivate an understanding of the mine and its workings by performing a stability assessment. Site stabilization is paramount to the rehabilitation of orphaned and abandoned mines as deterioration over the years of inactivity and ground movement will have created potential instability. Often, some impacts have already been seen with surface subsidence and sinkholes occurring in and around the pits or the underground, however the full extent of hazards underground may be unknown. One component of underground stabilization for mine closure can be to backfill underground voids to prevent collapse, or backfill other portions of the mine that pose immediate risk to the public and worker safety. For this to be completed successfully, a stability assessment should be performed first to help understand the extent of the risk, map out areas of priority and then assess the strength requirements of the backfill to support the area.

Stability assessments are generally completed using an iterative/phased approach. The phased approach generally includes: data gathering and validation; desktop stability and data gap analysis; planning and execution of a physical investigation; stability assessments; and identification of what mine openings require rehabilitation. Once this has been completed, remediation options can be developed and assessed to determine the most appropriate hazard mitigation and management plan for the site or for particular areas within the site.

2.3 Options Development for Hazard Mitigation and Risk Management

Once the site investigation and stability assessment for an abandoned mine has been completed, unstable and stable workings will have been identified and a hazard mitigation plan can be developed to fit the findings. This can be achieved by using a phased approach which includes: identifying suitable rehabilitation options; order of magnitude costing and data gap/advantage/disadvantage assessment; detailed option design and assessment; and prioritizing rehabilitation methods as part of the rehabilitation strategy. Prioritizing rehabilitation methods is an important step as these may impact cost and schedule. Typical options considered for hazard mitigation are capping, exposing the void and/or backfilling.

When considering these options, each is valid and can be the preferred choice for a particular site. Capping typically presents as a temporary solution – concrete degrades over time and the underlying hazard still exists. Permanent solutions are exposing the void and backfilling of the void. Exposing the void can involve blasting or excavation of the hazard and depending on the depth and dip of the void this may or may not be possible, especially if a community is present near the hazard. Backfill can be utilized in congested areas and can be done with a mobile set up to avoid some of the proximity issues but there should be an available source of backfill material to avoid escalation of costs.

2.4 Backfill System Development and Execution

One of the remediation options available is backfilling voids to limit the progression of any failure and reduce or remove the potential for surface impacts. Once backfill has been established as the mitigation method of choice, the type of backfill is then determined. There are three main types of backfill: paste backfill, rockfill, and aggregate fill. All three types of backfill can be applied as cemented or uncemented material. To determine which type of backfill to apply, the next step is to estimate the backfill strength requirements, volume requirements, delivery locations and any other special considerations such as availability of backfill feed material. This is carried out through analysis of existing mine plans, surveys and/or exploratory drilling programs. Once strength targets are determined, typically a laboratory testing program on the source materials for backfill is required. The lab program will develop a suite of "recipes" to meet the strength, flow, and permeability targets depending on delivery routes and requirements.

Establishing the design criteria for the backfill and methodology of execution are the next steps to the backfill system plan. Process selection and planning (including equipment selection) should take into consideration the site specific circumstances such as access, available laydown areas, material delivery, proximity of the voids to the production area, the public, and of course, health, safety, and environment.

2.5 Execution of Stabilization Options

After all critical planning steps have been completed, the execution phase begins. During execution many things can change, therefore the program needs to be flexible to respond to what is happening underground and on surface. One of the key execution mindsets is to go slow at the start of a new pour and make sure that leaks are capped as soon as they are identified and that the backfill is settling where planned. This is key for minimizing waste of material and effort. This is not a typical contracting philosophy which means communication between the contractor and engineering team is critical. Once the voids are filled, as part of the quality assurance / quality control (QA/QC) program, confirmatory drilling and inspection should be conducted to verify volumes and strengths are meeting the technical specifications of the design. Once backfilling testing and verification has completed, the voids can confidently be called rehabilitated.

3 Case Studies

3.1 Case Study 1 – Three Sisters

Three Sisters is a site located in the northern region of the northwest trending Cascade Coal Basin of Alberta on the eastern edge of Canmore, Alberta. Coal mines opened up in 1887 in support of the Trans Continental Railway. Since that time, 17 different coal operations have existed, the last having ceased operation in 1979. The mining method was room and pillar and there is a history of ground subsidence in the area. As with many coal mines, the underground drifts rise and fall with the coal seam, and at times to surface. Canmore is located in the foothills of the Rocky Mountains and as such there is a propensity by both locals and visitors to spend time in the outdoors. Hiking, skiing and mountain biking amongst others are all common activities in this part of the country. With so much of the area near Canmore being undermined, there was a hazard to people being on or near the old mine workings. The possibility of a sudden collapse was very real and in fact had already occurred in a number of places. This hazard also applied to wildlife which use the area to forage and as a corridor during seasonal movements.

Three Sisters Mountain Village Development received permission in the early 2000's to develop an 800 ha site in the area encompassing the old mine sites. It was planned to build a housing community of 10,000 people, with a completion date of 2010 (it has been largely completed to date). The development includes wildlife corridors (60% of 800 ha), two 18 hole golf courses, wellness centre, school, commercial buildings and residential condominium complexes. To date, between $150M and $200M in property has been sold. Prior to proceeding with the developments, the Alberta Provincial Regulation (114 / 97) requires any land developer to have their situation studied by a geotechnical engineer with experience in underground mine ground control and subsidence engineer, who prepares a report and recommendations. When these recommendations are carried out, the engineer certifies the results, which in turn are certified by an independent expert. Golder Associates Ltd. was commissioned by Three Sisters to study the site and make recommendations. Cemented paste technology was chosen as the practical and most economical solution but as part of this assessment it was required to prove to the regulator that this solution was "proven" and would provide the necessary geotechnical stability to the area. This was done via previous projects and test examples to demonstrate the effectiveness of paste backfill. Once the approval was granted then the implementation phase began.

Site conditions in the area were highly mountainous and tree lined, which limited the backfill requirements to a mobile plant, as a fixed plant solution was not appropriate. An innovative, new delivery method was required and by working with local contractors, modified concrete equipment was developed that could deliver paste backfill from a mobile operation.


Figure 1 Three Sisters mobile set up and a paste in the underground

Boreholes were mapped based on the geometry of the mine per the mine plans and on a maximum spacing of 15 m between holes. The depth of boreholes and the amount of material required per hole depended on the intended development. The undermined land was and will continue to be developed as anything from park land (low mitigation requirements) to multi-story resort hotels (high mitigation requirements) therefore understanding the intended development was essential.

Pipe was laid out to various holes within reasonable distances of the set up and pressure transmitters were installed to monitor pressures in the line as the holes were filled. Data on fill volume and pressures was monitored and recorded, and an extensive QC program was also conducted to ensure the strength of the material delivered underground. Areas to be backfilled were established using the model of the underground workings that was developed based on old mine plans and surveys done during the drilling program. The feed material was a challenge as no tailings were locally available. Fortunately, local borrow sources were located that would provide material 'as is' with the appropriate particle size distribution. This became one of the main environmental positives coming out of the project as once an area of development was certified and construction on housing began, the material excavated for roads and basements became the feed material for the next phase of backfill. In this way thousands of cubic metres of material was diverted from landfills. In total at Three Sisters, 600 exploratory and injection holes have been drilled, with 24,000m^3 of paste injected to date. This abandoned coal mine was rehabilitated successfully to develop a resort community including wildlife corridors, hiking trails, schools, condos and golf courses.

3.2 Case Study 2 – Giant Mine

Giant Mine is a closed gold mine located in Yellowknife, NWT that operated from 1948 until 2004 and was officially abandoned in 2005. Studies have also shown that the existing bulkheads and stope pillars (both crown pillars and pillars between stopes) needed to be reinforced to ensure they do not fail during the long term closure of the underground workings. Giant Mine is currently under care and maintenance by Aboriginal Affairs and Northern Development Canada (AANDC). The site has long been an area of concern for the government and is a very complicated physical situation which exacerbates the difficulty of finding solutions. Close proximity to the city of Yellowknife (approximately 5 km) and a local waterway, Baker Creek, which runs through the site, require protection during remediation operations. Another example of the complexity of the operation is the accuracy of the mine level plans, which in some cases decade by decade contradict each other. Giant, during production, had such competent rock that little was done in the way of support underground – there are few rock bolts, almost no screens and little backfill. What this has meant over time is that things have moved and shifted in areas of the mine and in particular the crown pillars are becoming potentially unstable.

An innovative and efficient approach to stabilizing the underground voids was selected using cemented paste backfill. This minimizes potential failure of the underground workings, especially for stopes that are near to surface. Without structural fill in the underground, studies showed that there could be a significant risk of crown pillar collapse in one part of the mine that could propagate and cause failure elsewhere. This would have environmental ramifications, especially for the stopes running near Baker Creek. As part of the rehabilitation approach, and before underground reinforcement could begin, multiple investigation methods were used to close gaps in the understanding of the underground geometry for the stabilization assessment and remediation planning. This included: a 3D model built up from scanned and digitized historical level plans and geology sections; high-accuracy investigative drilling; borehole camera inspections; borehole Cavity Monitoring Systems (CMS) scans; and unmanned aerial vehicle (drone) flights. Once complete, geotechnical investigations and process design studies were completed to analyze the unreclaimed tailings at Giant for suitability as a feed material for paste backfill. For the production of cemented backfill, a mobile backfill system was set up between the open pit and existing ventilation station on the surface. The system included a modified mixer truck, cement silos, water tanks, and a boom pump truck.

Figure 2 Paste trial in seacan and surface set up of equipment

From October to December 2013, paste backfill was used to stabilize crown pillars using tailings. The mobile operation was executed in temperatures ranging from +10 C down to -50C which had not been done before according to a literature search. The Giant Mine project team utilized thousands of tonnes of tailings that had been deposited on surface as a waste by-product during historical mining as the primary component of the backfill. It is cost-effective to use onsite tailings material for underground backfilling, but its use also reduces the future effort required to remediate surface tailings pond areas. Twelve paste recipes that were utilized for stope specific pour requirements and approximately 11,470 m^3 pumped underground in approximately 2.5 months.

Figure 3 Paste barricade mix delivered via borehole to plug the door to the shaft

4 Closure

In dealing with abandoned or orphaned mines, long term stability is a key goal whether the intention is to promote urban development or simply address remediation and closure concerns. Long term stability and thus successful rehabilitation requires optimizing the rehabilitation strategy for all hazards by using all disciplines. This approach will promote innovative solutions and can avoid the duplication of cost and effort. Mobile paste backfill systems are an innovative and feasible alternative to fixed plants and can provide owners with flexibility and adaptability to site conditions while still maintaining the quality and reproducibility of a traditional paste plant. In addition, paste backfill is a proven technical solution in active mining and the two case studies presented here show how it can be modified and tailored to each of these different applications to create long term physical stability. The key is to understand the underground environment as well as the surface implications, such as but not limited to: set-up; moves; paste recipe development; infrastructure or material constraints; and the development of a specific plan to address these items in a timely and cost effective manner. This is especially true if the owner is local, regional or federal governments who typically do not have the resources – technical or otherwise – to engage in these activities themselves.

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The Highway to Hell: Proclamation and transfer of Kleinzee Township

WG Macdonald, *De Beers Consolidated Mines, Namaqualand Mines*

Abstract

Diamonds were discovered at the mouth of the Buffels River on the West Coast of South Africa in 1925. In 1942 De Beers Consolidated Mines purchased the Kleinzee Diggings from the Cape Coast Exploration Company and established the Private Mining Settlement of Kleinzee. As a private Mining Settlement; Kleinzee was constructed, owned and operated entirely by De Beers as a closed town. World-class sporting facilities, assorted residential accommodation, recreation clubs and other facilities were constructed as a means of attracting skilled staff to the otherwise isolated area.

By 2005, with the diamond resource nearing the end of its economically viable life, the mine began the process of downscaling production activities. This phase in the life-of-mine included the decision to proclaim Kleinzee as a Municipal Township and transfer it to the local municipality. The economic collapse of late 2008, coupled with changes in mine management, resulted in the proclamation process being fast-tracked. Numerous mine-closure planning processes were circumvented in order to achieve this, and Kleinzee was proclaimed as a municipal township on the 12th August 2012.

The impact of five key factors on the ensuing process of town transfer to the municipality are discussed as follows:

1. *As a private mining settlement, Kleinzee was not designed or constructed in accordance with municipal norms and standards. Numerous aspects of the town that were regarded as beneficial to the mine created both a maintenance and a financial burden in the hands of the local municipality.*
2. *Post-mining sustainability projects aimed at injecting new life into Kleinzee were severely impacted by the 2008 economic crisis, and predicted non-mining economic activities and employment goals were not realized.*
3. *Staffing structures and technical expertise aligned to the mining industry did not fit the requirements of a town.*
4. *Stakeholder dynamics changed rapidly as the town proclamation and transfer progressed. Cordial and cooperative mine employees quickly changed to unhappy and disgruntled property owners.*
5. *Environmental rehabilitation as an alternative to proclamation was not adequately explored or understood in the haste to proclaim the town after 2008.*

The above factors necessitated a re-assessment of the process of town transfer to the local municipality. With a better understanding and appreciation for the requirements and functions of the municipality, the mine has re-structured the transfer of Kleinzee to the local municipality. Kleinzee now has the opportunity to become a successful and sustainable town, rather than a liability to the municipality.

Keywords: *private mining settlement, town proclamation, municipal township, municipal services transfer, mine closure planning, sustainability, local municipality, stakeholder*

1 Introduction

The town of Kleinzee, situated some 45 kilometres south of Port Nolloth on the arid Namaqualand coast of South Africa (Figure 1), owes its existence entirely to the discovery of diamonds in the area in 1925. Diamonds had been found a short distance south of Port Nolloth in 1913 by a local shop keeper William (Bill) Carstens who spent weekends searching for minerals along the Namaqualand coast. The onset of the First World War however, resulted in a collapse of the diamond market, and Bill Carstens was not able to develop his find further (von Zeil, A 1989).

It was not until 1925 when Bill's son Jack Carstens returned home and began prospecting south of Port Nolloth that the Namaqualand finds were finally registered. Jack had taken up a number of claims and towards the end of 1926 had established himself in a small stone house at the mouth of the Buffels River where Kleinzee is today (NM Chronicle, 1995). Jack Carstens however, was not to reap the benefits of his finds and in his memoir (Carstens, 2002), he relates the devastating story of how in November 1927, his partner in the Kleinzee finds sold all farms and claims between Port Nolloth and Kleinzee to the Cape Coast Exploration Company for a mere 30 000 pounds. Jack Cartens' memoir is aptly named "A fortune through my fingers". Sir Earnest Oppenheimer was appointed chairman of the Cape Coast Exploration Company in 1929, and it is no surprise that by 1942, De Beers Consolidated Mines Limited had purchased all interests in the Cape Coast Exploration Company (Coetzer et al. 2000).

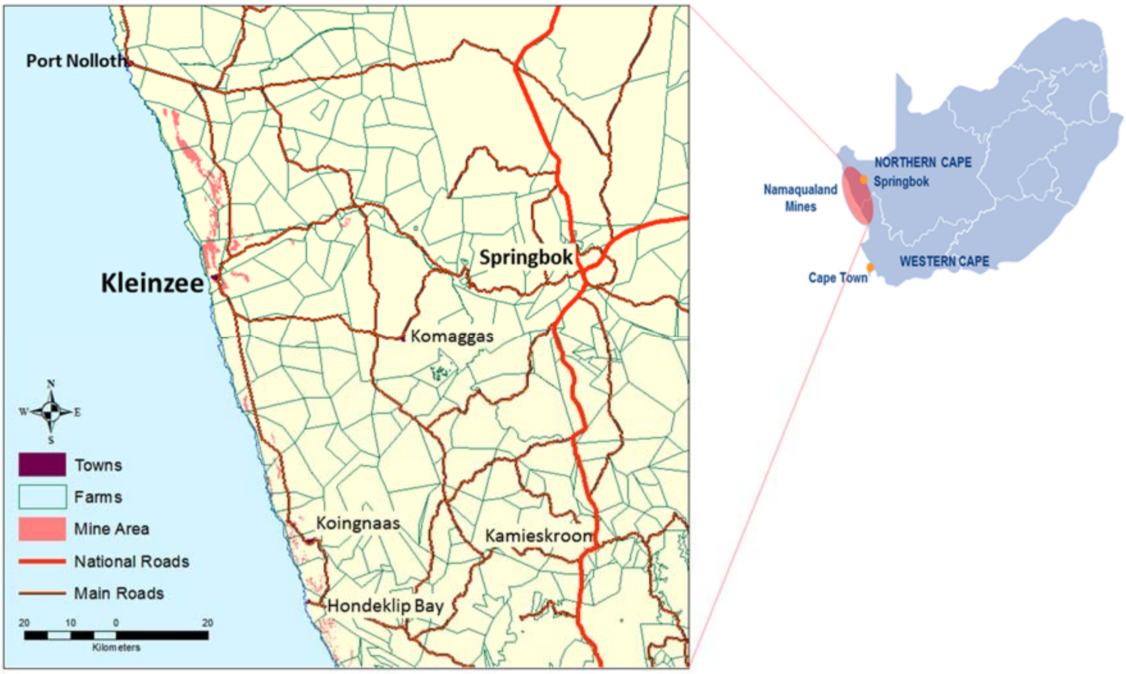

Figure 1 Kleinzee town is situated on the arid Namaqualand coast of South Africa

In the early days, the settlement at Kleinzee was little more than an open village where people could come and go as they pleased. A number of houses had been built to house the mine management, there was also a small hospital and a post office building, as well as single quarter buildings that were little more that temporary sheds. De Beers however, set about establishing a privately owned town, and in 1946 the first company houses were built in what would later become First Avenue (Coetzer et al. 2000) (Figure 2).

Coetzer et al. 2000, describe how Kleinzee Town continued to grow during the 1940's and 1960's as accommodation was required for the rapidly growing workforce. De Beers Namaqualand Mines records show how the expansion of Kleinzee only accelerated during the sixties with the expansion of the Recreation Club in 1962, houses for married employees in 1964, the main administration buildings and Third Street Church in 1967, additional workshops in 1968, and senior staff houses in 1969. This trend continued during the seventies as De Beers continued to construct houses, hostels and recreation and company facilities, all required to keep-up with the mining activities. A large number of stories originating from this period provide a foretaste of some of the challenges to come later. Houses and buildings were frequently moved or modified on request from some or other senior mine official. Legend has it that 2 houses in Second Street were built facing away from the river because the mine official's wives simply did not want their neighbours overlooking their houses (Engelbrecht, W 2018, *pers com*).

Figure 2 The first company houses were built Kleinzee in 1946 (Namaqualand Mines Photo Archive)

A large number of the De Beers Namaqualand Mines internal policies and procedures reflect the degree to which the company was prepared to go in order to attract and retain staff in this arid environment. All houses were fully refurbished every time they became vacant, and funding was frequently made available to upgrade houses and facilities. More senior personnel were often afforded an opportunity to move to a better house. New employees were issued with brand new furniture and were allowed to select their carpets and upholstery material prior to relocating to Kleinzee. One drawback was that all employees were required to move to an upgraded house immediately on promotion. This forced move was softened by an 'upset allowance' that was paid for each and every house move.

By the mid 1970's, Kleinzee had grown to such an extent that it required a full time township office to administer, and a dedicated town building section to keep up with new constructions and building refurbishments. A vast list can be made of all the facilities that De Beers provided in Kleinzee. This would include the numerous recreation clubs, 3 school campuses, a 54 bed-fully equipped private hospital, competition sized swimming pool, an 18-hole golf course and a number of other sports facilities (Figure 3). All of this was constructed and maintained by the company without any requirement for planning permissions or town-zoning consideration. Many a General Manager would commission the construction of a club or sports facility, simply because they wished to participate in their favourite pastime or sport after hours.

In 1978, the construction of well over 130 kilometres of privately owned high-tension electrical distribution lines was completed, as well as all the associated reticulation infrastructure. This was followed in March 1981 by an 85 kilometre freshwater pipeline constructed to supply drinking water to Kleinzee from the nearest municipal source at Springbok (Bentley, R 1981).

Kleinzee continued its existence as a private mining settlement in support of the De Beers Namaqualand Mines mining activities in the greater Namaqualand area. The town expanded or contracted as necessary in response to mining activities, with the company having the benefit of complete control over all activities. All residents were employed directly by the company and on termination of employment were required to vacate their houses and move out of town. By 2000, Kleinzee was supporting a population of 12 500 people living in 392 houses and 16 large hostel complexes. This population was supported by no fewer than 14 specialised sports facilities, a host of recreation clubs, and a number of company sponsored shopping outlets. The company also ran a dairy farm, sheep farm, abattoir and an ostrich farm. A highlight in Kleinzee was the fully functioning air-field big enough to handle large long-distance aircraft and equipped for night landing. The daily company flights to and from Cape Town ensured that the company ran post office was able to offer an over-night delivery service to the outside world (Bentley, R 1981).

Town life in Kleinzee was as near to perfect as could be found anywhere else, as long as residents could overlook the remote location and harsh surrounding environment.

Figure 3 An aerial view of Kleinzee showing the swimming pool, tennis courts and netball court in the foreground and hostel accommodation and town-centre in the middle distance
(Namaqualand Mines Photo Archive)

2 Town proclamation

During 2003 De Beers initiated a project to re-consider the long-term future of Namaqualand Mines. Geological resources were nearing the end of their viable life under prevailing economic conditions, and exploration activities had failed to identify new payable resources. The project outcomes were delivered in August 2005 and amongst the usual focus on mining methods and efficiencies, were a number of project charters developed specifically to investigate the future of the private mining settlement of Kleinzee. These projects were as follows:

- Transfer of the Kleinzee School to the State.
- Transfer of the Kleinzee Hospital to the state.
- Outsourcing and privatisation of town services.
- Removing town access control.
- Proclamation of Kleinzee under the local municipality.

It is important to note that at this time, the option of demolishing and rehabilitating Kleinzee was never considered. Mine management rather focused on Kleinzee becoming a centre for economic development and sustainability in the region.

The 2005 project charters were all implemented and by early 2008 had grown and morphed to include a number of additional projects focused on Local Economic Development. These new projects involved various partnerships established to develop a post mining sustainable economy centred on Kleinzee. The 2008 economic crisis, which resulted in the abrupt and unforeseen cessation of mining activities at Namaqualand Mines, suddenly focused all attention on the perceived economic benefits to be had through the proclamation and privatisation of Kleinzee town. Many of the projects which had been initiated since 2005 were still in a concept phase and far from implementation. The town proclamation project on the other hand, had made good progress and was therefore fast-tracked towards conclusion. Town proclamation was also regarded as the catalyst necessary to start many other projects.

The town proclamation process itself required a large number of specialist studies, all of which were completed by consultant companies. Engagements with the Local, District and Provincial authorities were fairly productive as De Beers was able to present a number of well-articulated reasons why the proclamation of Kleinzee would be beneficial to the entire region.

The private mining settlement of Kleinzee was finally proclaimed as a town in the jurisdiction of the Nama Khoi Local Municipality on 22 August 2012. Proclamation triggered the process to transfer the delivery of municipal services to the municipality, a process that has proved to be significantly more complicated and time-consuming than town proclamation.

3 Key learnings

A large number of factors have influenced both the town proclamation process and the ensuing transfer of municipal services. Not all of these were within the control of the company despite the sometimes significant impact they may have had. Some of the more obvious examples and their immediate impacts can be summarised as follows:

- Changing government policy frequently necessitated changes to, or termination of local economic development projects such as the wind farm and the public-private partnership correctional facility project.
- Suggestions of inappropriate procurement procedures resulting in delays with the awarding of contracts.
- Changes to the political environment that required the re-establishment of relationships with appointed public officials.
- The global economic crisis leading to the sale of the mining assets, which in turn directly impacted the number of company employees living in Kleinzee.

Five factors that are well within the influence of a mining company are identified as having had a significant impact on the transfer of municipal services from De Beers to the local municipality. These are by no means the only learnings from the Kleinzee proclamation and services handover process however, they have had the most significant impact on the process. Had these factors been better understood, managed and incorporated into the mine-closure decision making processes, the outcome for Kleinzee may well have been different.

3.1 Private mining settlement

As a private mining settlement, Kleinzee was not designed or constructed in accordance with municipal norms and standards. During the town construction boom between the 1940's and late 1970's all buildings in Kleinzee were constructed by the mine's dedicated town building section, and this included all municipal services infrastructure. Some of the more obvious issues that have impacted on town-services handover include:

- Potable water, sewerage and electrical infrastructure was installed on an as-needed basis. With no need to plan for the intricacies of private land ownership, services infrastructure was frequently laid along the shortest line irrespective of the properties that were crossed.
- Infrastructure was installed according to the mine standards which more often than not far exceeded standard municipal specifications. At first this was considered as an advantage however, the cost of maintenance and replacements often could not be carried by normal municipal service delivery tariffs.
- The hospital, airfield, sports and recreation facilities and most other facilities in town were designed and constructed to provide services for a booming mine town. Mine employees had disposable income since most of their requirements were provided by the company. These employees where therefore able to engage in a host of recreational and sports activities and the mine readily provided the facilities.
- Of significant importance is the 85 kilometre privately owned water pipeline, without which Kleinzee would not exist in its current form (Figure 4). Built over-capacity to supply potable water to Kleinzee and the mine, this infrastructure is burdened with significant operating costs. These costs translate directly into the cost of water in Kleinzee.
- The privately owned electrical distribution and reticulation infrastructure was also constructed to mine specifications and has proven difficult for the national energy supplier to take over and operate (Figure 4).

Figure 4 Drinking water is delivered to Kleinzee over a distance of 85 kilometres via a privately owned and operated pipeline. The electricity distribution and reticulation infrastructure is also privately owned and operated

Additional to the above issues are a number of more obscure characteristics of a private mining settlement that have also played a defining roll in the proclamation process and transfer of municipal services.

- In the mining town of Kleinzee, house designs were determined by an employee's seniority in the company. Houses for similarly senior officials were grouped together, with the General Managers house being widely regarded as standing in the most desirable part of town.

- Buildings were frequently positioned or modified to satisfy a particular request from a senior mine manager. Such positioning or modifications were done without any consideration for a future town planning scheme.
- There is no allowance for the establishment of low-cost housing units in Kleinzee and significant to the Namaqualand region, the town has no commonage or communal lands.

Characteristics of a private mining settlement that were originally considered beneficial have imposed an additional financial burden to both the municipality in their delivery of municipal services, and to property owners with regards service delivery costs, and compliance to prescribed town planning requirements.

3.2 Post-mining sustainability

With the implementation of the projects identified in 2005, the need for post-mining economic activity in Kleinzee became an important driver. As an initial attempt to extract De Beers from the town, all non-critical services were outsourced and a number of employees were assisted in establishing business in town to service the mine's needs. The mistake that was made in this process is that the newly established businesses relied entirely on the patronage of a functioning mine to survive. The economic crisis of 2008 resulted in all of these outsourced services being closed. By mid-2013, however, as activities began to pick-up in Kleinzee again, a number of smaller business start-ups were established focusing on the needs of the community and not those of the mining company. This has seen a number of entrepreneurs moving to Kleinzee town to establish business ventures that could never have been imagined in 2008.

Additional to the more local sustainability initiatives implemented in Kleinzee itself, were a carefully selected number of large-scale projects that were planned in the immediate vicinity of Kleinzee. Of specific interest was the establishment of a number of wind farms, a marine aquaculture venture with dams and infrastructure established on old mining disturbances, and a focus on establishing the Kleinzee School as a full-service public school under the direct management of the local Department of Education. Other projects that were not progressed included a correctional training facility utilising mine-hostel accommodation, various tourism initiatives, and a carbon sequestration algae farm in old mine excavations.

Of significance to the establishment of the post-mining sustainability projects implemented at Kleinzee, is not the success of the projects but rather their location. When considered within the context of the larger Namaqualand region, it is only the establishment of wind farms along the coast that has an appropriate place in the post mining environment.

The establishment of the Kleinzee marine aquaculture project drew focus and investment away from the existing aquaculture farm in the town of Port Nolloth, some 55km to the north of Kleinzee. A pilot aquaculture project in Hondeklip Bay, 75km south of Kleinzee, has not been able to develop further. While there is no doubt that the Kleinzee aquaculture project has developed into a major success story for Kleinzee Town (figure 5), the towns of Port Nolloth and Hondeklip Bay will not gain benefit from the Kleinzee project. Unemployment and poverty in these towns is significant and De Beers has been required to commit social funding towards alternative projects in these towns. It is possible that an opportunity to strengthen investment and credibility within the regional and provincial community was lost.

By 2012, the Kleinzee Primary School was facing closure with scholar numbers having dropped from more than 450 in 2005 to a total student body of 45. There is no doubt that the facilities available at the Kleinzee School represented a major opportunity to develop a first class public education facility. Continued investment by De Beers and many other parties has resulted in the transformation of the Kleinzee School to a public school offering education to both physically and mentally challenged children, as well as main-stream children in a single facility. The option to close the Kleinzee School in 2012 and focus the project on developing and supporting the school in the town of Komaggas, some 45km east of Kleinzee, was never considered. At the time, the Komaggas School accommodated both primary and secondary scholars, many of whom were the children of ex-De Beers employees.

The need to preserve the mining related infrastructure in the town became the dominant driving factor in identifying and initiating post-mining sustainability projects. This drew focus away from similar projects in surrounding towns that may have been more beneficial to support.

Figure 5 Marine aquaculture project established using old mining disturbances

3.3 Transition team

The project teams established between 2003 and 2008 to investigate the proclamation and subsequent transfer of services for Kleinzee were all drawn from mine employees. The project management team simply transferred from the town services and town building sections to the town proclamation and services transfer projects. Many of these managers had years of experience working in Kleinzee and had seen the town at its peak in the late 1970's and 1980's. In their new roles, they were required to formulate and implement programmes that were specifically focused on transitioning Kleinzee from a private mining settlement to an open public town managed by the local municipality.

All aspects of life in Kleinzee Town were required to change, from the free maintenance of company owned houses, through to the maintenance and support of the numerous sports facilities and clubs. Outsourced businesses were no longer company sponsored and Kleinzee residents were required to pay full price for their purchases.

To further complicate this situation, all Namaqualand Mines employees were to be afforded an opportunity to purchase their company house at a significantly discounted price. What followed was a rush to complete company funded refurbishments, and a jostling to complete moves to upgraded houses ahead of the implementation date for property sales. The town management team was required to manage this process despite the fact that they were intimately involved in their personal capacities.

It was not uncommon for a post-mining sustainability project focusing on one or other sporting or club facility, to be proposed by a senior mine manager who was the chairman of that particular club. Most of these initiatives did not progress beyond the concept phase.

A number of the challenges that faced the town proclamation and municipal services handover management team could have been averted by the introduction of independent and impartial management that had no personal or emotive connection to Kleinzee and the surrounding community.

3.4 Changing stakeholder dynamics

Stakeholder management forms an integral part of any project and this was certainly the case for the Kleinzee proclamation and transfer of services. Elaborate and comprehensive stakeholder engagement plans were drafted and closely followed to ensure that all stakeholders remained abreast of development within the project. What was however, not adequately understood and managed was the manner in which key stakeholder interests changed as town proclamation progressed:

- Company employees were regarded as a key stakeholder grouping and an effort was made to ensure that they were consulted and informed. This worked well for as long as the employees were working for the company and living in company houses that were maintained and serviced free of charge. It was assumed that the purchase of a property of their own would conclude engagements with this group. What was not adequately appreciated, was that most Namaqualand Mines employees had never purchased or owned a private property and were completely unprepared for the responsibility.
- Other employees simply purchased a property and then dumped it onto the market before leaving Kleinzee for their home town. The lack of town commonage for communal grazing made Kleinzee an unattractive proposition.
- Properties were on-sold to people who had no history with De Beers and therefore no appreciation for the process that was involved in proclaiming the town and transferring services to the municipality. Happy and content company employees were soon replaced by agitated town residents who wanted to interact directly with a municipality and were not prepared to deal with delays in services transfer.
- On the municipal side, the initial support for town proclamation and willingness to take over the town services was soon replaced with suspicion and even resentment. Town services infrastructure that was not compliant with municipal standards, and did not follow municipal design specifications, soon derailed the transfer process leaving De Beers in the position of having to continue with town service delivery long after proclamation was concluded. The local municipality had dealt with 2 other town proclamations that had gone very wrong and required that De Beers undertake a municipal infrastructure refurbishment project before services could be transferred.
- The period between town proclamation and mid-2017 was spent resolving the municipalities concerns. The private water pipeline and electricity reticulation infrastructure remain unresolved and De Beers and the municipality have had to establish supply and sales agreements to manage these services going forward.

Other stakeholders have certainly played a role at various stages in the town proclamation and municipal-services transfer, but their impact has not been as significant in the changing dynamic experienced with the company employees and the local municipality.

3.5 Town rehabilitation

Environmental rehabilitation as an alternative to proclamation was not adequately considered by the various project work streams that were established between 2005 and 2008.

- A mine rehabilitation liability exercise concluded in 2004, suggested that the complete demolition and rehabilitation of Kleinzee town would be costed at ZAR 120 million.
- By mid-2008, a town proclamation business case had been drafted that showed an income of ZAR 284 million could be generated through the proclamation of Kleinzee. This model was used as the financial motivator for all subsequent decisions relating to the proclamation of Kleinzee.
- The decisions made based on these assumptions had become so entrenched in the operational side of Namaqualand Mines life of mine planning, that a rehabilitation liability assessment conducted in 2010 entirely disregarded the rehabilitation of town.

Had the impact of the aspects presented in this paper, been better understood and incorporated into a rehabilitation model for Kleinzee Town in 2010, the financial assessment would have shown that town proclamation would end at ZAR 80 million negative. The simple model developed to test this scenario at 2010 costs, does not take into account all the costs that had already been incurred through additional projects and stakeholder engagements required in adjacent towns. Costs incurred since town proclamation in 2012 would push this estimate to well over ZAR 100 million. It is fair to say that the business model for proclamation versus rehabilitation was not seriously revisited once the initial decision to proclaim Kleinzee was made in mid-2008.

4 Conclusion

The proclamation and transfer of municipal services for Kleinzee Town serve as an ideal case-study into the potential pitfalls associated with the mine-closure aspects of private mining settlements. The factors discussed above can all be rolled into the overarching question of whether Kleinzee should ever have been proclaimed or not, a question that may be directly asked of any private mine town.

- The town municipal infrastructure has required major refurbishment work to comply with municipal standards and despite the best efforts of the company and the municipality, will remain a town planning challenge for years to come.
- The decision to constrain post-mining sustainability projects to Kleinzee has allowed opportunities to be missed in areas where projects may have been better suited or had a more significant impact on local communities. The company has had to undertake additional projects in these area.
- The establishment of a proclamation and transition team from mine employees undoubtedly created situations where management decisions were influenced by personal or emotional circumstances. Senior staff who had been resident in the town for many years were required to manage the project that would ultimately lead to the undoing of the most attractive aspects of Kleinzee as a private town.
- Stakeholders who had originally supported the proclamation of Kleinzee and the transfer of services to the local municipality rapidly changed their expectations and demands as their position in both the project and the community changed. Happy employees did not translate to happy ex-employee property owners, and municipal services transfer requirements changed as the full implication of town management became apparent to the municipality.
- The option of demolishing and rehabilitating Kleinzee town had not been adequately considered, primarily because all the factors were not adequately understood or appreciated.

Mining companies faced with the decision of how to proceed with private mining settlements at the end of life of mine would be well advised to look beyond the simple solution of proclaiming a town and transferring it to the nearest local municipality. Whilst this may seem an ideal solution at first glance, the lessons learned from Kleinzee suggest that the demolition and rehabilitation option should be considered well beyond the constraints of a rehabilitation cost model.

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Innovative Landform Design to Address some Unique Challenges in the Pilbara, Western Australia

G Davies *Rio Tinto Iron Ore, Australia*

M McLeary *Jacobs, Australia*

C Waygood *Jacobs, Australia*

Abstract

This paper presents a case study of an innovative rehabilitation design for a large waste rock dump in the Pilbara region of Western Australia. The dump presented some significant rehabilitation design challenges, being a 120m high linear slope at angle of repose in hilly terrain with restricted access and topographical footprint constraints. A generic benched rehabilitation design was found to be very costly to implement (largely due to the need to construct a land bridge to provide suitable access) and was also vulnerable to run-on from the natural ground adjacent to the dump. Physical waste characterisation and erosion modelling was conducted to support the development of an alternative design involving a non-linear slope, and a capped linear slope separated by a wide berm shedding water away from the main slope. The design incorporated the use of natural analogues in support of the steep capped linear slope. A construction plan was developed to support a detailed cost estimate, which proved to be less than that of the generic design. The rehabilitation design was presented to regulators who gave tentative endorsement to the approach pending the results of physical trials.

Keywords: *landform design, natural analogues, innovation*

1 Introduction

The Pilbara is a steep and arid portion of north-western Australia, characterised by low average rainfall but paradoxically, also high intensity rainfall associated with cyclonic storm events. The site under consideration is a large operational iron ore mine located in the Hammersley Range of the Pilbara, the location being shown in Figure 1.

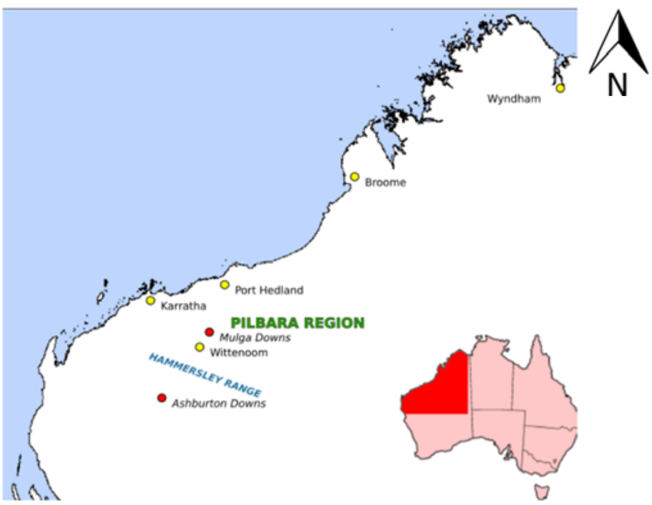

Figure 1 Site location

The site required detailed rehabilitation designs to support the development of a closure cost estimate as part of the commercial arrangements between two joint owners. Despite this being a hypothetical closure exercise, the cost estimate needed to be robust, effectively providing the same level of confidence as if the site was in the process of closing. One of the benefits of this level of work during the operational phase is that it allowed consideration of innovative strategies that may require further testing and proving ahead of an actual closure. Additionally, the work provided insight into how and where closure costs could potentially be reduced by optimising life of mine planning.

For many mines, a significant proportion of the closure cost is due to the earthworks required to form the final landform, and landform design was a key component of the study. In the Pilbara, the dry arid conditions tend to limit the extent of basal vegetation cover even in the natural environment, and although the cyclonic storm events tend to be infrequent, they are also characterised by intense and high energy rainfall. This combination of sparse vegetation and high energy rain events can present a significant erosion risk for post mining landforms. The general topography in the Pilbara adds a further complexity, with iron ore reserves often being located within the upper slopes characterised by ridges and peaks. Access to the iron ore requires the construction of steep haul roads and land bridges across steeply sloping terrain, and these are typically constructed using waste rock tipped to angle of repose. The subject of this paper is one particular large land bridge and waste rock dump (WRD) combination within steep undulating terrain.

2 The design challenge

The mined landform on which this paper focusses is shown in Figure 2, and presents as prominent feature within the broader landscape.

Figure 2 Mined Landform to be rehabilitated

Key parameters of the feature include:

- An overall height of the order 120m to the toe, with the natural ground at the toe of the dump falling steeply down to the downstream creek bed.
- An area of instability in the northern corner of the feature with some surface settlement occurring.
- Limited access to the toe and sides.
- Areas of cultural and environmental significance immediately below the dump.

The closure objectives for the mine including the landform presented in this case study required the need to:

- achieve a safe and stable landform;
- avoid adverse impacts on water; and
- ensure the final landforms are compatible with the landscape.

Initial designs for most of the site largely followed a generic approach to WRD rehabilitation that is common in the Pilbara. This approach requires flattening slopes to 1v:3h, with contour banks and benches used to limit the flow length for the different material types, typically to less than 20m vertical elevation spacing. Waste rock material is characterised in terms of erosion risk through Particle Size Distributions and flume testing, from which the limiting flow length to achieve particular maximum erosion rates are computed. Once this is known, the waste rock is generally tipped to angle of repose in bench lifts that match the bench elevations required so as to allow easy cut to fill.

An example of an existing rehabilitated landform is shown in Figure 3.

Figure 3 Typical Pilbara WRD rehabilitation design

In evaluating the application of the generic benched design, the design team were aware of both some of the limitations of benches and risk of potential failure (Loch & Willgoose 2000; Vacher et al. 2004; Loch & Vacher 2006; Stevens 2006; Roddy 2016) even in arid environments. Consequently, on most of the WRDs an effort was made to tie slopes into more robust features, typically by extending a slope slightly to pick up an existing mining bench or haul road, and employing a concave profile to allow the longer slope to be stable. This more flexible and "common sense" adaptation of the generic design achieved potentially more stable final designs for similar costs.

However, on some more challenging features, even adaptation of the generic design was unable to achieve a cost effective and robust final outcome, and one of these is the landform featured in this paper.

Firstly, erosion modelling of the landform by Landloch (2014) identified a high likelihood of excessive erosion of the benches resulting in failure of the benches on the edge. This erosion risk assessment was undertaken using SIBERIA and erodibility parameters measured by flume tests in the laboratory. The design had allowed for the expected sediment for a period of over 200years and together with the 1 per cent Average Recurrence Interval (ARI) flood event, but run-on from the adjacent natural ground on to the feature resulted in the SIBERIA model predicting significant gulley formation.

While there are options to enlarge the benches on the edges to achieve flow attenuation for the run-on, there will always be water running on from the areas in between the benches.

Secondly an assessment of the constructability of the benched profile from within the current disturbance footprint found that, even with ramps from the back of the feature down towards the toe, it was not practical to construct the benched profile. The only practical option to reach the lowest areas of the feature with the available construction equipment was considered to be a land bridge around the side of the hill. The construction of this land bridge would be both challenging and costly, and rehabilitating it post construction would in itself present more difficulties.

Thirdly, even with construction of a new land bridge to facilitate access, there was no practical means identified to reshape the lowest bench of the landform due to topographical constraints, and it would have needed to be retained at angle of repose. Erosion of this lower section of the slope would have been a point of weakness in the landform that increased the risk of a catastrophic slope failure.

Given the drawbacks in the required construction, and the fact that once constructed, the feature would not achieve the intended design life, alternative options were considered.

3 Considering innovative rehabilitation strategies for challenging features

3.1 Development of the conceptual framework

For the landform design process, it is beneficial to understand the stable natural landforms in the local environment, and how the materials in the landforms impact on the form and function of the landform. Clearly many of the mined landforms will present with different materials and erosion risks compared to the adjacent natural environment, but understanding the natural processes as well as the differences and similarities to the mined materials is a useful process. Some design approaches make use of natural analogues in compiling new post mining landforms (Bugosh, 2003), and the authors have design and construction experience with this approach.

A further benefit of evaluating natural systems in the local environment is to provide a framework for assessing what landforms might be socially and environmentally acceptable to the community, even in sparsely populated arid regions. This natural analogue assessment proved to be a key step in the development of possible alternative landforms for the more challenging features and the presentation of these to the Regulator.

3.2 Scree slopes; a valid analogue?

Natural landforms in the vicinity of the site and their possible applicability to the mined landscape are summarised in Table 1.

Table 1 Natural landforms in the local environment and possible applicability to the mined landscape

Natural Landscape	Potential Applicability
Low relief areas, being generally gently undulating and mainly weathered materials	Infrastructure areas and other relatively flat areas
Hills, characterised by a high percentage of exposed rock or even outcrop for longer slopes	Linear slopes, benches or even concave slopes but with the need for rocky material to limit erosion risk where vegetation is likely to remain sparse
Outcrop, being exposed vertical and sub-vertical rock faces, in some cases remarkably similar to mined faces	Pit highwalls, but with consideration that most natural rock faces tend to be broken, that is, a mixture of rocky and weathered material limiting the vertical face height
Scree / talus slopes, characterised by rocky material formed due to weathering and collapse of upper cliff faces	Could be applicable to material at angle of repose provided the outer face is formed by appropriately sized rocky material

In considering alternative options for this landform, scree or talus slopes were an obvious natural analogue. One of these is shown in Figure 4.

Figure 4 Scree slopes in the natural environment adjacent to the site

Evaluation of the scree slopes in the area found that, as expected, they are generally at or close to the angle of repose, and are comprised of an extensive rocky layer being formed by the weathering of the upper rocky slopes. The features evaluated also tended to be limited in height, generally not higher than 100m from crest to toe. Although these scree slope features are expected to continue evolving with time due to additional deposition of rocky material from above and some ongoing slippage within the surface of the slopes, no significant gullying or areas of collapse were noted in the natural analogues. Given the evolving nature of a scree slope, studies were undertaken to evaluate whether this landform is a valid analogue for a closure landform. The strategy adopted was to assess whether a slope at angle of repose clad with durable rock of a particular size could have a reasonable geotechnical and erosional stability, as set out below.

4 Design and proposed construction methodology

The first step in designing the feature was to decide on a practical limit in scree slope height.

Landloch (2014) collected samples of the waste stored within the land bridge and waste dump for physical characterisation. The WEPP model was then used to predict erosion rates for a range of slope heights and surface particle sizes. This data is presented in Table 2.

Table 2 Predicted mean erosion rates for an angle of repose slope (Landloch, 2014)

Mean rock size (mm)	Predicted mean annual "peak" erosion (t/ha/yr.) for batter heights of			
	40m	60m	80m	100m
50	50	60	60	60
75	10	50	65	65
125	<5	<5	10	35
150	<5	<5	<5	5

Note: figures rounded to the nearest 5t/ha/yr.

Target average erosion rates of the order of 5-10 t/ha/yr. have been used historically in the development of what might be an acceptable rehabilitation design in the Pilbara. If this range of erosion rates is considered reasonable, a 60m tall slope would have an acceptable erosion rate at angle of repose as long as it is armoured with a surface layer of minimum 125mm diameter rock. This assessment led to the concept of shaping the 120m slope into two 60m slopes separated by a berm (Figure 5) although only one of the slopes (the lower extent) would be a scree slope, the upper more accessible slope being rehabilitated using a concave profile. The individual slopes would be separated by a berm that is sufficiently wide to limit hydraulic flows and enable construction. A berm width of 80m was assumed. The final rehabilitated landform would be constructed as follows:

1. Material excavated from the top of the slope in dumped into the adjacent pit void, to create a relatively shallow concave slope, toeing into a wide berm.
2. Placement of graded material (>125mm diameter) on the edge of the berm and dozed down the slope to create an engineered scree slope. Uniform coverage was not expected, with the armour expected to be thicker at the base and sides and relatively poor coverage at the top of the slope.
3. Some degree of slope erosion, particularly at the top section of scree slope with less cover, would be expected. This was accommodated by the placement of a 10m blanket of graded material on the edge of the berm, which would fall down the slope as its base becomes undermined. The surface would eventually stabilise when the slope angle and rock coverage reach the right balance. It should be noted that the blanket would be incorporated into the construction methodology, allowing dozers to avoid operating close to the edge of the berm.

This design concept underwent a geotechnical assessment that indicated some limited potential for ongoing surficial slippage (Figure 6). However, deep seated failures were considered unlikely for this particular material, largely due to the relatively elevated location of the feature within the catchment reducing the risk of developing a perched aquifer. The slope in its current state has been evaluated to have a geotechnical Factor of Safety between 1.06 and 1.1, although some areas are noted to be currently unstable. The Factor of Safety was predicted to improve after rehabilitation to 1.15.

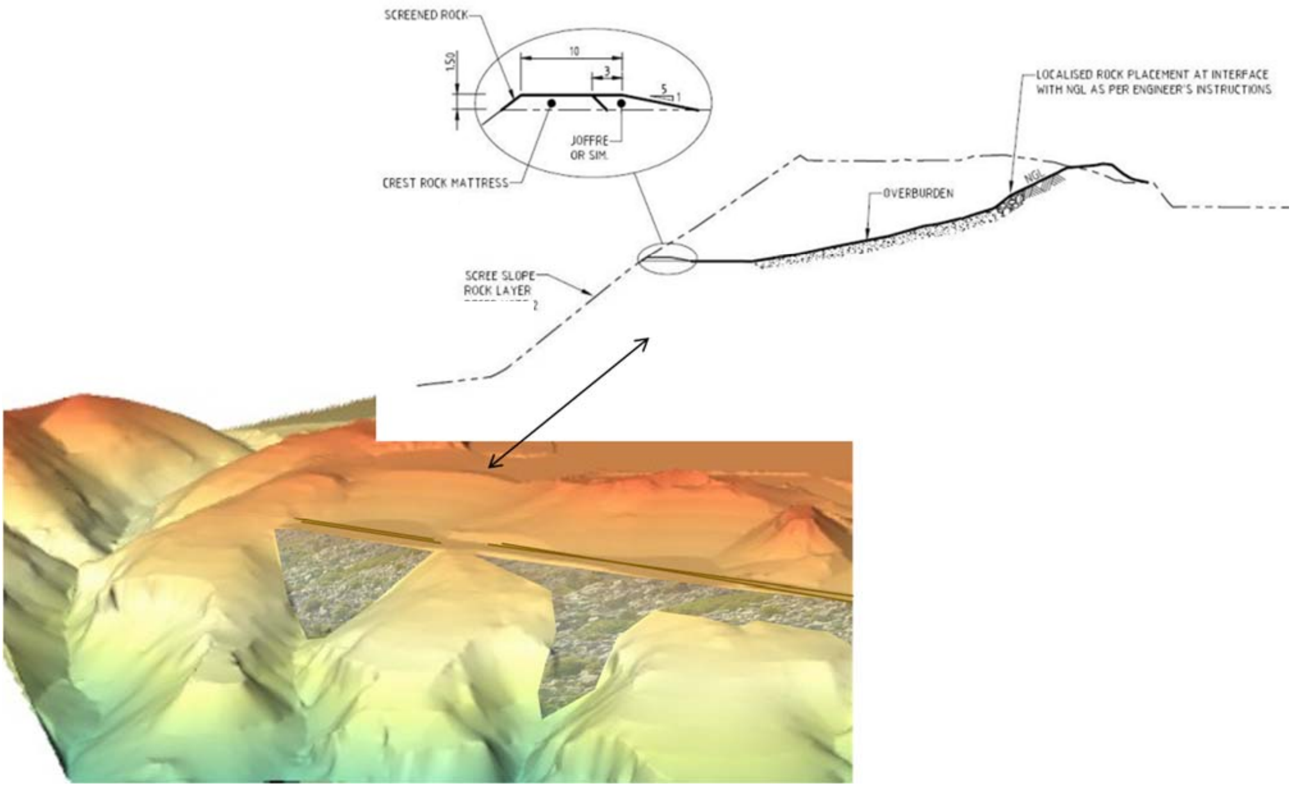

Figure 5 Proposed rehabilitation layout for the feature

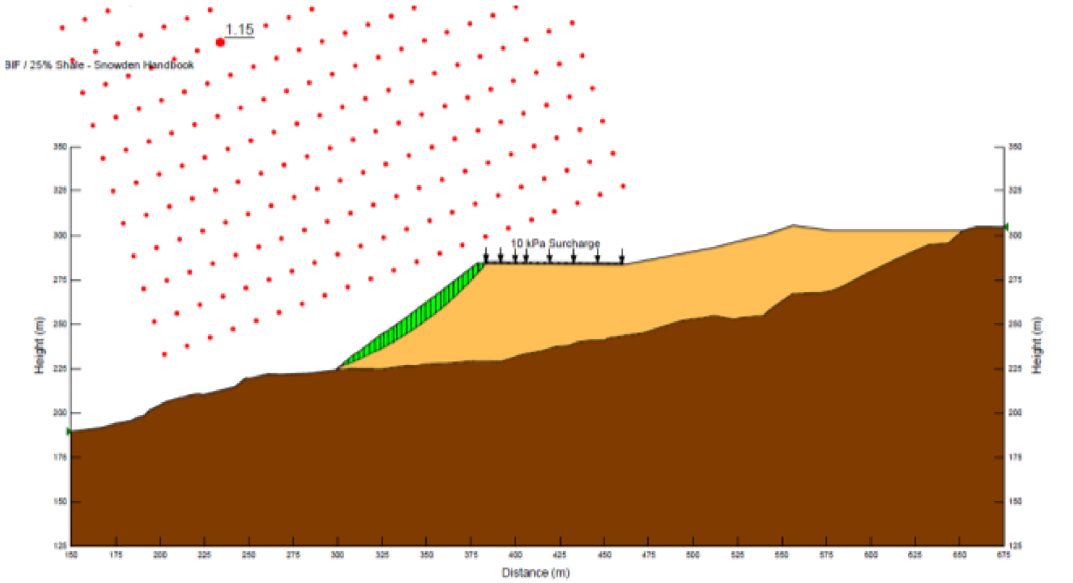

Figure 6 Geotechnical Analysis of modified slope

The wide terrace above the scree slope allows for the capture of water far enough away from the edge to minimise the risk of ponding and associate piping failure. The terrace is also shaped to drain towards the edges so that there will be a shedding of water over the edges along the flatter interface with the natural surface as shown in Figure 7.

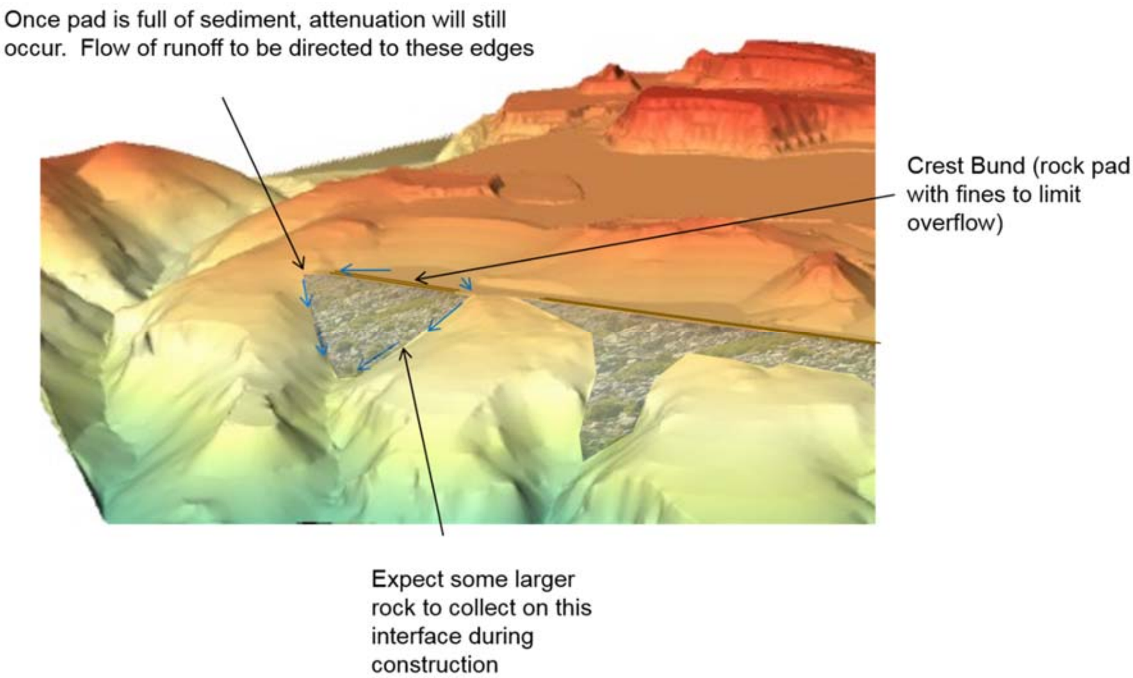

Figure 7 Longer term water management

One key concern that was raised about leaving relatively steep slopes in the final landform is whether these will be safe for anyone accessing the site. To reduce the risk of inadvertent access, the slopes were proposed to be kept remote from any access roads into the area, the site in itself being remote and difficult to access. As noted previously, these landforms do occur naturally in the area, so the risks associated with local slippage are not dissimilar to those in the natural environment. While the use of scree slopes can result in cost savings, the main focus is on the final outcome, and it is noted that the practicality of construction and the durability of the feature remains untested. Consequently, it is proposed to construct a trial slope to assess these aspects. This trial slope would include monitoring of the performance of the scree slope post construction.

5 Initial consultation

Stakeholders including the regulator were consulted on the proposed rehabilitation strategy, and it is fair to say there was a level of scepticism about the design when it was first proposed. This was largely due to the perception that the company was attempting to adopt a 'do nothing' approach to problematic landforms by incorporating the concept of scree slopes. However, responses were more favourable once it was understood that the slopes were fully engineered structures to be constructed to specifications based on site-specific data and conditions, that they would be safer to construct, and that the alternative design is expected to have an improved long term stability outcome. The proposed strategy is also considered to be better from an environmental perspective, primarily through limiting the off feature construction impacts.

6 Conclusion

In conclusion it should be noted that the use of scree slopes as part of the final landform is proposed only for a small proportion of total rehabilitation area. These scree slope features are proposed for areas where more conventional alternatives are either unlikely to function adequately or where the construction activities are both extremely difficult and costly with significant environmental impacts.

The design incorporating scree slopes will include fully engineered structures so as to be both stable in the longer term and compatible with the final landform. Stakeholders will be included in the assessment of this novel and innovative approach, and physical trials will be conducted to prove the concepts.

Acknowledgement

Landloch's contribution to the design process and erosion risk assessment, and the assistance of the Rio Tinto site team with materials characterisation is gratefully acknowledged.

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Investigations and Design for the Closure of Historic Arsenic-Bearing Tailings at Canada's Giant Mine

J Amphlett *Indigenous and Northern Affairs Canada (INAC), Canada*

TB Thomas *Indigenous and Northern Affairs Canada (INAC), Canada*

D Hango *Public Services and Procurement Canada (PSPC), Canada*

B Week *Golder Associates, Canada*

C Mundle *Golder Associates, Canada*

Abstract

Open pit and underground mining activities at the Giant Mine ceased in 1999 with the bankruptcy of the Royal Oak Gold Mines Inc.. Since that time, the mine has been the responsibility of Indigenous and Northern Affairs Canada (INAC), with administration by Public Services and Procurement Canada (PSPC). The site has been undergoing rehabilitation and closure activities, with final closure activities anticipated to be implemented starting in 2020. Historic activities at the mine have resulted in the generation of significant deposition of arsenic-bearing wastes, including arsenic dust disposed of underground, and two tailings containment areas (TCA) which cover approximately 104 Ha, and contain roughly 4.4 million m^3 of arsenic-impacted tailings. While several studies have been conducted in support of closure planning for the tailings in the early to mid-2000s, design work was initiated in 2015 with a new closure concept heavily influenced by the desires of the local stakeholders – particularly First Nations communities.

In support of the closure design, the tailings were characterized both physically and geochemically with a drilling program and geophysical work in 2015. This program allowed a much improved understanding of the tailings volume, distribution and geochemical/geotechnical properties. It also permitted the identification of a previously unknown discontinuous clay layer under the tailings, and characterization of the degree and depth to which this layer had been impacted by the overlying tailings. Based on the new information from the program, and the input received from stakeholders, a closure design for the TCAs was developed through a series of trade-off studies and multiple-accounts analyses. This included development of a plan to reduce the overall footprint of the TCAs through the complete removal of one tailings area. This plan would also allow restoration of natural flow in the recovered basin. A cover profile was also selected, and design work conducted to identify additional mine waste volumes that could be effectively disposed of in the remaining TCAs, promoting a final contour of the facility that would allow positive drainage of non-contact water from the covered site.

This technical paper summarizes the investigation and design works conducted in support of this closure design, as well as the decision making process used to ensure that the design incorporated stakeholder input..

Keywords: *tailings, cover design, arsenic, giant mine*

1 Introduction

The Giant Mine, which operated until 1999, is located in Northern Canada, adjacent to the town of Yellowknife, in the Northwest Territories, as shown in Figure 1. The bankruptcy of the operation meant that no closure activities were undertaken by site owners, resulting in significant environmental liabilities for the government of Canada. These liabilities include tailings containment areas (TCA), which require closure. As part of developing an updated closure plan for the site, a design for the closure of the TCAs was needed, that would provide adequate long term containment of the tailings, incorporate feedback from stakeholders (particularly First Nations from the area), and meet regulatory directives.

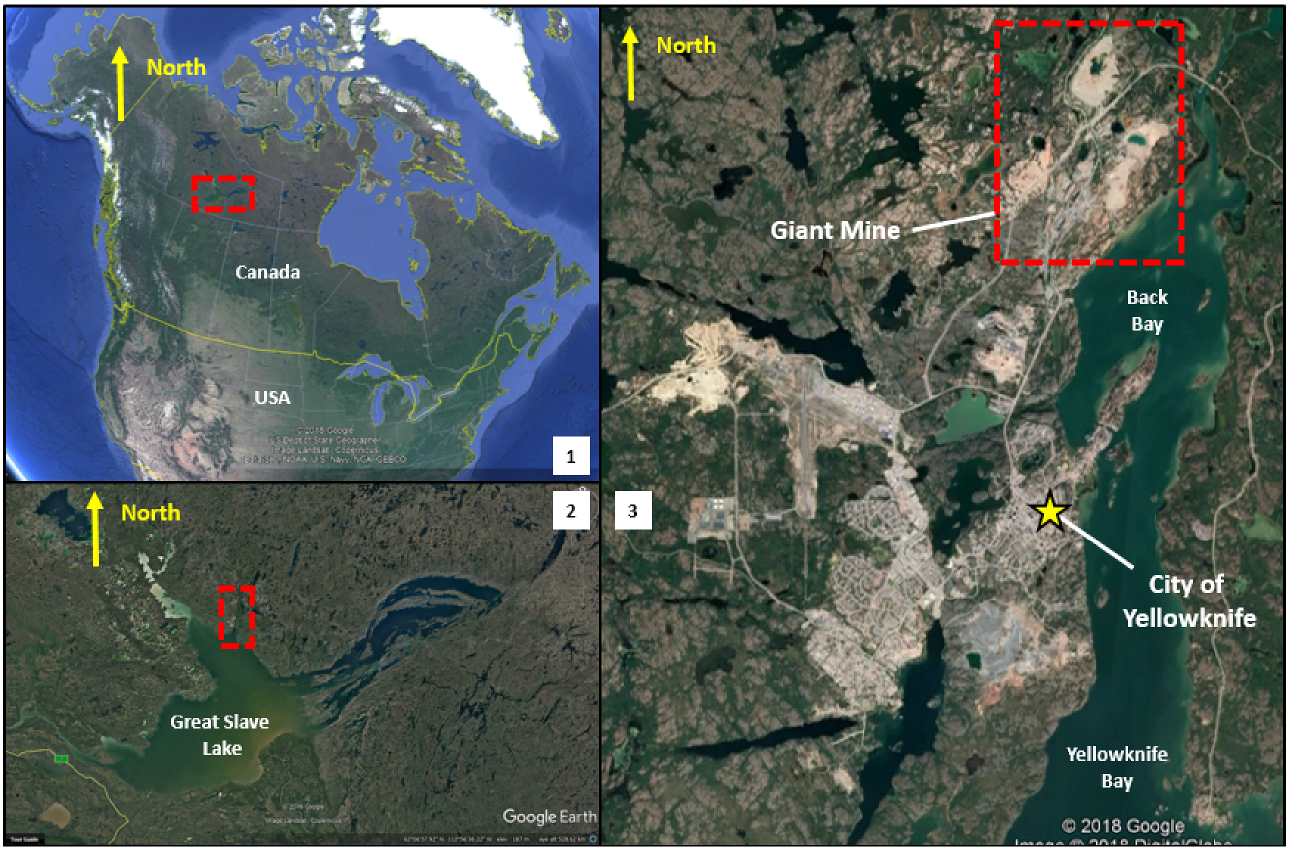

Figure 1 Giant Mine Location (1: International Map; 2: Regional Map; 3: City Map) (Image Source Google, 2018)

1.1 Study Context

The Giant Mine has had several owners and operators since the first mining stakes were claimed in 1935 (Silke 2009). During operations, roughly 7 million ounces of gold were obtained from the arsenopyrite formations. Extraction of this gold resulted in the production of tailings, which typically had elevated concentrations of arsenic.

The bankruptcy of Royal Oak Gold Mines Inc. in 1999 resulted in the site becoming the responsibility of the Canadian Federal Government. Mine rehabilitation works have been ongoing since the federal government took responsibility, with concurrent underground mining and off-site ore processing continuing until 2004 (Silke 2009).

Giant Mine tailings have been deposited into two tailings containment areas (TCAs): the Original TCA and Northwest TCA. The current configuration of the TCAs, shown in Figure 2, covers an area of approximately 103 Ha. Tailings were deposited into the Original TCA up until 1986. Thereafter, the majority of the tailings were deposited within the Northwest TCA. However, after 1986 some tailings deposition is anecdotally known to have occurred periodically within the Original TCA. The Original TCA is further subdivided into areas known as the North, Central and South TCAs. The Settling and Polishing Ponds, which are used in the site's water treatment process, are also part of the Original TCA.

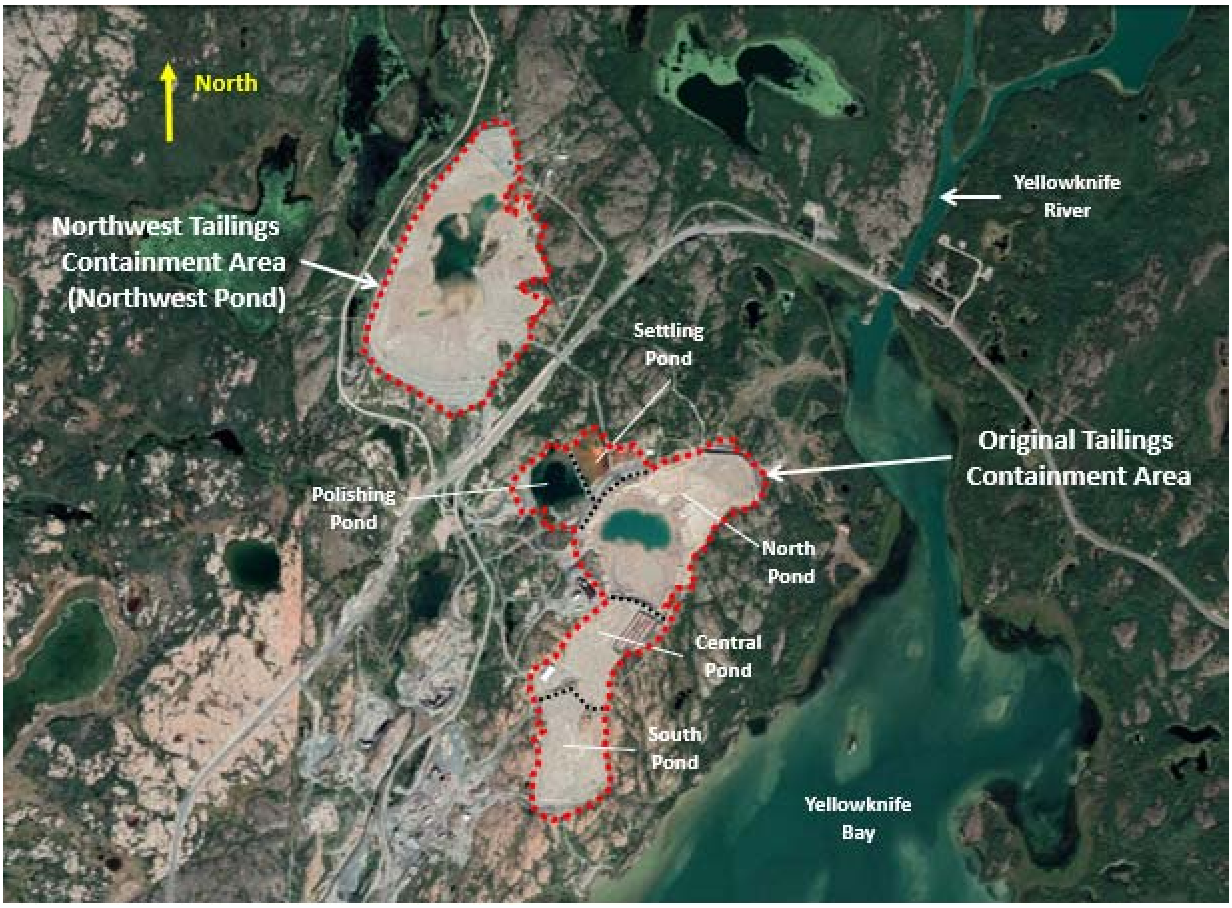

Figure 2 Tailings Containment Areas (Image Source Google, 2018)

1.2 Previous Cover Designs

The work documented in this paper is not the first round of cover design work done for the TCAs at the Giant mine. Previously developed studies, such as the "Giant Mine Remediation Project Developer's Assessment Report" (INAC 2010), identified capping of the tailings as the appropriate approach to control the human health and environmental risks associated with the exposed tailings. The conceptual design at that point consisted of a two-layer vegetated store-and-release and capillary barrier cover system, with a coarse bottom layer and a fine-grained upper layer. This was considered the preferable cover type for the area, based on materials availability for cover construction, local climate conditions and the cover objectives defined in the Remedial Plan.

The stated purpose of the coarse bottom layer was to (1) act as robust barrier preventing physical contact with the tailings, (2) minimize upwards wicking of arsenic through the cover (from tailings porewater), and (3) minimize the possibility of root penetration. For the fine-grained layer, the stated purpose was to (1) shed runoff, (2) allow vegetation to establish, (3) reduce infiltration, and (4) support future land use.

1.3 Engagement

An important component of the ongoing remediation design for the Giant Mine has been to develop ways to meaningfully engage with stakeholders, particularly the First Nations peoples who have been impacted by the historic activities at the Giant Mine. This engagement has taken various forms, with a process known as Surface Design Engagement (SDE) used between May 2015 and January 2016 to engage on a variety of topics related to the final closure configuration of the site, including the closure design for the TCAs.

Public input on the tailings closure obtained through the SDE has resulted in the development of an updated cover design concept, which differs materially from the concept that was presented in the Developer's

Assessment Report (INAC 2010). Feedback through the SDE process found that the preferred cover configuration for the majority of stakeholder groups, and particular the local First Nations, would incorporate a top non-vegetated rocky layer, which would eliminate risk of direct contact of human and wild life with the tailings, and also keep the area with the appearance of an abandoned site to communicate risks to future generations. The majority of participant groups in the SDE also demonstrated concern that vegetation could possibly become a pathway for contamination uptake by animals, and encourage future land use by humans. Further, there was a strong desire expressed to explore alternatives for reducing the overall footprint of land covered by the tailings (SRK, 2016).

As a result of this, the cover design was reevaluated, taking into account the desires and concerns of the public.

2 Characterization

Characterization of the tailings was required to provide inputs into closure design, both for evaluating alternative cover profiles, and for assessing options for relocation of the tailings. This characterization included both compiling and evaluating data obtained through past studies, and carrying out site investigations to address data gaps. This characterization work is described below.

2.1 Historic Data Review

Information collected in previous studies was reviewed to provide input into the closure design. This data included air photos, site topography, LiDAR surveys, test pit and drilling investigations, geochemical characterization studies, and test plots for the evaluation of previous cover designs. Additional relevant information included past dam inspection and investigation reports, and studies of potential borrow material for cover construction.

This information provided a basis understanding the dimensions of the facility, and some information on geotechnical and geochemical properties of the tailings. However, data gaps were identified. In particular, there was limited information on the thickness of the tailings throughout the deposit, which resulted in uncertainties in the total volume of the tailings (relevant for evaluating options to relocate tailings). While the tailings were assumed to have been placed over bedrock or lake sediments, there was no data to confirm this supposition. The level of the phreatic surface within the deposit (if present) and flow directions were uncertain, as was the saturation profile through the tailings. There was also limited characterization of the variability of the geotechnical properties of the tailings, either in terms of vertical distribution through the profile, or areal distribution over the footprint of the facility.

2.2 Site Investigation

As a result of the uncertainties summarized in Section 2.2, a field investigation program was designed, and carried out in 2016. This program included a geophysics program and a drilling program.

The primary purpose of the geophysical investigation was to better characterize the variable thickness of tailings throughout the deposit. A secondary purpose was to look for anomalies. Anecdotal accounts have indicated that tailings facilities may have been used to dispose of a variety of building and metallic wastes over the years, although past drilling and test pits had revealed no evidence of this. Geophysical methods used included seismic refraction methods were used for stratigraphic interpretations, while electromagnetic induction was used to detect metallic anomalies.

The drilling investigation provided ground truthing and calibration of the geophysical results, and allowed the collection of samples for visual and laboratory characterization (including both geotechnical and geochemical properties), and also the installation of standpipe piezometers in select locations to improve the understanding of groundwater within the tailings. Sonic drilling was used for its efficiency in fine grained materials, high sampling recovery, and the ability to confirm the depth to bedrock.

Drilling locations and the lines used for the geophysics are shown on Figure 3. Locations for this investigation were focused on the older tailings in the North, Central and South Ponds.

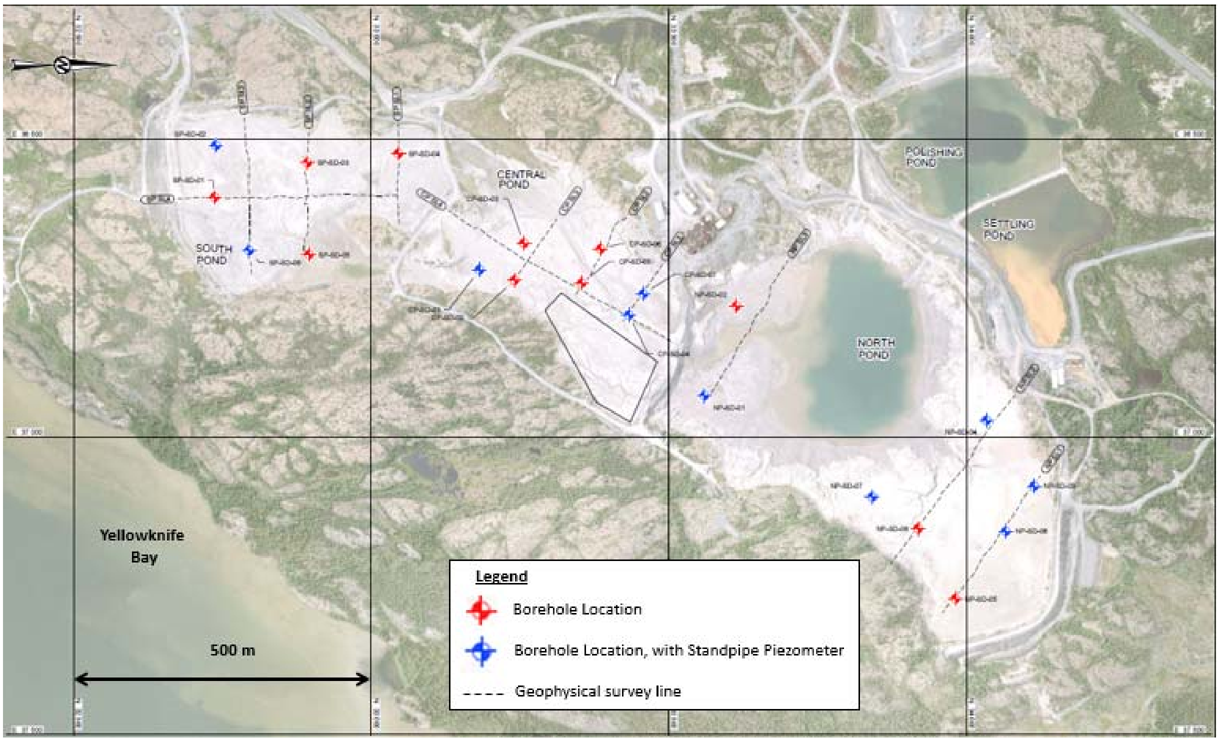

Figure 3 Investigation Points in the North, Central and South Ponds

A full presentation of the investigation approach and data collected is outside the scope of this paper. However, a summary of some of the key findings is presented in the following subsections.

2.2.1 Tailings Profile

Drilling within the TCAs showed that typical profiles consisted of tailings of variable characteristics either directly overlaying bedrock outcrops, or overlaying deposits of natural soil. Typical thicknesses of tailings were in the range of 6 to 19 m, but were as low as 2 and as high as 22 m. The natural soil encountered beneath the tailings was a till or clay soil, and both the thickness and extent of this material was greater than anticipated based on the review of historical data.

Based on the combination of historical data and the investigation results, Table provides a summary of the estimated quantity of tailings in each of the South, Central, and North Ponds.

Table 1 Summary of Quantities

Location	Estimated Tailings Volume (m^3)	Estimated Underlying Natural Soil Volume (m^3)	Current Facility Surface Area[a] (m^2)
North Pond	2,200,000	1,300,000	288,000
Central Pond	1,200,000	500,000	126,000
South Pond	950,000	320,000	92,000
Total	**4,350,000**	**2,120,000**	**506,000**
Total South and Central Ponds	*2,150,000*	*820,000*	*414,000*

a) Values originally reported in SRK (2005).

Figure 4 shows a three-dimensional representation of the tailings volume and distribution for each pond, as well as the underlying soils. The green surface represents the 2015 LiDAR surface outside of the ponds, with the interpreted top of natural soil and bedrock shown as cyan and tan surfaces, respectively (the top of tailings surface has been eliminated from the view for clarity). The top of bedrock surface in the vicinity of the dams shown in Figure 4 includes information obtained from interpolation of the assumed dam fill slopes. The borehole data is indicated as blue columns.

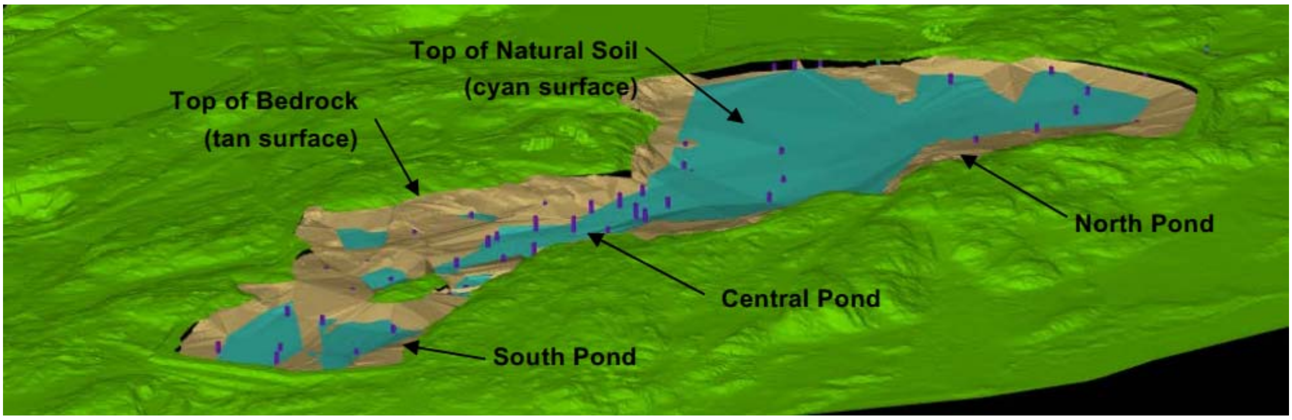

Figure 4 Three Dimensional Representation of South, Central and North Ponds

The total volume of natural soil under the tailings deposits was greater than expected based on the review of background data. If tailings are removed from the deposits, this material becomes available for use in reclamation and closure, potentially as a cover material.

There may be practical limitations on the volume of natural soil that could be extracted from the reserves under the South and Central Ponds. Due to geotechnical and geochemical considerations (e.g., high organic and water contents, arsenic concentrations) only a portion of this volume might be suitable for use in closure. For the Central Pond, a portion of this sector was originally a lake prior to tailings deposition (as was the North Pond), and there may be hydrogeological challenges associated with the removal of natural soil below the original water table (although ongoing dewatering may provide control on this water table). The volumes in Table reflect the volume of material that is physically present, but may not represent what is practically extractable.

2.2.2 Geotechnical Characteristics

The 2016 geotechnical investigation encountered three primary stratigraphic units: tailings, natural soil, and bedrock. During the investigation, core samples recovered were visually logged in the field and representative samples collected for laboratory testing. Standard penetration tests (SPTs) were also carried out.

Typically, the tailings are described as a loose non-plastic sandy silt to silt. There were instances of the particle size distribution being as coarse as silty sand and Atterberg limits indicating low plasticity behaviour, but these results were in the minority. From the testing of thin-walled steel tube samples, the average in situ water content (gravimetric) and dry density of the tailings is 29% and 1,430 kg/m^3, respectively. However, SPT results indicate that layers of very loose tailings exist within the ponds and these layers could not be successfully tube sampled.

When natural soil was encountered below the tailings, the interface typically consisted of organics transitioning into a fine-grained soil with increasing depth. Typically, the natural soil is described as a firm to stiff sandy clay to clay, with a medium to high plasticity. In certain locations, granular natural soil was intersected with gravel content between roughly 30% to 50% by mass. The granular natural soil is described as a silty sandy gravel.

The results of the SPTs and laboratory testing indicate that the strength of the tailings is highly variable. While laboratory testing indicates an effective friction angle up to 40 degrees, an overall average angle of 33 degrees is estimated based on SPT correlations (Mayne 2006). Furthermore, SPTs performed below the groundwater table typically correlate to values lower than 30 degrees. A total of 10 SPTs observed displacement of the rods due to either the weight of the hammer or drill rods and are not accounted for in any of the correlations. These readings would indicate friction angles as low as 25 degrees (Mayne 2006). In terms of undrained strength, laboratory shear vane testing indicates an average undrained shear strength of 40 kPa, within an overall range of 13 to 97 kPa. Due to the conceptual nature of the design studies, SPTs were selected over more expensive Cone Penetration Tests.

2.2.3 Geochemistry

Select samples from the drilling program were submitted for geochemical analysis, complementing information that had been obtained in previous studies for the tailings. Testing of natural soils under the tailings showed less distribution of arsenic concentrations that were necessarily expected. Consistent with past studies, tailings throughout the deposit were shown to have elevated concentration of arsenic (545 mg/kg to 4200 mg/kg in 45 samples). Concentration of arsenic was observed to be quite variable in terms of both depth and location. Underlying natural soils that were in immediate contact with the tailings showed evidence in some cases of elevated arsenic concentrations as well, but these elevated concentrations were limited to within a depth of roughly 1.5 m. Below this depth, all natural soils tested showed very low arsenic concentrations (less than 100 mg/kg), values that are below some current background concentrations in the immediate vicinity of the mine. As only 9 samples of natural soil were tested, further sampling and testing would be required to confirm the observed trend.

3 Alternatives Evaluation

Various approaches to the closure of the tailings facilities could have proven successful. In selection of the preferred options to be carried forward into more detailed design, alternatives were assessed, taking into account a variety of technical considerations, as well as input obtained through the SDE process. Two of the principal decisions evaluated were alternatives for relocating tailings, consolidating them into a smaller foot print, and evaluating alternative cover profiles for the deposits. The following subsections provide a summary of the approach used to evaluate these options.

3.1 Tailings Relocation

With the volume of the tailings better characterized, as well as the geotechnical conditions of the tailings, basic information was available to evaluate alternatives for tailings relocation, as well as alternative approaches for physically moving the tailings. Geometrical constraints were used to screen the potentially feasible options for relocating tailings and achieving a smaller total footprint. Based on this screening, three options were selected for further evaluation:

- Relocating the South Pond Tailings into the Central and North Ponds
- Relocating the South and Central Pond tailings into the North (and possibly Northwest Ponds)
- No relocation

Other options eliminated at a pre-screening level included relocating all tailings into the Northwest Pond, relocating the Northwest Pond, and using pits as repositories for tailings. The various permutations for relocating tailings into remaining ponds were screened out based on volumetric constraints. Such relocations would not be possible with the current dams, and would require significant dam raises. In contrast, either of the relocation options carried forward could be accomplished with relatively modest retrofitting of some existing dams. Relocation of some tailings into pits was also evaluated. As there are plans to backfill pits for control of flood hazards from a nearby creek, tailings provided a potentially attractive backfill medium (due to its relatively low hydraulic conductivity). These options were largely rejected due to geotechnical concerns with the tailings, including practical issues with placement of tailings in potentially unstable open pits (e.g. stopes below pit floors and/or unstable pit walls).

The selection of the preferred relocation option was developed through a technical study which evaluated each option, identifying conceptual level costs for each, as well as evaluating technical and environmental considerations. While a formal multiple accounts analysis (MAA) process was initially considered for the selection of the preferred option, a workshop to evaluate the technical, economic merits of the options, combined with consideration of preferences of the First Nations stakeholders resulted in a clearly preferred option without the need for a MAA. A trade off assessment was also conducted for approaches to transport tailings, considering their current physical state as identified in the site investigation. Conventional excavation and truck transport was compared to approaches for slurrying and pumping tailings.

3.2 Cover Profile

A wide range of potentially feasible covers for the tailings were available to meet design objectives. In order to select the preferred option for design, a formal MAA process was developed, to ensure that a range of technical, economic, and social considerations were incorporated into the decision. Qualitative and quantitative criteria were established and weighted, incorporating factors such as degree to which the cover would meet technical goals (such as physical isolation of tailings, protection of surface water runoff quality, erosion resistance, prevention of metal uptake into plants) as well as other factors important to the decision (uncertainty, construction complexity, and cost factors). A list of potentially feasible cover approaches was developed, with pre-screening of options based on factors such as stakeholder preferences. For instance, as indicated earlier, from the stakeholder perspective (particularly the Yellowknife Dene First Nation), non-vegetated covers were preferred as they would convey the appearance of an abandoned mine site to future generations.

The formal trade-off study using MAA provided a documented basis and rationale for the selection of the engineered cover design to be used for the TCAs. The MAA included a sensitivity analysis component to show how variation in uncertain parameter values within a reasonable range (such as unit costs and infiltration estimates) would affect the result rankings. This allowed greater confidence in the robustness of the final decision taken. Cover options that were carried forward into the MAA analysis included:

- rockfill cover with geosynthetic barrier layer
- a monolithic rockfill layer
- rockfill cover underlain with compacted fine-grained soil
- rockfill cover underlain by an amended fine-grained soil (ie, a soil-bentonite mix).

To support the MAA, for each of these options, ratings were applied to the qualitative and quantitative criteria. Application of ratings for qualitative criteria involved discussions with the project team and was guided by feedback from regulator and stakeholders. For the quantitative criteria, ratings were applied based on conceptual calculations (e.g. preliminary cost estimates, estimated infiltration rates). The overall score for each option was weighted 75% by the qualitative criteria and 25% for the quantitative criteria.

4 Selected Design

4.1 Tailings Relocation

The preferred option for the tailings relocation was to move South Pond tailings to the North and Central Ponds. Figure 5 shows the anticipated layout and direction of surface water flows following relocation. The option to relocate only the South Pond was selected as it would ensure that community desires for a reduced footprint were respected, with a 9 % reduction when compared to the current overall TCA area.

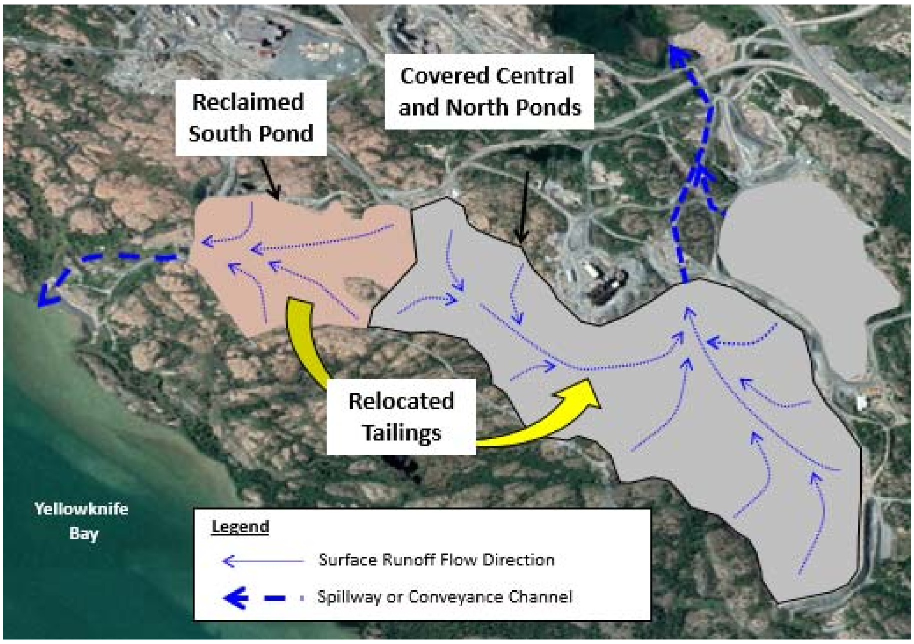

Figure 5 Original Tailings Containment Area After Tailings Relocation and Placemetn of Cover (Image Source Google, 2018)

Further reduction of the footprint by also relocating the Central Pond would result in a modest improvement (a further 4 % reduction of the footprint), but would generate the following technical challenges:

- Critically, while the Central Pond and South Pond are divided by a structural dam, the division between the Central and North Pond is a non-engineered berm. Removing the Central Pond would expose this berm, resulting in the need for the construction of a completely new dam to retain the remaining North Pond. The construction of this new dam would produce numerous logistical challenges, and increase the cost of relocation by an order of magnitude.
- Removal of the South Pond would restore natural drainage to the south in an existing valley, resulting in relatively straight-forward water management post closure. In contrast, the Central Pond is located on the opposite side of a natural surface water flow divide. If exposed, surface drainage in the former Central Pond area would tend to flow towards the toe of remaining facilities, creating a need for ongoing water management at the toe of the to be constructed North Pond dam. It is possible that this water could not be managed by gravity flow, and permanent pumping would be required.

Based on the above, the relocation of the combined South and Central Pond was screened out as an option. The cover in place option (no relocation) was screened out based on feasibility of respecting community preferences with the South Pond relocation. The preferred option to transport the tailings was conventional truck and shovel. While both slurry transport and conventional truck and shovel were potentially feasible for the site, and relatively close in unit cost, slurry transport created significant challenges with water supply and management. All slurry supernatant would become contact water, and require treatment for offsite discharge. Further, while much of the in-situ tailings is relatively wet, it has had the benefit of decades of drying and consolidation, which would be undone by slurry formation. Further, historic records suggest that slurrying of tailings from the North Pond had been tried in the past (for re-processing to recover residual Gold and subsequent disposal in the Northwest Pont). This was very challenging due to the presence of discontinuous frozen zones in the tailings (Silke 2009).

4.2 Cover Profile

The trade-off study resulted in the selection of a rockfill cover underlain by a layer of fine grained soil and a geosynthetic barrier layer as the preferred option. In Figure 6 a schematic profile of the selected cover profile is shown. Implicit in the outcome is that this option was assessed to best satisfy the design objectives as defined for the study. Key drivers that resulted in the selection of a geomembrane-based cover were the superior ability of this approach to physically isolate the tailings, the confidence this provides that runoff water would be unaffected by contact with underlying tailings, the well-proven capacity of this approach to reduce infiltration to very low levels, and elimination of root penetration into the underlying tailings (addressing any real or perceived concerns with respect to metal uptake in vegetation).

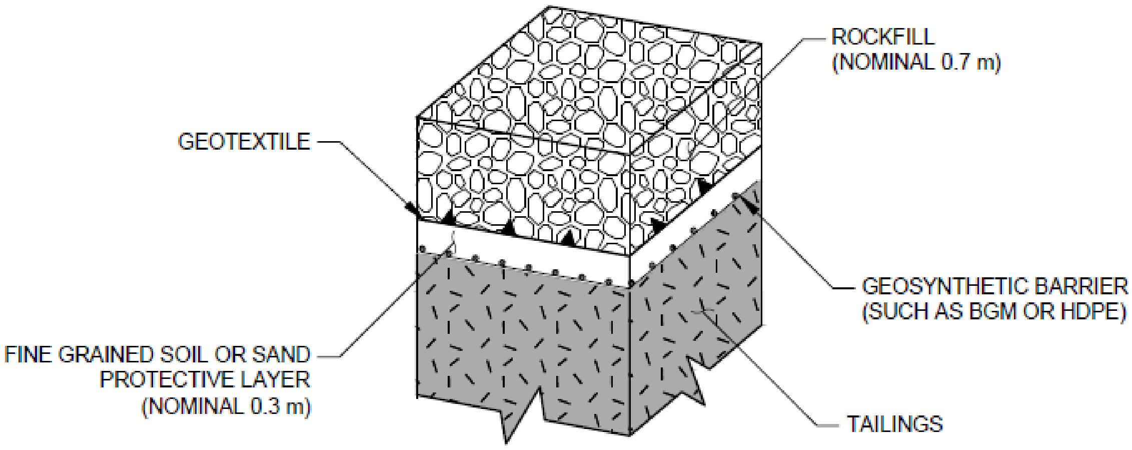

Figure 6 Selected Cover Profile

5 Conclusion

The tailings containment areas at the Giant Mine are a significant component of the legacy impacts that were left by the abandonment of this site. The closure concept for the facility has been developed incorporating community desires and technical considerations in a way that will provide long term risk reduction, fully integrated with the overall site closure concept. The cover concept for the TCAs will include the use of low permeability geosynthetics, overlain by coarse rocky material that will serve as both a protective layer, and as a testament to the mining impacts on the landscape for future generations. This rocky landscape was preferred by the First Nations stakeholders over the more conventional vegetated covers that seek to restore mining landscapes to an aesthetically pleasing approximation of pre-disturbance conditions. While the low-permeability geosynthetic layer is expected to reduce infiltration to the underlying tailings and impacted soils, its primary purpose will be to ensure that runoff from the TCAs is effectively non-contact water, suitable for discharge to the surrounding environment. Further design work refine the configuration of the final covers for the TCAs is underway.

Acknowledgement

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Appraisal of Strategies for Treatment of Abandoned Mine Shafts in the Giyani and Musina Areas of Limpopo Province, South Africa

SE Mhlongo *University of Venda, South Africa*

F Amponsah-Dacosta *University of Venda, South Africa*

A Kadyamatimba *University of Venda, South Africa*

Abstract

The safety of abandoned shafts is a major concern to communities, government, and the industry. These shafts usually present physical and environmental hazards and socio-economic concerns to the public. This paper is aimed at evaluating strategies for treatment of old mine shafts so as to determine their suitability for abandoned mine shafts. The approach used involved conducting preliminary assessment of the shafts to establish the nature of the hazards and evaluating the old shafts treatment strategies using the Analytic Hierarchy Process (AHP) and Pugh Matrix for their suitability for addressing the problems of abandoned shafts in the Giyani and Musina areas. Although the identified shafts in the Giyani and Musina areas presented varying degrees of physical and environmental hazards, falling into the shafts and the problems of ground movement were the major physical and environmental risks of the shafts. In view of this, strategies that provide long-term treatment of the shafts were rated high in combating most of the risks of abandoned shafts whist dealing with their socio-economic concerns. The priority list of strategies for treatment of abandoned mine shafts created in this work can be used elsewhere outside the studied sites. However, this will require preliminary assessment of the shafts in such areas to be conducted and the objectives of their treatment to be clearly defined.

Keywords: *shaft treatment strategies, abandoned mines, preliminary assessment, AHP, Pugh Matrix*

1 Introduction

In general, open shafts around abandoned mine sites in South Africa are considered serious public safety threats and in the second place in the priority of rehabilitation of abandoned mine sites in the county (DMR 2010; Matshusa & Makgae 2014). The most feared and obvious risk of open abandoned shafts is accidentally falling into them (Holmes 2008). This together with deliberate entering of these shafts by adventurous people can lead to death due to physical body injuries, drowning in flooded old mine workings, suffocation, and exposure to dangerous mine gases (Salmon & Degas 2003; Wrona et al. 2016). According to illegal gold miners who go underground through old shafts in the Witwatersrand Basin, at least every week one person dies in abandoned mine shafts in South Africa (Sieff 2016).

After recognizing the safety threats of abandoned mine shafts, the government and communities tried treating these shafts using a variety of temporal and long-term treatment strategies. However, this was in some cases done without any characterisation of the shafts to establish the nature of their hazards while ensuring that only appropriate strategies are adopted in the rehabilitation work. As a result of displayed haphazardness in the treatment of abandoned shafts, some of them were left out in the rehabilitation program while others were treated with inappropriate strategies which collapsed or easily got removed by illegal miners soon after installation. This resulted to a situation where even treated mine shafts found still presenting considerable physical and environmental hazards. The main aim of this work was to evaluate different treatment strategies for mine shafts to establish their suitability for dealing with the problems of abandoned shafts in the Giyani and Musina areas.

1.1 The study area

The areas of Giyani and Musina are respectively found in the east and northern part of the Limpopo Province of South Africa as shown in Figure 1. These sites are characterized by several abandoned underground gold and copper mining sites. The well-known abandoned copper mines in Musina are Campbell, Harper, Artonvilla, Spence, and Musina while the gold mines in the Giyani area are Klein Letaba, Louis Moore, Golden Osprey (also known as New Union), Fumani, Franke, and Birthday. According to Wilson (1998) and Bahnemann (1986), large scale underground copper mining is known to have taken place around Musina between the years 1906 and 1991. On the other hand, gold mining occurred in the Giyani Greenstone Belt (GGB) in 1930 and ceased in the early 1990's (Steenkamp & Clark-Mostert 2012). The exploitation of copper ceased when the depth of mining had reached 1310m in most of the shafts (Hammerbeck 1976; Vesser 1989). However, the gold mining operations ceased when mining rarely gone beyond 300m in the GGB.

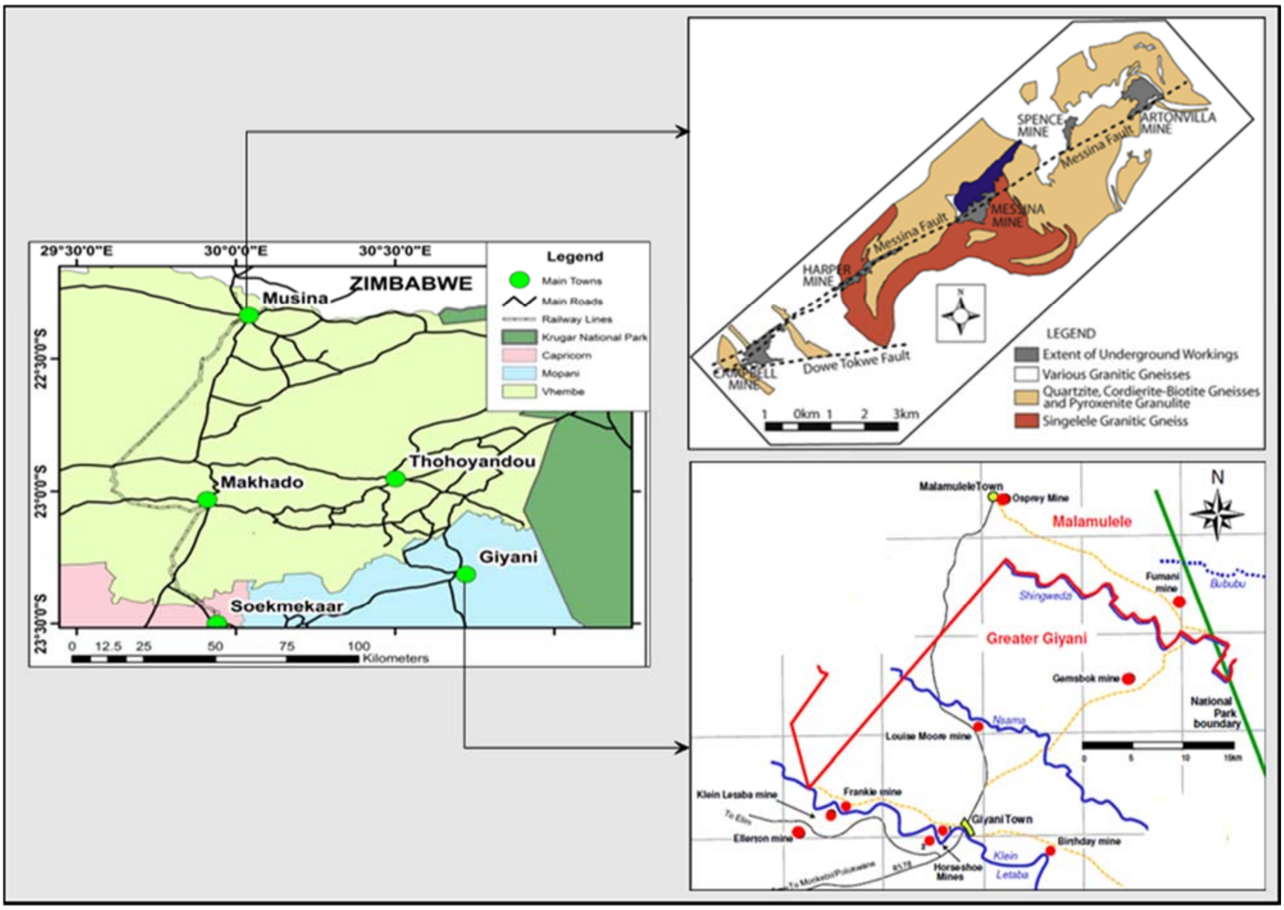

Figure 1 The distribution of abandoned mine sites in the Giyani and Musina areas (Chaumba et al. 2016; Parnham n.d.)

2 Methodology

The methodology of evaluating the treatment strategies for old shafts for their suitability for abandoned mine shafts in the study area was conducted in three phases which combined three different methods. The first step was the characterisation of abandoned mine shafts. The purpose of this was to quantify the environmental and physical hazards of the shafts. This was followed by using the Analytic Hierarchy Process (AHP) to rank the factors that influence decisions in the selection of treatment strategies for abandoned mine shafts. Lastly the suitability of different treatment strategies for dealing with the problems of abandoned shafts in the Giyani and Musina areas was determined using the Pugh Matrix method. The flowchart of the methodology used to assess different old shaft treatment strategies for the treatment of abandoned mine shafts in the two sites is shown in Figure 2.

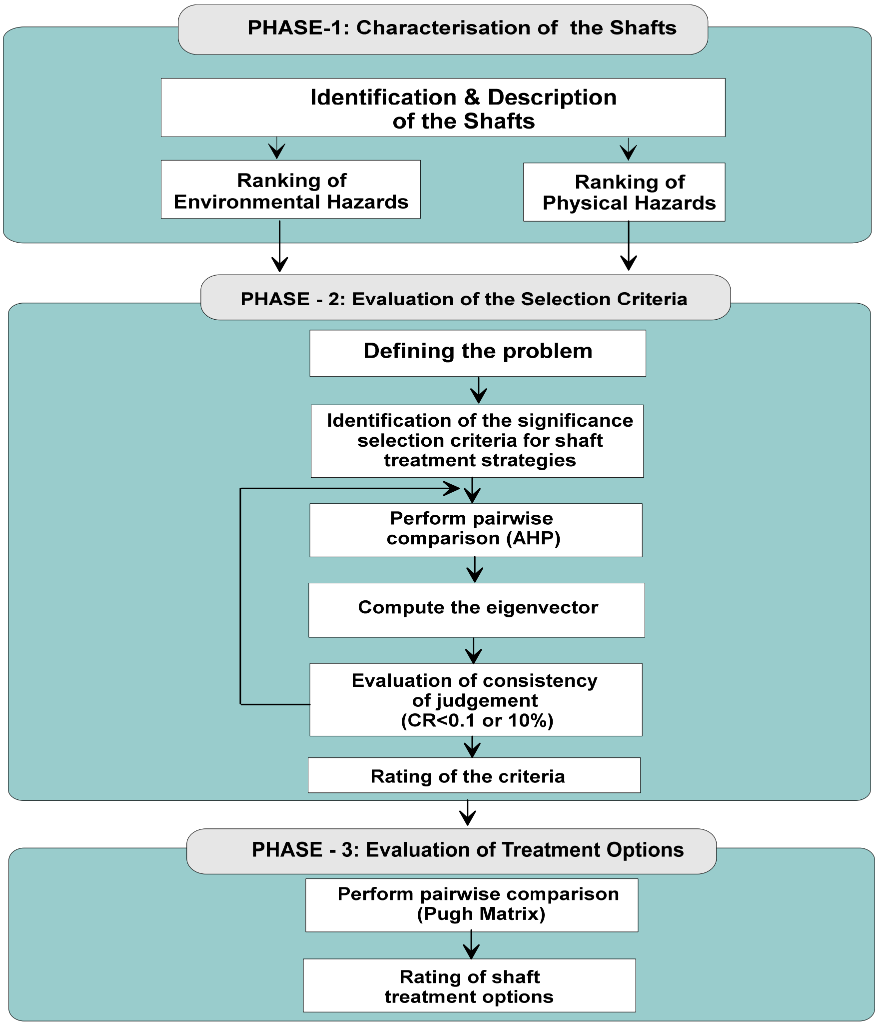

Figure 2 Flowchart for appraisal of treatment strategies for abandoned mine shafts

2.1 Field characterization of the shafts

The methodology used in this work involved carrying out a preliminary field assessment of abandoned mine shafts in the areas of Giyani and Musina. This was done to gain in-depth site-specific understanding of the major problems of abandoned mine shafts in these two areas. The field assessment process involved locating all known and unknown abandoned mine shafts in the study area and descripting them in terms of their current state, uses, and their potential physical and environmental hazards. This enabled both environmental and physical risks of the shafts to be evaluated using the least data demanding scoring and ranking method known as Abandoned Mine Entries' Hazard Ranking System (AME-HRS) which its details were given in the work by Mhlongo et al. (2017). Based on this method, numerical scores which represent the level of seriousness of the risk of the shaft being evaluated were computed. The evaluated physical hazards of abandoned mine shafts were: (i) falling into the shafts, drowning in water filling the underground mine workings, (iii) dangers of rock/ground falls, (iv) exposure to dangerous mine gasses, and (v) ingestion and/or having dermal contacts with contaminated mine water discharged by the mine shafts. On the other hand, the environmental hazards of abandoned shafts that were considered were (i) the problems of land degradation that limits the alternative use of the land, (ii) impacts of the abandoned mine shafts on the aesthetic beauty of the landscape, and (iii) the potential contribution of the shafts to pollution of the environment. This characterization of abandoned shafts assisted in defining what the priorities and objectives of abandoned shafts treatment efforts in the two areas.

2.2 Application of AHP model

The analytic hierarchy process (AHP) is one of the world celebrated and mostly used multi-attribute decision-making (MADM) technique that was developed by Thomas L. Saaty in 1980 (Ayag 2005; Musingwini & Minnitt 2008; Ataei et al. 2008). In this work, the AHP model was used to prioritise factors that are mainly considered in the selection of treatment strategies for abandoned mine shafts. These factors are depicted in Table 1. Based on the understanding of the situation of abandoned mine shafts problems in the areas of Giyani and Musina, a comparison matrix of the AHP was developed by comparing each factor over the other. The relative importance of each factor over the other was measured by assigning numerical values as defined in Table 2. The matrix was developed to be reciprocal and transitive. According to Masingwini and Minnitt (2008), Reciprocal matrix represents consistent judgments while transitivity matrix is the one which is developed to certify the rule that if the judgment detects that ***A*** is important than ***B***, and ***B*** is important than ***C***, then ***A*** is more important than ***C***.

Table 1 Rated factors for their influence in making decisions regarding the treatment of old shafts

Symbol	Description of the factors
PS	Ability of the strategy to protect the species that inhabits in old mine shafts (e.g. bat species)
DR	The durability of the strategy to ensure long-term treatment of the shafts
MR	Is the frequency of maintenance requirements of the implemented strategy
SI	Is the simplicity of implication or installation of the treatment strategy
CS	The performance of the strategy in saving cost during installation and maintenance periods
GE	The ability of the strategy to address the risk of gas emission
GM	The ability of the strategy to address the problems of ground movement
PI	The ability to the strategy to address risks of physical injury

Table 2 The scale of the relative importance of the factors (from Saaty and Vargas 1991)

Scale	Degree of Preference
1	Value equal important to the other criterion
3	Moderate important than the other criterion
5	Strong or essential importance value
7	Very strong
9	Extremely important
2, 4, 6, 8	Intermediate values between the two-adjacent judgment

From the developed matrix, the relative eigenvector (E_{ij}) and λ_{max} (largest eigenvector) were computed. The eigenvector was used as the measure of the significance of the factors and it was computed by applying the product of the entries of every row in the matrix to the n^{th} root (1/n) which was the number of factors (n) being evaluated. The obtained eigenvector was normalized (EN_{ij}) by dividing each entry of the matrix by the sum of the eigenvector value in a column of the matrix. In addition, the principal eigenvector (W_{ij}) was normalized by dividing the number of factors by the sum of the normalized column of the matrix.

Because the decision matrix was developed from human judgments, inconsistencies in judgment were likely to occur. The AHP allowed that the degree of such inconsistency is measured by calculating the Consistency Index (CI) which its value is used to calculate the Consistency Ratio (CR) using equation 1 and 2 respectively. The CI value is a measure of the degree of departure from consistency while the RI value is an average index of the randomly generated weights. The random consistency index values adopted from Saaty and Vargas (1991) and shown in Table 3 were used in the calculation of the CR values in this study.

$$CI(n) = \frac{\lambda_{max} - 1}{n - 1} \quad (1)$$

$$CR(n) = \frac{CI(n)}{RI(n)} \quad (2)$$

Table 3 Random consistency values (from Saaty & Vargas 1991)

Matrix order (n)	1	2	3	4	5	6	7	8	9
Consistency Ratio (RI)	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.49

2.3 Application of the Pugh Matrix methods

The strategies for treatment of old shafts were evaluated using the Pugh Matrix method. The purpose of the evaluation was to establish the suitability of these strategies for treatment of abandoned mine shafts in the Giyani and Musina areas. The use of Pugh Matrix method for this purpose was found appropriate since it is generally known for being an excellent method for evaluation of alternative solutions against the important criteria where there are several factors that might influence the outcome of the decision-making process (Lonma & Muller 2014; Gervone 2009).

Based on the results of the rating of important factors in the selection treatment strategies for abandoned mine shafts conducted using the AHP, the datum scores for comparison of the strategies with the developed criteria were determined. In this, the most important factor according to the AHP results was given the highest datum value of 8 while the least important was assigned the value of 1. The use of Pugh Matrix method in this work followed the traditional standard procedure of entering a **+** (where the strategy was judged to be performing better than the datum) and a **–** (where the strategy was judged to be performing worse than the datum). In cases were the worse or better performance of the strategy could not be clearly justified, the **S** (same as the datum) was entered in the comparison matrix. Based on the traditional Pugh Matrix model, each matrix cell ($\mathrm{A_{ij}}$) corresponded to mine shaft treatment strategy (***i***) and factor for decision-marking (***j***) as illustrated in Table 4.

Table 4 An illustration of the structure of Pugh Matrix method used in this work

Factors for selection	AHP Rating of the factors	Pugh Matrix Rating of the factors	Mine shafts treatment options		
			B_j	B_j	B_j
A_j	1	8			
A_j	2	7			
Sum of Positive (+)					
Sum of Negative (–)					
Sum of Same (S)					
Weighted Sum Positive (+)					
Weighted Sum Negative (–)					
Totals Score					

3 Results and Discussion

3.1 The state of the abandoned mine shafts in the Giyani and Musina areas

During the field assessment of abandoned mine sites in the areas of Giyani and Musina, a total of 39 underground mine entries were identified. Although the government and communities tried to close these shafts to reduce or eliminate their safety risks, about 18% of them appeared to have never been closed or treated. These shafts were found open and without lining and/or shaft collars. Open shafts in these conditions present high risks of falling in to them. This is because their top part turns to form a cone with loose and unstable steeply dipping slopes thus making it easier for people and animal who enter the cone to slide and fall into the deeper part of the shaft (Gunn et al. 2006).

The strategies used to treat some of the mine shafts in the two areas were heavy steel grate, concrete slab with steel wire screen, reinforced concrete slab, steel wire screens, and concrete plugs. The level of use of these treatment strategies and their current state are shown in Figure 3a and b respectively. It was noticed during the field assessment of the shafts that most of them were once treated with steel grates and concrete slabs. However, these structures were vandalized or removed by illegal miners who enter the shafts to mine the remnants of gold deposits underground. To address this, concrete plugs which provide long-term treatment of the shafts were used to close 13 shafts around Giyani. The plugs were installed and buried at 3 to 10m below the surface while only about 2.5 tonnes concrete landmark is exposed on the surface (DMR 2010). In general, concrete plugs have advantages of being self-supporting or anchored in the shaft, effectively dealing with risks of ground movement, falling into the shaft, and they can excellently close abandoned shafts for a period of not less than 100 years (Lecomte & Niharra 2013; Graves et al. 2000).

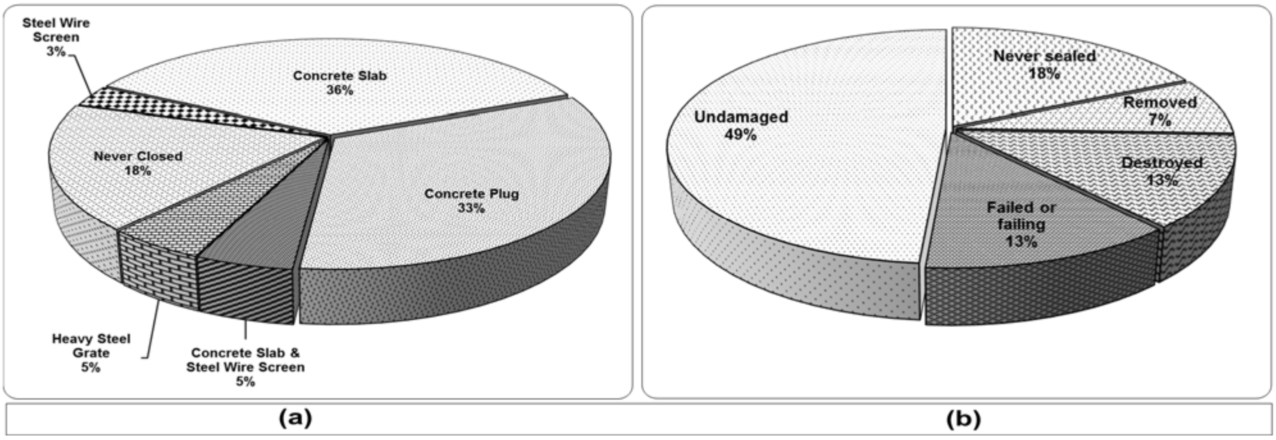

Figure 3 The current state of the mine shafts in the areas of Giyani and Musina, (a) the extent of used of different shafts treatment strategies and (b) is the current state of the treatment structures.

3.2 Physical and environmental risks of the shafts

The evaluation of the hazards of the shafts revealed that the mine shafts in the two areas had physical risks that are slightly higher than their environmental problems. Many shafts that had relatively high physical hazard scores were around Musina. These shafts had increased risks of falling into them due to that they were found open or inadequately closed and in highly unstable/subsiding grounds. The ground instability around the shafts is an indication of higher risks of rock falls and these present safety threats to adventurous people who might want to enter the mine workings. Moreover, the depth of mining (>1300m) contributed in having the risk of falling into the shafts rated high in the Musina area. This is because such risk is likely to lead to death with no hope for successful recovery of the body.

In Giyani, the shafts that were never treated and those for which the treatment structures were vandalised had relatively lower risks of falling into the shafts and rock falls (see Figure 4a). The fact that these shafts were without lining structures and/or shaft collars and that illegal miners at Klein Letaba Mine (i.e. GGB) go underground through the old inclined shafts in their endeavours of exploiting the remnants of the deposit underground increased the safety risks of the shafts. It increased the risks of falling into the shafts, exposure to the risks of drowning in water filling the mine workings, accidental or voluntary ingestion of contaminated mine water in the underground environment and getting exposed to harmful mine gases in historic gold mining shafts than copper mine shafts (see Figure 4a).

In general, the major environmental problems of the abandoned mine shafts are associated with discharge of contaminated and/or acidic water. In view of this, the shaft used to pump water for irrigation and other domestic purposes at Klein Letaba Mine results to high risks of environmental pollution. However, the principal environmental issue of most of the shafts in the Giyani and Musina areas was physical degradation of the land which also affects the aesthetic appearance of the landscape. The shafts found in physically unstable grounds around Musina presented the serious problems of land degradation (see Figure 4b). The main reason for this was that the land where these shafts are found cannot support even the basic post-mining land uses such as crop farming and development of animal grazing site.

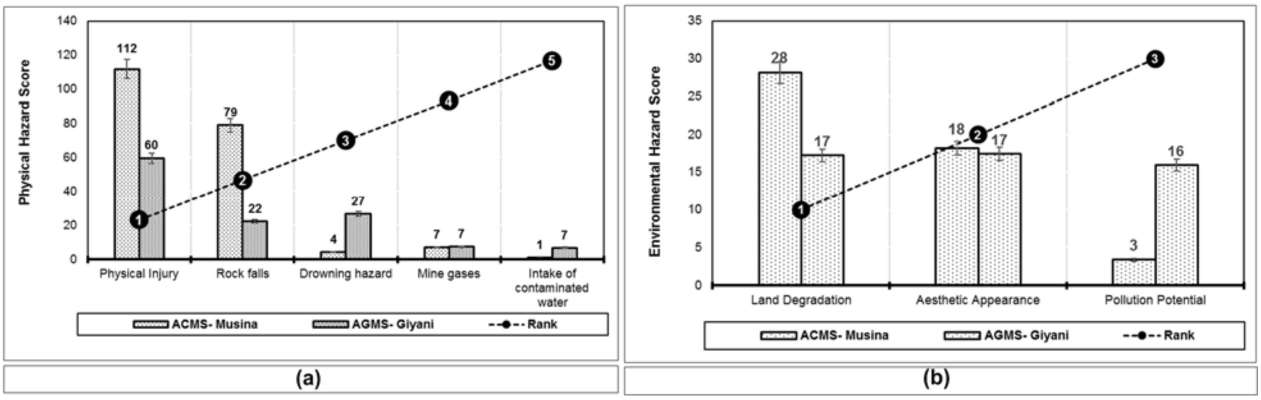

Figure 4 Comparison of physical and environmental risks of abandoned copper and gold mining shafts in the areas of Giyani and Musina.

3.3. Rating the criteria for selection of treatment strategies

The AHP was used to rank the significance of different criterion in the selection of strategies for treatment of abandoned mine shafts. The results of the AHP shown in Table 5 and Figure 5 were obtained within the acceptable level consistency in judgment (consistency index value of 0.083). According to different authors including Coyle (2004); Musingwini and Minnitt (2008), the consistency index values that are less than 0.1 suggest that the judgments made in the process of comparison of criteria were at a tolerable level of inconsistency. This together with that the criteria that were compered were less than nine made the results AHP method as used in this work acceptable and reliable. According to Musingwini and Minnitt (2008), results of AHP derived from eight criteria; as it is the case in this work; can be considered reliable. The results depicted in Table 5 showed that the important criterion in the selection of treatment strategies for abandoned shafts was their ability to address the physical impacts or injuries that might be caused by these shafts. The reason for this was mainly that most of these shafts are found in areas that are easily accessible to people and animals.

The durability of the shafts treatment strategies was ranked second in the selection criteria. The main advantage of durable treatment strategies is that they require very little maintenance thus reducing the cost of their maintenance. This criterion was about 10% less important than the ability of the strategies to address the physical hazards of the shafts and 7% more important than the ability of the strategies to address the risks of ground movement around the shafts. The significance of the prevention of ground movements is mainly because a considerable member of abandoned mine shafts are found within the communities with limited land for development. Therefore, expansion of any form of development towards the areas of abandoned mine shafts can have devastating effects on the land-used around the shafts if ground movement problems are not contained during the treatment of the shafts.

The issues of the cost of the treatment strategy and its ability to address mine gas emission problems obtained equal scores of 0.05 (5.2%) which is 13.6% less important than their suitability for address the problems of ground movement. The main reason for this, was that these criteria have less or no direct effect to the health and safety of the general members of the public or communities. The least important criteria had 0.03 scores. These criteria are the strategy's simplicity of implication, their requirements for maintenance, and their contribution to protection of species that hibernate in old mine shafts such as different species of bats which according to Barclay (2014) use old mine shafts seasonally for hibernation purposes.

Table 5 Pairwise comparison of the criteria for selection of treatment strategies for abandoned shafts

*Factors	PI	GM	CS	SI	MR	DR	PS	GE	Normalized weight
PI	1.00	3.00	8.00	8.00	7.00	3.00	8.00	8.00	0.36
GM	0.33	1.00	6.00	7.00	7.00	0.33	6.00	7.00	0.19
CS	0.13	0.17	1.00	2.00	5.00	0.14	2.00	0.50	0.05
SI	0.13	0.14	0.50	1.00	2.00	0.14	0.50	0.50	0.03
MR	0.14	0.14	0.50	0.50	1.00	0.14	2.00	0.50	0.03
DR	0.33	3.00	7.00	7.00	7.00	1.00	7.00	7.00	0.26
PS	0.13	0.17	0.50	2.00	0.50	0.14	1.00	0.50	0.03
GE	0.13	0.14	2.00	2.00	2.00	0.14	2.00	1.00	0.05
λ_{max} = 8.82; CI = 0.30; and CR = 0.083 (8.3%)									

***Note:** **PI** is the ability to address physical injury, **GM** is the ability to address risk of ground movement, **GE** is the ability to address the risk of gas emission, **CS** is the cost saving ability, **SI** simplicity of implication, **MR** is maintenance requirements, DR is the duration of the strategy, **PS** protect the species that are inhabitants of the mine shafts

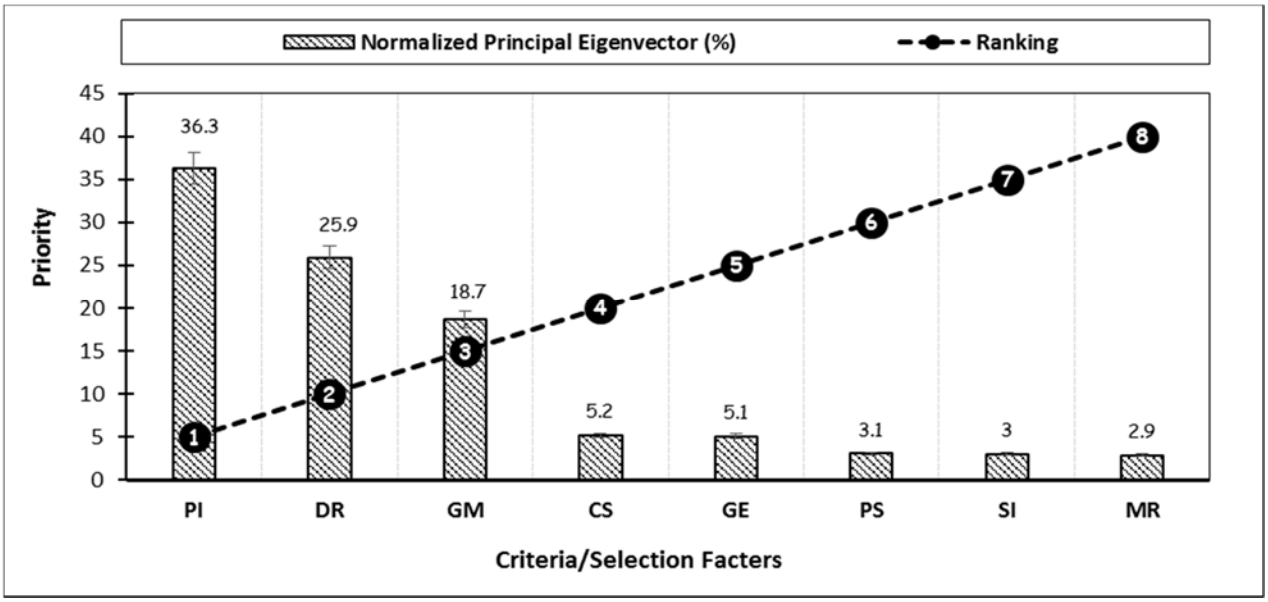

Figure 5 Comparison and ranking of the criterion for selection of treatment strategies

3.4 Suitability of treatment strategies for abandoned mine shafts

The evaluation of different treatment strategies for old mine shafts using the Pugh Matrix method allowed that strategies that can effectively address both environmental and physical hazards of abandoned mine shafts while addressing their socio-economic concerns are identified. A total of 19 strategies that are commonly used in treating old mine shafts were evaluated for their suitability for dealing with the problems of abandoned shafts in Giyani and Musina areas. As suggested by Madke and Jaybhaye (2016), the use of Pugh matrix in this work was to show the most un-preferred shaft treatment options instead of the most suitable strategy. This allowed that a cluster of strategies that are suitable for treatment of abandoned shafts for a given treatment objective be identified. This approach of selection of strategies for treatment of abandoned shafts is expected to have an advantage of providing guidance on the preferred strategy; which their implementation is to take into consideration some of the site-specific issues of abandoned shafts.

The results of the evaluation showed that the most preferred options for treatment of abandoned mine shafts were those with high potential to address both risks of ground movement and falling into the shafts. These included options such as backfilling with or without warning signs. This option also has an advantage of reducing or eliminating problems of emission of mine gas and restriction of downward flow and discharge of water. However, it is to be noted that these benefits of backfilling depend largely on the nature and design of the backfilling material and process of implementing the strategy. According to Davies (1988), the preferred backfill materials are the ones that are incombustible, chemically inert and with low compactability to minimums settlement of the backfill.

The second most attractive old shafts treatment option was injection/inclusion options followed by concrete plugs (both self-supported and anchored plugs). The blast-closure was the fourth most preferred treatment option. However, it should be noted that blast-closure option is best suited where the mine entry is an adit or a decline. This is because this strategy involves closing the mine entry with large boulders generated by blasting of the walls of the mine entry. Such treatment makes human and animal intrusion into abandoned mine workings very difficult. However; it can only effectively provide a deterrent to casual intruders of old mine workings, not those who are technological capable (Dixon & Keto 2009).

In their decreasing order of lack of preference, the least preferred options for dealing with the problems of abandoned mine shafts were dams sealing, steel capping, use of warning signs, steel grate, and concrete slabs. The lack of preference of these strategies is mainly because they do not address many of the major risks of abandoned mine shafts and they can be easily removed and/or destroyed by illegal miners thus making them to be also characterized by relatively high maintenance cost.

During the field characterization of abandoned shafts, it was found that where these strategies were used in the Giyani and Musina areas they were somehow vandalized, completely removed or collapsed due to minor ground movements. In view of this, these old shaft treatment options can be used as temporal treatment strategies in these areas. In the case where the protection of species that hibernate in old mine workings is deemed necessary, the use of steel grate, barrier sealing and fencing options can be adopted. Although, treating abandoned mine shafts to reduce their physical hazards by fencing and use of warning signs is common due to easy implementation (Holmes 2008), the socio-economic issues prevailing in most communities around abandoned mines in South Africa make these options less attractive. Thus, they were ranked slightly equal to closing of the old mine entries (i.e. adits) using the barrier seals. Figure 6 shows the priority of strategies for treatment of abandoned mine shafts in the Giyani and Musina areas.

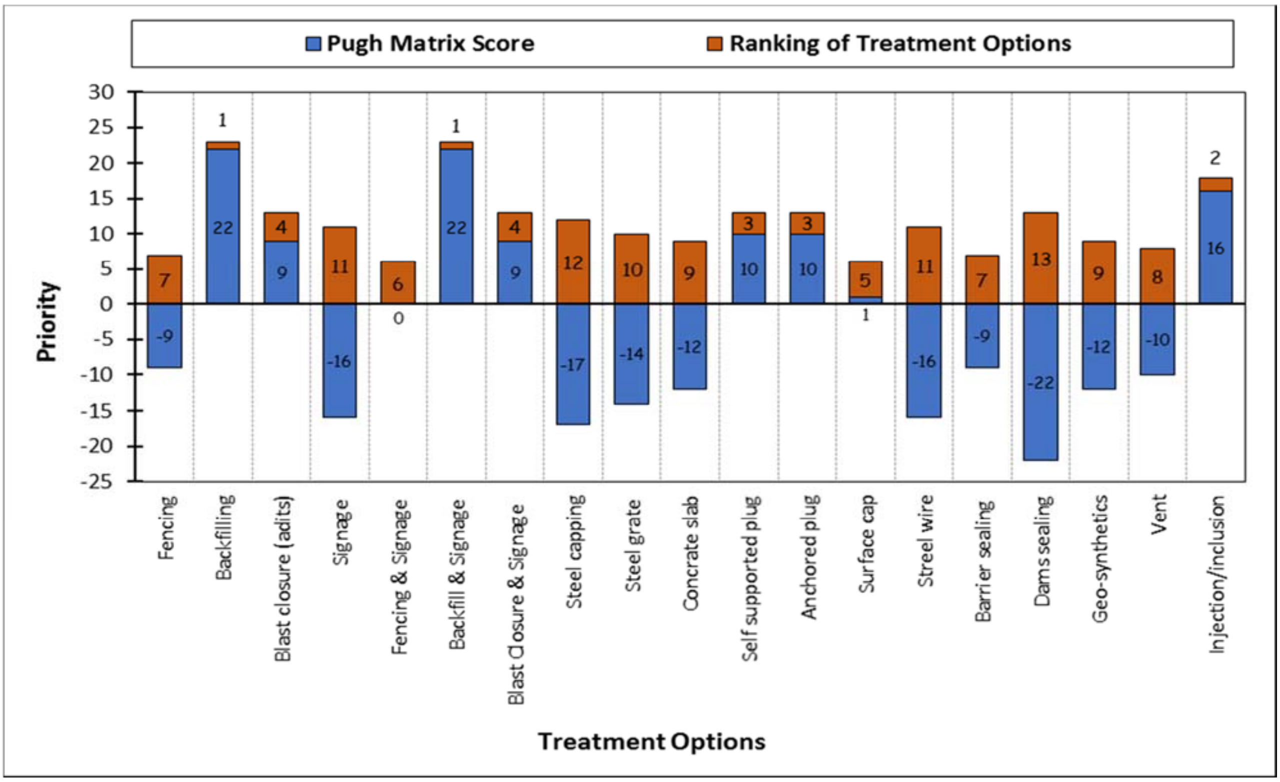

Figure 6 The rank of abandoned mine shafts treatment strategies in the Giyani and Musina areas

4 Conclusion

This paper presented the work that applied the Analytic Hierarchy Process and Pugh Matrix methods of Multi-Criteria Decision-Making (MCDM) techniques in finding the most suitable strategies for treatment of abandoned mine shafts in the areas of Giyani and Musina, Limpopo Province of South Africa. The results of preliminary field characterisation and the AHP revealed that the treatment of abandoned mine shafts in these areas should make use of strategies that provide long-term close-up of the shafts while preventing risks of ground movements. As a result, the evaluation of different treatment strategies showed that backfilling, injection/inclusion, use of plugs, and blast closure were the most preferred treatment options for the abandoned mine shafts in the Giyani and Musina areas.

The decision on which of these long-term or permanent strategies to use will need to take into consideration evaluation of future use of the land well as the future mining activities to be conducted. The reason for this is the fact that plugs can be designed in a way that they can be removed if the shaft is to be once again used for mining activities. However, if the surface use of the land requires that the void below the treatment structure is completely closed-up, permanent treatment of the shaft with appropriate backfilling material and use of blast closure can be considered.

Although this work was conducted in Giyani and Musina areas, the criteria for selection of treatment strategies and the priority list of shafts treatment strategies developed in this work can be used to guide decision-making in treatment of abandoned shafts in other areas where the situation is like that of the studied sites. However, to ensure that strategies that address site specific issues of abandoned shafts are implemented, preliminary site characterisation of the shafts is to be conducted. This allows the objectives of the shafts treatment process to be clearly defined and provide guidance on the nature of treatment options to be considered.

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4. Mine closure and mining infrastructure

The North Fork Rose Creek Realignment Project – Urgent Works Before Final Remediation

J Cassie *BGC Engineering Inc., Canada*

J Seto *BGC Engineering Inc., Canada*

Abstract

The Faro Mine, a former lead zinc open pit mining operation located in the central Yukon Territory, Canada, operated from 1969 until 1998, when the final owner filed for bankruptcy protection and the mine was subsequently abandoned. The liability and responsibility of the abandoned mine was assumed by the Federal Government and is managed by Crown Indigenous Relations and Northern Affairs Canada. The Faro Mine Complex is comprised of three open pits, one backfilled pit, a small underground mining operation, up to 320 million tonnes of acid-generating waste rock and 70 million tonnes of acid-generating tailings, three tailings dams, numerous diversion channels, and various haul and access roads. Remediation planning is currently underway but "urgent works" have been identified as being required to deal with significant contamination risks before final closure is implemented. The North Fork Rose Creek Realignment Project requires the design and construction of a new non-contact water diversion channel to realign the creek to protect the clean creek waters from impacted seepage originating from the waste rock dumps. The design and installation of a contact water collection and conveyance system will be required. Background conditions are reviewed. This paper will focus on the design criteria and challenges regarding the NFRC Realignment Project, including unspecified impacted seepage locations, construction conditions (e.g. permafrost ground conditions) and environmental management (e.g. protection of fish and fish habitat).

Keywords: *water management, fish protection, urgent works before closure*

1 Introduction

The Faro Mine Complex (FMC) is located in south-central Yukon Territory, approximately 200 kilometres (km) north-northeast of Whitehorse in northern Canada. The mine operated from 1969 through 1998 when the last mine owners abandoned the site. In the 1970s, it was the largest producer of lead and zinc in Canada, with an output of 15 percent of the world's output of these metals. The FMC consists of two main areas: the Faro Mine Area, which includes the Faro Pit and the Rose Creek Tailings Area (RCTA), and the Vangorda Plateau (Vangorda and Grum open pits) to the east (Figure 1).Together, the two areas contain over 320 million tonnes of waste rock and over 70 million tonnes of tailings. Of this, about 80% of the waste rock and all of the tailings are located in the Faro Mine Area and the RCTA. The majority of the waste rock and tailings are acid-generating and have released acid rock drainage (ARD) containing dissolved metals into groundwater, and surface water features that flow through the site. Metal leaching and ARD poses a direct threat to benthic and fishery communities that live in the creeks within and downstream of the FMC.

The Federal Government of Canada, as represented by Crown Indigenous Relations and Northern Affairs Canada (CIRNAC), is responsible for the management of the site including the following three main activities:

1. On-going care and maintenance activities including water treatment and site security; water quality monitoring; geotechnical monitoring; and surface water management.
2. Design and implementation of Urgent Works projects (Urgent Works) that are required before submission of a final closure plan to address immediate environmental and water management risks.

3. Preparation of a final remediation (closure) plan, including community and stakeholder consultation.

The Urgent Works are being designed on an emergency basis under the territorial *Waters Act* to control existing risks with site conditions and will be implemented before the remediation plan is prepared and submitted. Accordingly, the Urgent Works will not be subject to regulatory review (except for fish habitat issues). The final remediation plan will be subject to a regulatory review under the Yukon Environmental and Socio-economic Assessment Act.

Figure 1 Faro Mine Complex layout map showing the two main areas and the connecting Mine Haul Road (10 km+ distance)

Two Urgent Works are currently being designed: the North Fork Rose Creek (NFRC) Realignment Project and the Rose Creek Diversion Interim Hydraulic Upgrade (RCDIHU) Project. This paper will focus on the former project.

2 NFRC Realignment Project

2.1 Background and Project Development

Through routine surface water monitoring, elevated zinc concentrations were identified in the receiving environment downstream of the mine site in the fall of 2013. Sustained zinc concentrations greater than 0.4 mg/L and 1.0 mg/L were measured at Monitoring Stations X14 (last compliance point below the mine site) and at X2 (below the North Fork Rock Drain - NFRD) respectively. These measured concentrations are over 10 times the zinc concentration of 0.03 mg/L s listed in Canadian Water Quality Guidelines for the Protection of Aquatic Life (CCME, 2013).

A site investigation program was implemented to identify the source and seepage pathway of this new zinc load. However, the drilling of seven wells in the winter of 2014 did not identify a source zone or seepage path. It was concluded through trace metals analysis that the source of zinc is likely a small concentrated flow path, originating from within the Faro Main and Intermediate waste rock dumps (WRD).

In response to this increase in zinc concentration, the former site manager, Yukon Government (YG) implemented initial remedial responses during the fall and winter of 2014/2015 by constructing the NFRD seepage interception system (SIS). A localized seepage collection system with all-weather pumps and piping was constructed just downstream of the NFRD to collect contaminated seepage discharging on the western side of the NFRD and convey the seepage to Faro Pit for temporary storage and later treatment. This system was only partially effective in capturing the contaminated seepage, which was diluted by clean surface water flows from the NFRC. This SIS has only a limited-extraction capacity, which meant that elevated zinc still existed in the lower section of the NFRC at select times of the year.

Following a February 2015 meeting to discuss the design and sequencing of the North Fork Rose Creek Realignment Project, it was determined that a non-contact water diversion channel and a contact water (CW) collection and conveyance system would be designed and implemented on separate schedules with schedule priority given to the design of the non-contact water system. The two elements would be used to hydraulically separate the NCW from the CW by diverting the NCW NFRC flows away from the WRDs while CW would be collected and pumped to the Faro Pit for temporary storage and later treatment. From April 2015 until July 2017, various diversion alignments, collection approaches and structures and site investigation were undertaken to outline the potential options. In addition, closure planning and design for the final remediation was underway and as a closure feature, the NRFC Realignment Project needed to be integrated within that plan. Six NCW diversion alignments were assessed and in July 2017, a recommended alternative was presented to CIRNAC, followed by the conceptual design for the NCW Diversion. The detailed design for the NCW Diversion was submitted in April 2018.

2.2 Design Objectives and Elements

The NFRC Realignment Project will follow the previously established remediation objectives which are as follows:

- Protect human health and safety
- Protect and, to the extent practical, restore the environment including land, air, water, fish and wildlife
- Return the mine site to an acceptable state of use that reflects pre-mining land use where practical
- Maximize local and Yukon socio-economic benefits
- Manage long-term site risk in a cost-effective manner.

The NFRC Realignment will separate non-contact water from within the NFRC watershed from the CW (impacted seepage) believed to originate from within the WRDs. The proposed separation is required in the short term for Urgent Works and in the longer term for closure design. Physical separation of the non-contact and contact water will be provided by a 1.9 km long engineered channel mostly constructed within the NFRC Valley. The NCW diversion channel will allow the flow of non-contact water through a slightly elevated and engineered channel (just above the existing NFRC) past the impacted seepage and return it back into the NFRC at a lower elevation just upstream of the confluence with the South Fork Rose Creek (SFRC). This diversion is intended to function with a CW system designed to collect impacted seepage (current seeps and those yet to be developed) along the NFRC. Due to uncertainties regarding location(s), quantity and quality of impacted seeps from the WRD's, the CW system is planned to be implemented in a staged approach coupled with adaptive monitoring and is not the subject of this paper.

The major elements of the NCW diversion channel are shown on Figure 2 and include the following:

- The NCW diversion channel (1.9 km long shown in orange) above and below the Mine Haul Road and associated access roads;
- A 1.1 km long construction diversion channel (CDC) will be constructed to divert the non-contact water during construction of the NCW diversion, a large portion of which will be constructed over the existing NFRC channel;
- A low-head Inlet Dam at the start of the NCW diversion channel which will form a pond (fish habitat) and will divert NCW flow into the channel;
- A Zone II Outwash Pond will be used during the construction of the diversion channel to manage metals contaminated construction water;
- Several proximal borrow areas (shown in red) that will be used for construction materials;
- Several stockpile areas (shown in pink) will be developed for waste and rip rap materials;
- A culvert replacement on the Mine Access Road at the NFRC crossing; and
- Several fish overwintering ponds required as compensation for fish habitat loss.

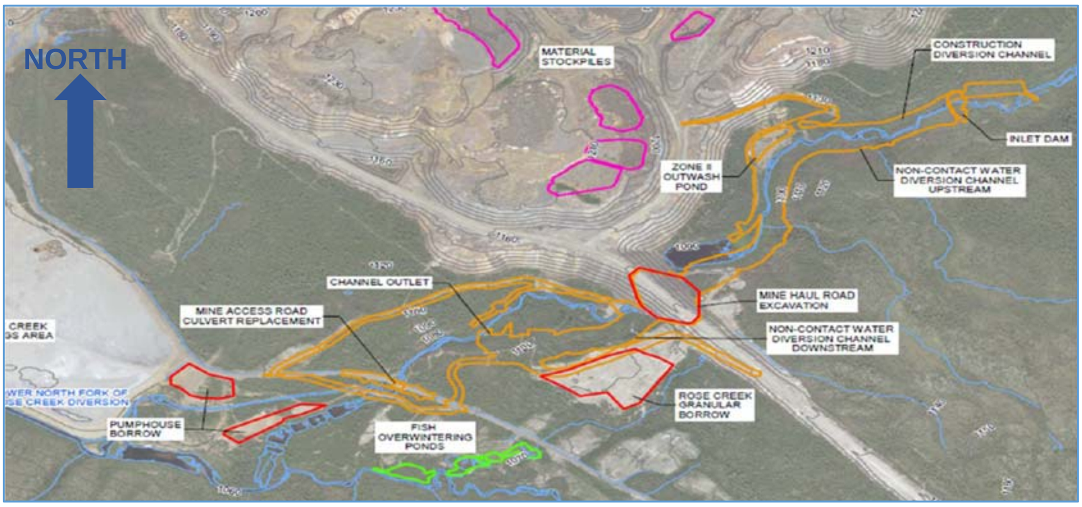

Figure 2 General layout for the NCW Diversion Project (RCTA to the left and WRD's to the top) with current NFRC shown in blue

2.3 Site Conditions

2.3.1 General

2.3.1.1 Climate

The FMC is located within the Central Yukon Basin climate zone and the climate is characterized as sub-arctic continental. The mean annual air temperature at the site is approximately -2°C with July and January mean monthly temperatures of +12°C and -15°C. Faro typically sees above-freezing mean daily ambient temperatures between the months of May through September and sub-zero mean daily ambient temperatures between the months of November through March. Estimated annual precipitation totals from 1978 to 2016 ranged from 238 mm to 662 mm, averaging 443 mm. Average monthly precipitation is highest from June to October and lowest from February through April.

2.3.1.2 Hydrology and Physiography

The NFRC drains south from the Anvil Range and conveys water from the upper NFRC watershed and the Faro Creek Diversion (FCD) past the WRDs, through the NFRD in the Mine Haul Road, and the Mine Access Road crossing (consisting of two culverts) to the SFRC and the Rose Creek Diversion (RCD) and eventually back into the undisturbed Rose Creek. The creek itself is typically 5 to 10 m wide.

The NFRC is located along the eastern toe of the Main and Intermediate WRDs. North of the Mine Haul Road, the NFRC floodplain is approximately 100 m to 200 m wide, and is bound to the east by hillslopes that slope to the NFRC Valley at approximately 4H:1V to 3H:1V and to the west by the WRDs. Along the NCW diversion alignment, two tributary streams flow into the NFRC from the southeast. South of the Mine Haul Road, the NFRC becomes narrower (down to approximately 20 m wide at the floodplain) and bound by slopes that rise approximately 20 m above the floodplain and range from approximately 4H:1V to the west and 2H:1V to the east. Bedrock outcrops are also visible in the steep slope east of the creek and adjacent to the creek just north of the Mine Access Road crossing. Most of the area along the NFRC is undisturbed and vegetated and frequently covered by small brush and deciduous trees.

Figure 3 provides mean monthly averages flows in the NFRC (at Station R7 located upstream from the Mine Haul Road), along with monthly minimum and maximum values through the year. Maximum flows occur in May and June following melt of the winter snow pack.

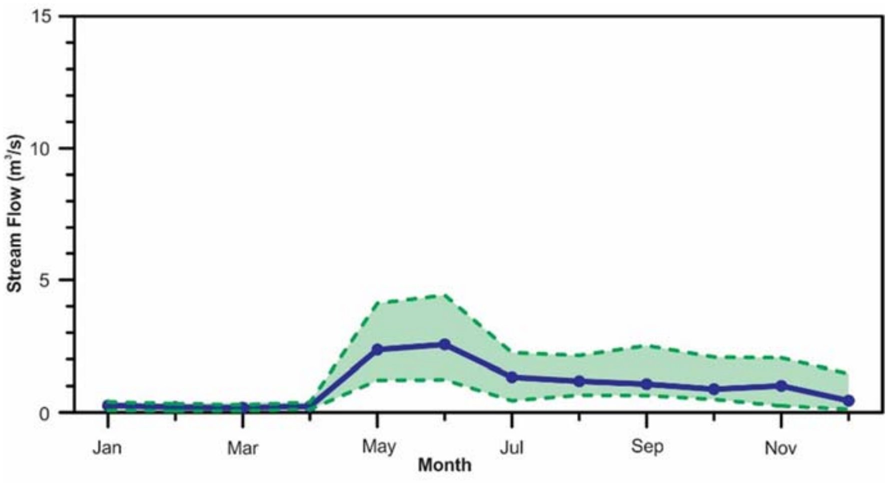

Figure 3 Average monthly stream flows (blue line) along with monthly maximum/minimum range for R7 (at confluence with FCD and NFRC)

2.3.1.3 Geology and Permafrost

The surficial geology of the area is largely a product of glacial activity during the Pleistocene, combined with more recent Holocene modification by fluvial erosion and deposition, as well as colluvial and cryogenic processes. All the surficial materials and glacial landforms that currently exist in the area were deposited in the most recent, late Wisconsin McConnell glaciation. All but the highest peaks in the area were ice-covered during the last glaciation (Bond 2001).

Deglaciation in this region consisted mainly of melting large stagnant ice blocks, a complex system of glaciofluvial deposition, and glacial lake resultant formation and drainage disruptions. Glacial deposits are typically of till, glaciofluvial, and glaciolacustrine origin. During the Holocene, a number of geomorphic adjustments occurred as the landscape transitioned from a glacial to a non-glacial regime, including erosion and colluviation.

A surficial geology map of the Faro area was prepared by Bond (1999), based on field mapping and regional sampling. The map shows that the terrain along the current NFRC floodplain is predominantly alluvial/fluvial deposits, with colluvium and glaciofluvial deposits beneath slopes above the floodplain, and tills at higher elevations. Much of the FMC area is blanketed by McConnell till that is typically less than 20 m thick. In many cases, the till is interbedded with glaciofluvial and glaciolacustrine sediments as a result of complex deglaciation processes and active ice retreat.

The FMC lies in the sporadic and discontinuous permafrost zone, meaning that 10 to 50% of the ground is underlain by permafrost. Geotechnical investigations in the NFRC valley indicate that permafrost, where present, is generally warmer than -1°C and of thickness ranging from approximately 2 m to greater than 20 m, with the thickness decreasing with increasing distance away from the Mine Haul Road. Ground ice is in the form of visible (e.g., as ice lenses or ice grains) to non-visible. Ice content varies, both spatially and with depth, and depending on the soil texture. Both ice-poor permafrost (visible ice content less than approximately 10% by volume, or the material is in a damp to moist state when thawed) and ice-rich permafrost (visible ice contents exceed approximately 10% by volume or the material is in a saturated or wet state when thawed) are present.

2.3.1.4 Hydrogeology

Water table elevations are interpreted to be similar to estimated pre-development topography, with limited drawdown due to the Faro Pit and generally, little groundwater mounding beneath the WRDs. Seasonal fluctuations in groundwater levels typically range from about 1 m below ground surface in valley bottoms to 3 m below ground surface along valley flanks. Within the NFRC Valley, the water table is generally shallow along the channel and is located at depths of 1 to 2 metres below ground surface (mbgs). Artesian (i.e., flowing) conditions have been encountered at several locations along the NFRC.

North of the Mine Haul Road, groundwater depths increase to 10 to 20 m below ground surface outside of the valley bottom on the eastern side of the drainage. On the western side between the WRDs and the channel, groundwater depths are typically shallower at less than 5 mbgs.

2.3.2 Site Investigation and Test Programs

Extensive site investigation programs were undertaken for this project (and including some aspects of other Urgent Works projects), as summarized in Table 1;

Table 1 Summary of site investigation programs for Urgent Works project

Program Dates	Major Investigation Activities
April 2015	8 boreholes
July and September 2015	51 boreholes and 63 test pits Surface and downhole geophysics
January 2016	Permafrost test cut
September/October 2016	58 boreholes and 109 test pits Downhole geophysics Test excavation along channel alignment
July, August, September and December 2017	23 boreholes and 102 test pits Well development and sampling 10 hand-augered holes

Samples from all these programs were submitted for geotechnical, aggregate and geochemical testing. In addition, site investigation information collected before 2015 was also compiled where relevant to the NFRC Realignment Project.

3 Non-Contact Water Diversion Project

3.1 Design Criteria

During initial discussions for this project, the use of the Probable Maximum Flood (PMF) was used as the design criteria for conceptual options scoping and cost assessments. Following assessment of the failure consequences from extreme events, including environmental impacts, the 1:200 year return period flood event was chosen for the design criteria. Table 2 outlines this and other design criteria for the various components of the project.

The NCW diversion channel will include an Inlet Dam that will direct clean surface flow into the diversion channel. The dam is designed as a zoned earth and rock fill dam with a low-permeability core that is partially keyed into the foundation soils; chimney/blanket drains will be located downstream of the core. The dam will incorporate a shallow cutoff trench, but some seepage loss through the dam foundation is expected and permissible. The dam will be approximately 90 m long, up to 5.5 m high, with a 10 m wide crest and 3H:1V slopes (upstream and downstream). The construction of the Inlet Dam will create a pond and has been sized to store the 1:200 year flood event.

Table 2 Summary of design criteria for NCW diversion channel

Project Component	Design Criteria
Hydraulics	NCW Diversion Channel sized for design flood event = Q_{i200} = 78 m^3/s with 0.3 m freeboard. Mine Access Road crossing also sized for design flood event = Q_{i200} = 78 m^3/s. Grade along the channel alignment will be between 0.5 and 5%. Approximately 1.6 km of the 1.9 km long channel will be lined with a composite liner (bituminous geomembrane liner and low-permeability fill), to minimize seepage loss of NCW that could otherwise mix with and dilute impacted seeps being collected and result in inefficient CW collection. The section of channel from the channel inlet to the Mine Haul Road (1.2 km length) has a low gradient (0.6%) and has been configured with a low-flow (pilot) channel to minimize the potential for aufeis formation and ice blockage. Construction diversion channel (CDC) sized for design flood event = Q_{i5} = 11 m^3/s with 0.3 m freeboard.
Channel Side Slopes	No steeper than 3H:1V for lined NCW diversion channel. 1.5H:1V slopes for riprap-lined CDC.
Geotechnical (embankments)	Factor of Safety (FS) > 1.3 for during construction (under static loading). FS > 1.5 for long-term static stability; FS > 1.0 for seismic stability. Seismic: 0.126g, corresponding to peak ground acceleration hazard for a 1-in-2,475 year return period.
Service Life	75 years. Channel design incorporates a bituminous geomembrane liner that is reported to have a design life exceeding 300 years.
Fish Habitat or Passage	Fish passage is facilitated by the use of shallow channel grades (less than 5%) and a low-flow pilot channel. NCW Diversion Channel design includes creation of habitat, such as overwintering ponds, boulder clusters that provide resting habitat for migrating fish under moderate to high flow conditions, natural substrate fills, and step pools for the steeper channel segment located downstream of the Mine Haul Road. In addition, the realigned channel will reconnect the upper and lower sections of the NFRC that are currently separated by the NFRD.

3.2 Construction Considerations

The construction considerations for this project are significant. Seasonal construction requirements and design details to address permafrost subgrade conditions are briefly discussed. In order to limit the thermal disturbance of excavated permafrost materials, all excavation of permafrost subgrades will occur during the sub-zero season only to minimize exposure to warm air temperatures and solar radiant heating of exposed subgrades. Partial sub-excavation of permafrost soils will also be undertaken to minimize post-construction thaw settlement. High strength geotextile layers will be placed over the permafrost subgrades to minimize thaw-associated differential settlements. Granular fills, much less sensitive to sub-zero compaction conditions, will be used to cover permafrost subgrades to minimize thermal disturbance and to create a trafficable surface for later warm season construction. Layers of granular fill will also be placed over other exposed permafrost subgrades to serve as thermal insulation and to attenuate thaw rates into the subgrade and also allow for any excess pore pressures caused by thaw to dissipate.

3.3 Environmental Management

This Urgent Work is being undertaken to improve water quality in the NFRC and to protect the aquatic environment and fish habitat. Since the construction of the NCW Diversion Channel will require the destruction of existing fish habitat, the project is required to apply for a Fisheries Act Authorization through the Federal Department of Fisheries (DFO). Before any construction may begin, fish in the NFRC within the construction area will need to be salvaged and relocated outside of the construction area. This fish salvage will be the first activity carried out and must be completed outside of the freshwater timing window for Arctic Grayling and while the creek water temperature is 4°C or warmer, which is generally before mid-September each year. The fish salvage operations will be supervised by professional aquatic scientists using local staff to capture (using electro-fishing and net methods). To prevent fish from re-entering the construction area post-salvage, fish barriers will be placed upstream and downstream of the construction area. Given that these barriers are to remain in operation over the winter, protection of these barriers from ice and debris will also be required.

The NFRC Realignment Project will alter the existing fish habitat in NFRC. While the new channel will connect the upper and lower reaches of the NFRC currently blocked by the NFRD, the project will need to create some critical overwintering fish habitat by constructing 5 new ponds that will be deeper than 2 m depth (so that they will not freeze to the bottom). One of the new ponds will be located within the reservoir formed by the Inlet Dam while four other ponds and associated channels will be created next to the SFRC. These ponds will be created early in the construction schedule to let the ponds develop during the construction process.

The new diversion channel will be constructed in a contaminated area, and it will be necessary to protect the existing downstream water quality from all construction water impacts. A construction water management plan was developed for both sediment-impacted water and metals-impacted waters and extensive sediment and erosional control measures during construction have been developed. Construction water found to be impacted by metals will be dewatered by vacuum trucks and transported to Faro Pit for storage and later treatment.

4 Conclusion

The design and construction of a 1.9 km long NCW diversion channel, in association with a later phase of CW collection and conveyance as part of the NFRC Realignment Project, will improve the water quality and protect fish habitat both within and downstream of the NFRC which has been impacted by mining. Significant challenges exist with the construction of a diversion channel within an already impacted area while protecting and enhancing the downstream aquatic environment. In addition, construction of the channel will be challenging in the northern environment with subarctic climate and the discontinuous permafrost conditions. Extensive investigations, test fills and site experience have all been reviewed as part of the detailed design process. Construction of the project is to be initiated in Fall 2018.

Acknowledgement

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A Process-based Approach to Mine Rehabilitation Decision Making Illustrated Through Bayesian Modelling and a Risk-based Approach to Practices for Dispersive Spoil Rehabilitation

GT Dale *Verterra Ecological Engineering and University of Southern Queensland, Australia*

K Reardon-Smith *University of Southern Queensland, Australia*

E Thomas *Verterra Ecological Engineering, Australia*

J McBennett *University of Southern Queensland, Australia*

L McCallum *Verterra Ecological Engineering, Australia*

S Raine *University of Southern Queensland, Australia*

Abstract

Rehabilitation of dispersive spoil is technically complex and requires detailed understanding of the key site characteristics affecting spoil behaviour and their interaction with numerous management decisions. The appropriate rehabilitation approach may vary from site-to-site and within sites. Detailed spoil physical and chemical characterisation is critical to inform effective interventions.

To assist mine environmental staff with understanding the key considerations of dispersive spoil rehabilitation, a framework founded on an expanded form of the Universal Soil Loss Equation (USLE) was adopted. Opportunities for intervention, the collective outcome of which represent the residual vulnerability to erosion, were grouped into five classes comprising: spoil characteristics; slope characteristics; erosion practice control factors; crop management factors; and tunnelling influences. Rainfall factors, representing exposure to erosive forces, were grouped into a sixth climate class.

A process-based approach to integrating contingent interactions between site characteristics and management interventions was developed using Bayesian modelling. Bayesian models provide the capacity to conceptualise and analyse complex management system by enabling the likelihood of a particular outcome to be predicted given the condition or state of each factor in the model.

Built around the expanded USLE framework, the Bayesian model comprises six sub-models with a total of 104 variables. The model presents the outputs of surface erosion and tunnelling risk as a matrix of exposure by vulnerability. Conditional probabilities informing the Bayesian model were developed using established literature; assessment of prior dispersive spoil rehabilitation outcomes; preliminary results from field trials; and expert knowledge. The resulting model was built into a user-friendly web-tool linked to a spoil chemistry calculator and rehabilitation cost model.

Spoil behaviour from field experience and modelling was captured in a set of Best Management Practices (BMPs), each presented as a risk matrix of management intervention by the interaction of sodicity (exchangeable sodium percentage) and soil salinity. The BMP's provide a guide for inputs to management decisions selected in the Bayesian model. The Bayesian model and associated BMPs provide field practitioners with the capacity to explore alternative management options and make informed decisions based on cost and risk. An iterative process, using feedback from industry will support adaptive evidence-based best practice dispersive mine spoil management and model refinement.

Keywords: *bayesian modelling, dispersive spoil, risk-based decision making, sustainable closure, rehabilitation, environmental risk management*

1 Introduction

Sustainable closure of coal mines in Australia remains one of the industry's biggest challenges. A significant proportion of mines in Australia have dispersive spoil. Based on an estimated area of 20,000ha and a rehabilitation cost of AUD$100,000 to AUD$150,000/ha, the instantaneous rehabilitation liability for the Bowen Basin alone is estimated at AUD$2 to $3 billion.

Dispersive soils are a common feature of the Australian landscape, covering 25% of Queensland (Shaw *et al*., 1994). Similarly, dispersive spoil material is a significant feature of sediments overlying coal deposits throughout the Bowen Basin and, to a lesser extent, the Clarence-Moreton Basin. Dispersive spoils present problems in post-mining rehabilitated land-forms due to their increased potential for both surface and tunnel erosion, compromising ability to achieve the fundamental mine closure objectives of a safe, non-polluting, stable and self-sustaining post-mining land form (Minserve, 2004).

Dispersive spoils are characterised by weak aggregate stability, and spontaneous dispersion of clay particles in contact with water (Vacher *et al*., 2004a; Minserve, 2004). Dispersion of clay particles may lead to blocking of pores, resulting in surface sealing and crusting, the formation of hard-setting layers, and reduced permeability, which further increases runoff (Dang *et al*., 2018). These factors, in-turn, create hostile conditions for plant establishment and growth (DNR, 1997; Vacher *et al*., 2004a).

Runoff resulting in overland flow may result in surface rilling, gullying and other erosion features that concentrate flow paths, further exacerbating erosion (So *et al*., 1998; Minserve, 2004). Dispersion of clay particles, even in still water, and associated loss of structural strength, may result in movement through internal spoil cracks or pores. Ponded water, variable compaction, localised zones of high infiltration and restrictions that lead to accumulation of water and preferential sub-surface flow paths, may all contribute to development of tunnel erosion (Minserve, 2004).

The potential for dispersion is a function of fundamental spoil properties. However, the expression of erosion as a consequence of dispersive spoil in rehabilitated mine landforms is a function of design and management. A number of studies have found that the potential impact of vegetation on erosion from rehabilitated soils is substantial (So *et al*., 1998; Carroll *et al*., 2001; Carroll *et al*., 2004). Similarly, other studies have found strong interactions between the design of constructed landforms and the development of tunnel erosion, particularly land forms that lead to ponding over saline sodic spoil (Minserve, 2004; Loch, 2010). Variations between these reports on the requirement for individual parameters to minimise erosion of dispersive spoils reflects the inter-related nature of fundamental soil properties, landscape design and construction characteristics, climate and management practices (particularly as they influence vegetation success and structure) on the ultimate performance of dispersive spoils. For example, between the three studies mentioned above, the reported level of cover required to minimise erosion risk varied from 30% to 80%.

A number of prior studies have developed detailed quantitative relationships and models describing the behaviour of sodic spoils and landforms (So *et al*., 1998; Vacher *et al*., 2004a; Minserve, 2004). However, no prior studies have integrated this information into a costed, risk-based framework that will assist operators to firstly characterise and understand the expected performance (or likelihood of failure) of constructed landforms in dispersive spoil landscapes, and secondly, to assess the trade-offs between risks and cost of alternative options.

A key objective of this study was to develop a risk-based decision support framework to inform practical, cost-effective management of dispersive mine spoil, together with a set of Best Management Practices (BMPs) and costed, risk-based decision support tools. Benefits of improved mine spoil management will include enhanced capacity to meet closure criteria; improved regulator consideration of closure standards; improved post-closure land capability; improved community acceptance of post-closure land condition;

reduced contribution to cumulative impacts; enhanced social licence to operate; and, in the case of eastward draining catchments in the Bowen Basin of Australia, improved Great Barrier Reef water quality.

2 Methodology

Data collection to support the development of a quantitative, process-based model of dispersive spoil behaviour was undertaken in five stages: a survey of mine site representatives; field assessment of historic rehabilitation; physico-chemical analysis of soil and spoil samples; workshops with industry representatives; and establishment of validation field trials.

2.1 Site representative survey

Twenty-three site environmental managers, industry experts and consultants participated in an industry survey to document current rehabilitation practices and identify sites covering a range in dispersive characteristics and erosion performance. The survey comprised 33 questions covering: inventory of dispersive site locations; site management practices; design intent; characterisation data; climatic conditions; remedial action; cost data; regulatory requirements; and performance perception.

2.2 Field assessment of historic rehabilitation sites

Historic rehabilitation sites were selected to cover a full spectrum of physical and chemical conditions, e.g., sodicity, slope, slope-length, vegetation cover, rainfall/climate, erosion status, and rehabilitation performance. A total of 40 sites across seven mines were inspected and assessed.

Erosion condition at each assessment point was evaluated in accordance with procedures set out in the National Committee on Soil and Terrain (2009). This involved qualitative assessment for erosion type, state and severity within 20m of each assessment point. In later assessments, erosion was also estimated quantitatively by use of UAV-based photogrammetry to construct digital elevation models.

Ground cover was estimated visually, using a standardised cover percentage reference diagram, as the percentage of bare soil, rock, litter or vegetation. The number of trees, shrubs and Acacias within the 20 m plot was recorded, along with the number of grass species. In later assessments, cover was estimated quantitatively by UAV-based multispectral imagery and calculation of the modified soil adjusted vegetation index (MSAVI).

Photographs were taken in all four cardinal directions around the assessment peg in each plot so that the peg appeared in all four photos. A vertical photograph was taken over the peg at each site. In later assessments, a digital orthophoto was captured by UAV-based imagery.

2.3 Spoil analysis of historic rehabilitation sites

Substrate chemistry was assessed from samples collected in topsoil (0 to 10cm) and underlying spoil (30 to 40cm). All samples were assessed for physico-chemical properties (pH, EC1:5, texture, particle size), and exchangeable cations (Na, K, Mg, Ca, Al, CEC). From these analyses, values were estimated for EC_e, ESP, CROSS, Ca:Mg, ESP/EC_e, CEC to clay ratio (CCR), mineralogy, gypsum requirement and plant available water capacity (PAWC). Topsoils were also analysed for macro nutrients (NH_4, NO_3, NO_2, total N, Colwell P, Colwell K, sulphate); carbon (organic carbon, organic matter, C:N ratio); and micronutrients (B, Zn, Fe, Cu, Mn).

Spoil chemical data and qualitative erosion characteristics were analysed by correlation analysis to explore relationships between parameters, and linear regression to identify key explanatory variables for erosion state, type and severity.

2.4 Bayesian model construction

A framework to capture site characteristics and management interventions was developed based on an expanded form of the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) to include tunnelling influences. Using this framework, an iterative process was applied to develop a Bayesian model capturing biophysical and management elements, plus processes influencing rehabilitation performance. Workshops were held with industry rehabilitation experts to review the model structure, parameter interactions, management interventions and the range of states within these. Workshops were held with industry rehabilitation experts to review the model structure, parameter interactions, management interventions and the range of states within these.

2.5 Bayesian model parameterisation

Variables (‘nodes’) in the model were categorised into states (‘conditions’) which encompass the expected range of values for each variable. These were defined as either Boolean (e.g. true or false), categorical (e.g. high, medium, low), or continuous (value range divided into sub-ranges with discrete values). Node state sub-ranges were identified based on documentary evidence of relevance (e.g., response thresholds for chemical parameters). Where such evidence was limiting, states for continuous variables were defined based on equal proportions of the value range of the parameter and categorical states were based on stakeholder advice.

Each variable in the model was defined by a conditional probability table (CPT), which specifies the likelihood of the system being within each of the states defined for each variable. CPTs were parameterised using a combination of evidence from the literature, quantitative data (with probabilities defined by the frequency distribution of the data) and expert opinion).

2.6 Validation field trials

An established site at German Creek was assessed and spoil analysed as for historic rehabilitation sites. Treatments at German Creek were: full rock mulch cover at 500mm; half rock mulch cover at 250 mm; gypsum and 100mm rock mulch; contour benching with rock-lined drains; topsoil, rip, and seed plus gypsum as required.

New trial sites were established at Moranbah North and Lake Lindsay mines to test the effectiveness of parameters demonstrated to influence dispersive mine spoil behaviour based on the literature survey, field inspections of historic rehabilitation and regression analysis of rehabilitation performance (erosion type and severity) with site factors.

Base treatments at Moranbah North were: sub-grade gypsum, ripped to 300mm to achieve a residual ESP of 5% (requiring 20t/ha); 100mm of topsoil; gypsum applied to topsoil to achieve a residual ESP of 5% (requiring a rate of 10t/ha); manure to achieve approximately 2% organic matter (requiring 50t/ha); a successional pasture seed mix comprising a fast-establishing cover crop and slower establishing, stoloniferous pasture species at a combined rate of 40kg/ha; light harrowing of seed to 50mmm (i.e., not ripping); and sprinkler irrigation. Variable treatments were contour bank construction (earth or porous hay); contour spacing (10 or 20m); and fertiliser application (plus/minus).

The Lake Lindsay trial is a randomised complete block design with six spoil treatments and two replications. For treatments other than the rock mulch control, base treatments were: ripping of spoil (pre-topsoiling) to a depth of 20cm; application of topsoil to a depth of 15cm; incorporation of organic matter into the topsoil to achieve an organic matter content of 2% (requiring 52t/ha); application of a custom fertiliser blend to address all identified nutrient deficiencies; cultivation of topsoil (post fertiliser, organic matter and, where relevant, gypsum), to a depth of 15cm; application of a successional pasture seed mix at the rate of 42kg/ha. Variable treatments (other than the rock mulch control) were: rate of gypsum treatment of spoil (20cm) (1x and 2x the requirement to achieve a residual ESP of 5% (requiring 9 to 36t/ha); rate of gypsum treatment of topsoil (15cm) 1x and 2x the requirement to achieve a residual ESP of 5% (requiring 1 to 2t/ha); and drip irrigated bands at 5mm/week (irrigated/unirrigated).

3 Results

3.1 Industry survey

The industry survey identified areas of consensus and divergence in approaches to management of dispersive spoil. It also identified critical knowledge gaps.

It was universally recognised that Tertiary sediments in the Bowen Basin contain dispersible material, and that Permian sediments are more stable. The dominant practices included: selective placement and burying of dispersive material where possible (preferred); rock mulching - competent rock intermixed with topsoil and spread to a depth of 0.5 to 1m; and Permian capping - encapsulation of dispersive material with 0.5 to 1.0m of Permian rock covered with 10 to 25cm of topsoil. Vegetation establishment was considered critical on all sites, as was the need for construction and active management of graded banks during vegetation establishment. Maintenance or removal of contour banks once vegetation was established was recognised as important to prevent surface ponding or development of preferential flow paths.

Industry opinion varied in relation to appropriate slope shapes and lengths, grades, ameliorants and landform design. In particular, opinion varied in relation to the efficacy of gypsum. Some considered that it '*did not work'*, while others noted that it required time and potential retreatment to ensure that successful exchange had taken place.

Despite continuing issues with erosion, not all spoil material was characterised. Once a 'recipe' was established for a site, it tended to be applied unless observation or new data indicated an alternative approach was required. Concepts of performance perception differed between respondents.

3.2 Field inspections

Inspection of historic dispersive spoil rehabilitation sites indicated that there was a preference for application of rock mulch with establishment of vegetation. The slope of constructed landforms varied from 10% up to angle-of-repose (33%), with most sites adopting 15-20%. Where topsoil had been placed over rock mulch or competent spoil, rilling was often observed down to the surface of the more competent layer.

Where rock mulch was not adopted, a higher likelihood of poor performance was evident, often requiring considerable remedial work. Failure of rehabilitation, resulting in gullying and tunnelling, appeared to be generally initiated by poor control of surface waters resulting in ponding of water. Tunnelling was observed where surface water was able to pond and seep into the soil.

The incorporation of ameliorants such as gypsum into dispersive material had not been completely successful through trials to date. Issues with the method of incorporation may explain this limited success, justifying further consideration of this approach.

3.3 Site data analysis

Analysis of field characteristics and spoil chemical data found a negative correlation between erosion severity and cations with higher levels of iconicity (Ca^{2+}, Fe^{3+}), plus silt. This indicates that amendment of dispersive spoil conditions, particularly low exchangeable calcium, is an important requirement to control erosion. This finding accords with a large body of literature (e.g., Rengasamy and Marchuck, 2011; Bennett *et al*., 2016) and underpins the importance of characterising spoil and applying targeted amendments based on the evidence of data (Spain and Hollingsworth, 2016).

3.4 Mechanistic framework

Review of the literature, industry survey, historic site remediation approaches and spoil chemical analysis identified the need for a mechanistic process model to: (i) provide a framework to assist understanding and evaluation of the varying site conditions, environmental factors and management practices influencing dispersive spoil performance; and (ii) to test hypotheses for dispersive spoil rehabilitation.

The Universal Soil Loss Equation (Wischmeier and Smith, 1962), developed to describe surface erosion in agricultural systems, was considered a useful base to accommodate most observations, with the inclusion of a factor to accommodate the ability of mine rehabilitation to influence slope shape (Sh), plus a factor to describe tunnelling influences (T). The resulting framework model is illustrated in Figure 1.

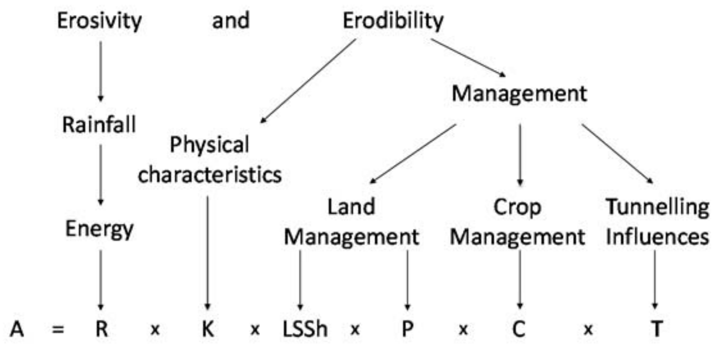

Figure 1 Modified format of the Universal Soil Loss Equation (USLE) incorporating slope shape and tunnelling influences

3.5 Bayesian model construction

The Bayesian network model was constructed using 'nature' (or 'chance') nodes which describe the potential empirical states exhibited by each component within the system. This incorporated the following groups of characteristics: (i) climatic conditions; (ii) inherent soil characteristics (physical, chemical, biological); (iii) landform characteristics; (iv) management practices to modify inherent soil characteristics and mitigate erosion; (v) vegetation management practices; and (vi) tunnelling initiation factors.

Links between variables were defined according to current mechanistic/process-based understanding to create a graphical representation of the system. The model was then spatially arranged as a number of pseudo 'sub-models', although these are not discrete, as interactions between individual variables in different sections of the model were accommodated (Figure 2).

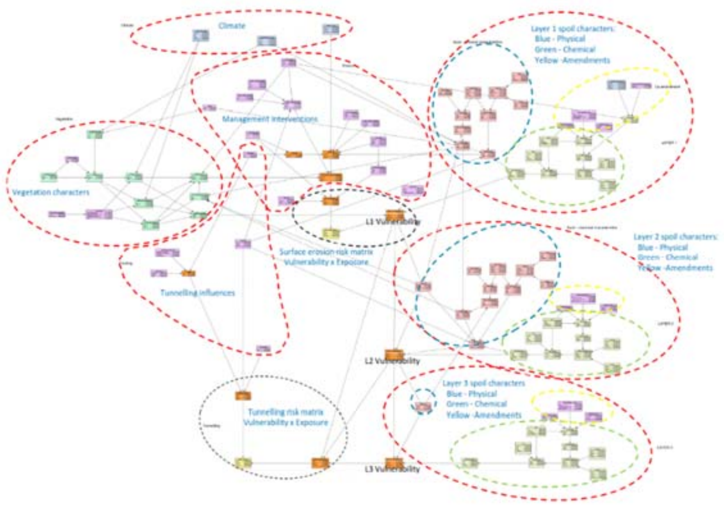

Figure 2 Dispersive spoil risk management Bayesian Network model

3.6 Model parameterisation

Conditional probability tables (CPTs) for each variable were parameterised using a combination of evidence from the literature, quantitative data (with probabilities defined by the frequency distribution of the data), observations from field observations, initial results from field trials, and expert opinion. The probability values applied represent the best initial estimate. For this reason, the network is a base working model which can be iteratively improved and refined over time with additional data collection and feedback from industry.

3.7 Model sensitivity analysis

Sensitivity analysis conducted for several key outputs indicated reasonable sensitivity to variables that would logically be expected to strongly influence the output in question (Figure 3). This confirms the model follows the programmed logic, but still requires independent validation. Greatest sensitivity is apparent to variables which are closely positioned within the current model structure, reinforcing the need to simplify the model by reducing the number of links wherever possible (as recommended by Pollino and Henderson, 2010).

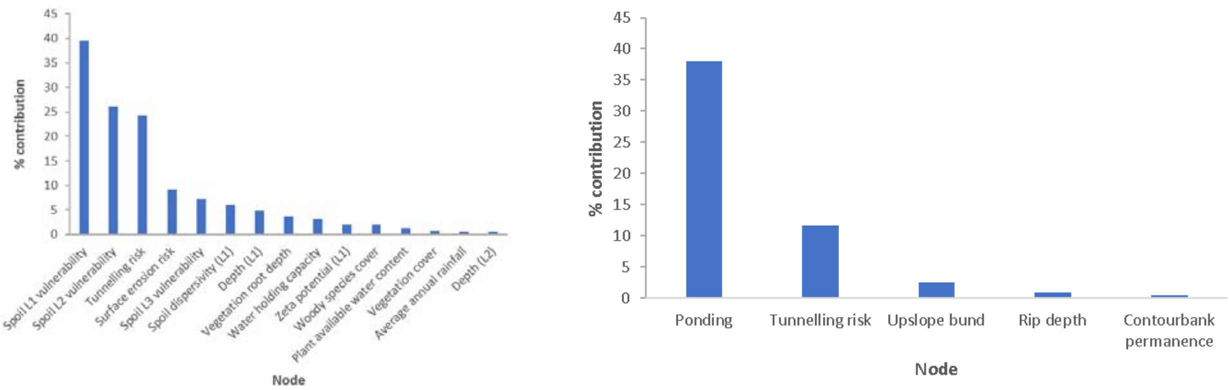

Figure 3 Sensitivity analysis result – (left) Profile vulnerability (nodes with >0.5% variance reduction values are presented; both preceding and subsequent nodes in the model are included); (right) Tunnel exposure (nodes with >0.5% variance reduction values are presented; both preceding and subsequent nodes in the model are included)

3.8 Field trials

3.8.1 German Creek

Rill and sheet erosion of varying severity were the most common types of erosion across all treatments. No gully erosion occurred under any treatment. Tunnel erosion was observed only under treatments 3 and 4 (i.e., non-rock mulch treatments on batter slopes). Both the severity of surface erosion (sheet and rill) and the occurrence of bare ground (excluding rock) was least in treatments 1 and 2 (rock mulch cover at 500mm and 250mm), and most in treatment 5 (topsoil, rip, seed, gypsum) (Figure 4).

The results superficially indicate that surface erosion severity decreased and vegetation cover increased as rehabilitation treatments were increasingly armoured. However, these results reflect the geotechnical influence of rock armouring on erosion and not the influence of vegetation. The trial was implemented as operational rehabilitation prior to commencement of the study. In the context of the mechanistic model, prior characterisation of gypsum requirement and plant nutritional deficiencies was not carried out. Soil analysis results indicate high ESP and severe nutrient deficiencies. Hence, poor vegetation establishment and more severe erosion are expected outcomes for the unarmoured treatment.

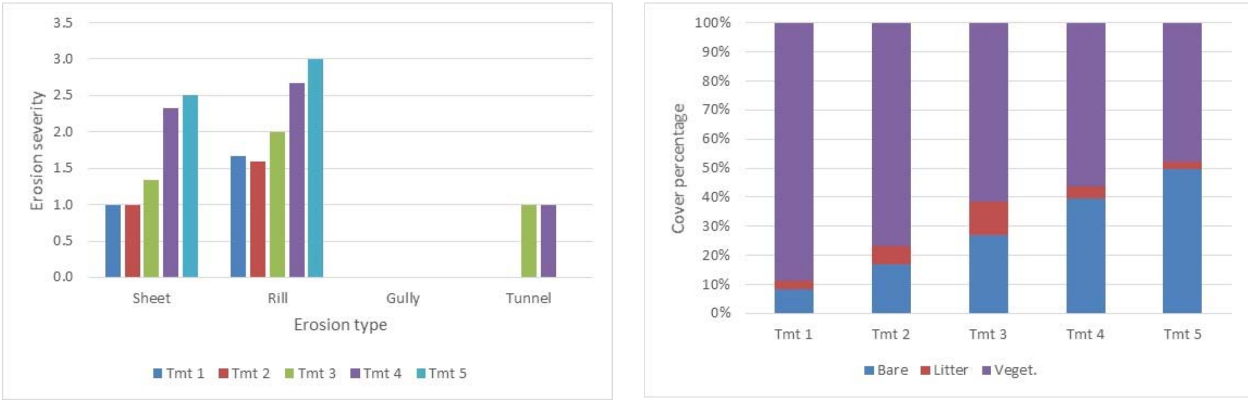

Figure 4 Left: Erosion type by severity by treatment at German Creek East mine: 0 = Nil; 1 = minor/present; 2 = moderate; 3 = severe; 4 = very severe. Right: Cover percentage excluding rock

3.8.2 Moranbah North

Pre-site assessment identified extremely dispersive spoil (mean ESP = 24.3% with samples up to 57.1%) with mass erosion and tunnel development (Figure 5 left). The soil also displayed severe nutritional deficiencies with limited organic matter. Photographic records of the site at 1, 4, 7, and 11 months post rehabilitation and spoil amendment to address both dispersive properties and nutritional deficiencies demonstrate progressive establishment of a uniform, perennial pasture cover with no obvious difference between treatments and no serious erosion development (Figure 5 right).

Figure 5 Left: Gully and tunnel erosion on Moranbah North spoil pile pre-treatment March 2016. Right: Stabilised mound with well-established body of grass post-treatment (March 2017)

The absence of serious erosion to date, even where bare soil is exposed, indicates the process of site characterisation followed by targeted treatments to address critical site limitations, in accordance with the proposed mechanistic framework has been successful in achieving site stability without the need for geotechnical-only approaches such as rock mulching.

The site has remained stable through the 2016/17 wet season, plus significant rainfall events in March 2017 (Cyclone Debbie – 122mm over 3 days) and May 2017 (45mm over 2 days), indicating that the package of treatments confers resilience.

4 Discussion

4.1 Mechanistic framework

The mechanistic model provided by the modified Universal Soil Loss Equation (USLE), has provided a useful conceptual basis for describing processes influencing erosion of dispersive mine spoil, and a valuable framework for construction of a Bayesian network model.

An important outcome of this mechanistic framework, despite the subsequent complexity built into the Bayesian network model, is that it provides a simple structure to inform practical management of dispersive spoil. The utility of the framework is demonstrated through comparison of the review of historic site remediation, considerations; well-established theory; and results from both the German Creek and Moranbah North field trials.

Both the industry survey and review of historic dispersive site rehabilitation demonstrated a strongly geo-technical focus on rehabilitation. In the context of the framework, rehabilitation focussed strongly on the land management parameters slope (S) and slope length (L), as well as on practice control factors (P) evidenced by techniques such as rock mulching and contour bank construction. Some sites also gave a level of consideration to tunnelling influences (T) by removing contours to avoid ponding once vegetation became established.

However, no prior rehabilitation inspected gave adequate consideration to physical characteristics (K) or crop management (C). This was evidenced by a general lack of spoil characterisation necessary to determine appropriate amendments to address dispersivity and plant nutritional requirements. While all sites attempted revegetation, success was variable, often due to severe macro and micro-nutrient limitations and virtual absence of soil organic matter. In only one historic rehabilitation site inspected was gypsum applied to adequately reduce sodicity despite this characteristic being the key differentiator between dispersive and non-dispersive spoil.

Application of the mechanistic model to design of rehabilitation treatments at the Moranbah North site indicates the utility of this framework. Spoil characterisation by chemical analysis to inform targeted treatment design addressing all factors in the modified USLE framework has delivered promising early results. Fifteen months after rehabilitation, during which period the site has experienced a number of significant rainfall events the site is well vegetated with stable spoil mounds.

Although requiring further validation, this result, contrasted with prior rehabilitation practices leading to poor performance outcomes, indicates that limitations across all factors of the mechanistic model must be addressed to reduce the risk of erosion and achieve a stable, post-mining landform.

4.2 Bayesian modelling

The ability to model and predict risks in complex dynamic ecosystems was, until relatively recently, limited due to difficulties in: (i) quantifying the causal relationships between multiple interacting factors and outcomes; and (ii) capturing uncertainty. Bayesian network tools - based on Bayes' theorem which describes the likelihood or probability of an event given prior knowledge of the conditions related to the event - are increasingly used to understand and manage such systems (Hart and Pollino, 2008; Pollino and Henderson, 2010; Troldborg *et al*., 2013).

Troldborg *et al* (2013) used a Bayesian network model to estimate the risk of soil compaction from agricultural operations. Their model followed a standard risk assessment approach, where the risk was quantified by combining assessments of vulnerability and exposure. In this instance, the soil's vulnerability to the threat of soil compaction was determined from inherent soil and site characteristics as well as from climatic factors influencing soil characteristics, while the exposure estimate was based on an evaluation of the stresses inflicted by land management and climate.

A similar approach was adopted in this study. In a risk management framework context, the six groups of factors contributing to the mechanistic model were grouped into two categories:

1. ***Exposure:*** Comprising exposure to erosive energy forces (cumulative rainfall, rainfall intensity, frequency, duration); and
2. ***Vulnerability:*** Comprising the combination of inherent soil erodibility (resistance/susceptibility to erosion) landform design and management practices that modify erodibility.

In this way, the model presents erosion risk as a matrix of exposure by vulnerability in a similar manner to the intersection between likelihood and consequence in a conventional risk assessment matrix (Table 1). Risk was expressed in the endpoints: 'surface erosion risk', and 'tunnelling risk'.

Table 1 Comparison of conventional risk matrix (left) and matrix for erosion of dispersive soils (right)

Consequ-ence / Likelihood	Minor	Severe	Catast-rophic	Vulnera-bility / Exposure	Low	Med-ium	High
High				High			
Medium				Moderate			
Rare				Limited			

Sensitivity testing demonstrated that the Bayesian model follows programmed logic, but it still requires independent validation across multiple sites. Scenario modelling results indicate that, for the most part, the model is operating logically. User feedback with targeted data collection and incorporation into the model is required to inform further refinement.

The process understanding captured in the Bayesian model provides a means for practitioners to adapt this understanding to any specific site, obviating the need for an empirical 'recipe' based approach to dispersive spoil rehabilitation.

4.3 Best management practices framework

Based on learnings from the study, a seven-step best management practices framework for rehabilitation of dispersive mine spoil was developed (Figure 6).

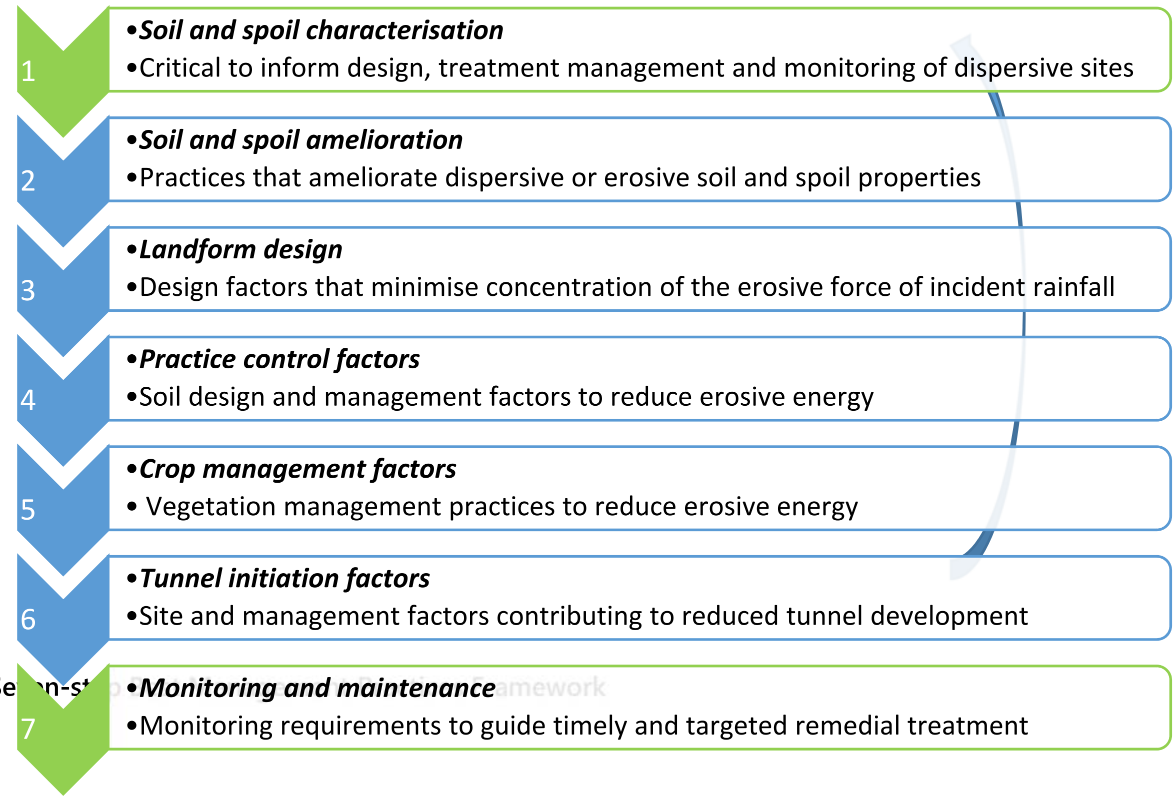

Figure 6 Seven-step Best Management Practices Framework

The framework comprises two monitoring and assessment steps (1 and 7) and five active design and practice steps (2 to 6). A critical element of this framework, arising from the findings of this study, is that all steps must be addressed to reduce the risk of erosion. Failure to address an issue in any step that contributes a significant proportion of soil loss will likely result in potential rehabilitation failure.

The BMP framework provides a basis for both capturing the mechanistic model developed in this study and for implementing the more complex Bayesian model and making sense of model outputs in terms of rehabilitated slope performance risk.

5 Conclusion

Use of a framework founded on an expanded form of the Universal Soil Loss Equation, combined with adoption of a Bayesian modelling approach, has enabled assimilation of disparate data sources from established literature, expert opinion, field observations, field assessment and preliminary results from field trials to develop an initial, risk-based framework that provides a process-based understanding of the behaviour and management of dispersive spoil on mine-sites. This has informed a set of Best Management Practices based on site characterisation, addressing each factor of the mechanistic model, followed by monitoring and targeted, timely maintenance.

From a practical perspective, by encouraging characterisation of inherent site properties as the basis for informed decision making, and a methodical, process-based approach to dispersive spoil treatment and rehabilitation design, the mechanistic framework and associated model have potential to increase industry understanding of the behaviour of dispersive spoil materials, and enhance capacity to address this industry challenge.

Notwithstanding the findings of this study, successful rehabilitation using both reduced depth of rock mulch in combination with soil amelioration, and comprehensive site characterisation with targeted spoil and soil amelioration guided by a process-based framework, has only been demonstrated on two sites. Further work should aim to operationalise the findings of this study, with quantitative monitoring of rehabilitation performance to inform model improvements.

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Integrated Design-Build to Rehabilitate Tailings and Crown Pillars at a Decommissioned Uranium Mine Site

M Gunsinger *Golder, Canada*

A Auckland *Golder, Canada*

K De Vos *Golder, Canada*

S Longo *Golder, Canada*

J Taylor *Golder, Canada*

Abstract

During the late 1950's to early 1980's, historic operations at a former uranium mine site in Canada has resulted in an extensive network of underground workings that includes mine openings to surface and near-surface stopes. The mining and milling operations at the site produced about 5 million tonnes of tailings, which were deposited into two Tailings Management Areas (TMAs). In the 1980's, the site was rehabilitated to the standards of the day, which included demolition of the mine and mill infrastructure, at-surface concrete capping of the shafts and raises, and barricading the adits with bulkheads. The TMAs were rehabilitated by placement of a simple soil cover over the tailings, which consisted of a single, 0.3 to 0.5 m thick layer of sand and gravel.

Since 2010, the past decommissioning efforts have been evaluated through a risk review process, which consisted of environmental and geotechnical investigations, ecological and human health risk assessments, and comparison of previous closure measures relative to current regulatory standards. The review also considered the overall closure objective for the site, which is to have to the extent practical no ongoing detrimental effects to the public, the environment, and adjacent lands. The review was completed by 2013 and concluded that the site required further rehabilitation to meet the current regulatory standards. The TMAs were identified as needing upgrading, including drainage improvements and a new cover system. Furthermore, seven near-surface stopes were determined to have crown pillars considered not long-term stable and therefore required rehabilitation.

To upgrade the closure measures at the site, a design-build project was initiated in 2013 and an ongoing multi-year construction project was initiated in 2015. The soil cover over the TMAs is currently being upgraded by constructing a multi-layer sand-gravel-bentonite (SGB) cover system to control radon emissions, promote runoff, and decrease the rate of infiltration into the tailings. The crown pillars considered not long-term stable are being rehabilitated by backfilling the associated near-surface stopes with a cemented paste backfill produced from tailings excavated from the TMAs. Because the paste backfill is using tailings as feedstock, an integrated approach to the rehabilitation of the TMAs and crown pillars was required to source tailings that meet the paste backfill specifications while minimizing material movement effort. Furthermore, the construction planning needed to consider an integrated sequencing of the TMA and crown pillar rehabilitation work over a multi-year period.

This paper provides an overview of the rehabilitation work that has been completed to date and discusses the integrated design-build approach to rehabilitate the TMAs and crown pillars.

Keywords: *uranium tailings, covers, paste backfill, design-build, integrated closure, crown pillar rehabilitation*

1 Introduction

Mine closure projects that integrate the environmental, engineering, and construction execution aspects early in the design and planning process better position the project for successful implementation and performance over the long term. Open engagement across multiple disciplines allows for the project to develop practical and innovative solutions that align with the closure objectives for the site. While applying an integrated approach to mine closure is not a new idea, the mining industry often faces difficulties associated with Asset Retirement Obligation (ARO) planning (e.g., schedule delays and inaccurate cost estimating) due to poor communication and inadequate consideration of environmental drivers, permitting requirements, engineering challenges, and constructability issues. Furthermore, poor integration across disciplines can lead to missed opportunities for multi-faceted approaches and synergies between closure designs for various site components.

The case study presented in this paper is a multi-year, integrated design-build project to rehabilitate the Tailings Management Areas (TMAs) and near surface stopes with associated crown pillars considered not long-term stable at a former uranium mine site located in Ontario, Canada. Although the TMAs and crown pillars are separate features of the site that require rehabilitation, several components of the project required careful planning and close integration between the environmental, engineering, and construction teams. These aspects included health and safety planning, satisfying environmental drivers, permitting, constructability challenges, material sourcing, water supply, logistics and execution planning, and implementation. In the case of this project, the design-build approach provided added value due to the high degree of integration between the environmental, engineering, and construction teams.

2 Background

2.1 Mine Operations History

Historical operations at the site extracted uranium ore from the underground mine that targeted pegmatite dykes. Mining and milling of uranium ore occurred on the mine site during two separate periods: 1957 to 1964 and 1976 to 1982. The underground mining resulted in the development of an extensive network of underground workings, including numerous shafts, raises, near-surface stopes, and a stope extending to surface (glory hole). The uranium ore was transported to surface where it was milled and concentrated on-site to produce yellowcake. Uranium ore beneficiation consisted of crushing, grinding, leaching, filtration and hydrometallurgical processes with a milling capacity of about 750 tonnes per operating day. Approximately 5 million tonnes of tailings were generated as part of the uranium ore milling and processing, which are stored in two TMAs, referred to as TMA-1 and TMA-2. The uranium tailings contain radionuclides by virtue of the ore processing methods, including uranium progeny, and therefore are considered to be high volume, low-level radioactive wastes.

Mining operations ceased permanently in 1982 at which time decommissioning activities were initiated and consisted of demolition of buildings and infrastructure, securing mine openings to surface, establishment of vegetation in areas previously disturbed, and covering and vegetation of surfaces of TMA-1 and TMA-2. By the end of the 1980's, the site decommissioning activities were complete and the site was rehabilitated to the standards of the day. Site maintenance and monitoring work was started once the decommissioning work was completed, which continued into the 1990's and 2000's.

2.2 Site Characterization Studies and Risk Review Process

During the mid- to late-2000's, the performance of the past decommissioning work was evaluated through a series of site characterization studies. These studies were conducted by professionals from various disciplines and included geotechnical investigations of the TMAs, geomechanical investigations of the mine openings to surface and crown pillars, comprehensive environmental investigations, and ecological and human health risk assessments. Since 2010, the past decommissioning efforts have been evaluated through an overall risk review process that considered the collective information gathered as part of the comprehensive investigation work. The review also considered the overall closure objective for the site, which is to have no ongoing detrimental effects to the public, the environment, and adjacent lands. The review was completed by 2013 and concluded that certain aspects of the site required upgrading and further rehabilitation to meet the current regulatory standards. The TMAs were identified as needing upgrading, including improvements to water management and a new cover system. Furthermore, seven near-surface stopes were determined to have unstable crown pillars considered not long-term stable and therefore required rehabilitation; the crown pillars are being rehabilitated through a paste backfill program.

3 Rehabilitation Design Objectives

The overall objective for the site is to ensure that it is closed and managed in such a way that the legacy mining and milling operations have to the extent practical no ongoing detrimental impact to the public, the environment and adjacent lands. In addition, the site needs to satisfy the current mine rehabilitation regulatory standards and the regulations associated with the management of low-level radioactive wastes. As part of the development of the conceptual design for the aspects of the site that require upgrading, a series of design objectives were defined to guide the detailed design process.

A summary of the rehabilitation design objectives for the TMAs are as follows:

- Reduce radon flux from TMAs such that the radon concentrations in the air are reduced to meet the Radiation Protection Regulation for non-nuclear energy worker dose limits and/or As Low as Reasonably Achievable (ALARA) principles.
- Physical stability of the TMAs are maintained or improved such that the TMA dams continue to meet regulated stability requirements, the final landform is stable against expected erosive forces, and positive drainage conditions are developed that mitigate the potential for overtopping of dams and the potential for ponding of water on the TMA surface.
- Chemical stability of the TMAs is maintained or improved over the longer term, noting that the risk assessments for the site have indicated that the water quality under current conditions is not a significant risk with respect to ecological or human health.
- Remediated landform should be aesthetically pleasing and assimilate into the surrounding environment to the extent practicable, including encouraging stable vegetation growth at the TMA surface that does not affect the performance of the soil cover.
- Engineering design should perform as intended and be durable/robust when exposed to a range of conditions (e.g., freeze/thaw cycles and wet/dry seasons) over the longer term and provide for limited maintenance and monitoring requirements after construction.
- Engineering design should not be overly complicated, it should be constructible using established equipment and construction techniques, and it should be flexible and able to accommodate unexpected field conditions without major design revisions.

In addition, the rehabilitation design objectives for the seven near-surface stopes with crown pillars considered not long-term stable and associated mine openings to surface is as follows:

- Maintain public safety by mitigating the hazards associated with the mine openings to surface and mitigating the potential for crown pillar failure.

4 Tailings Management Area Rehabilitation

There are two tailings areas, TMA-2 is located to the southeast, and at a lower elevation than TMA-1. The detailed design for TMA-2 was completed in 2014-2015 and construction was completed over a multi-year period between 2015 and 2017. The detailed design of TMA-1 was completed in 2017, which was followed by the start of construction also in 2017. Currently, there are two stockpiles of tailings located on TMA-1 for paste backfill feedstock (see discussion in Section 5.2), which need to be removed prior to continuing TMA-1 cover construction. The paste backfill program is currently planned for 2018 and part of 2019; after which, the TMA-1 construction is expected to continue during the latter half of 2019.

The rehabilitation design of the TMAs consists of modifying the surface grades of the TMAs to improve drainage and reduce erosion potential, installing a new drainage management system, and construction of a new soil cover to control the release of radon gas and decrease the amount of infiltration into the tailings. Summaries of the grading, drainage channel, and soil cover profile designs, and also the cover construction methodology, are provided below. For the purposes of this paper, the discussion is focused on TMA-2. The same general design-build approach for TMA-2 will continue to be applied for the rehabilitation design of TMA-1.

4.1 Grading and Drainage Channels

The surface of TMA-2 was re-graded to achieve the desired final topography and drainage pattern prior to the placement of the multi-layer soil cover system. The excavation of tailings included cutting in a main drainage channel and a series of swales that collect and convey runoff from the surface of the TMA to the main drainage channel. The cut-to-fill balance was designed such that about 73,000 m^3 of the tailings were transported to and stockpiled on TMA-1 for future use as feedstock for the paste backfill program. The remaining excavated tailings were placed within TMA-2 as fill to achieve the desired final topography.

The grading plan objectives include:

- Provide for the long-term physical stability of the cover against erosion.
- Maintain or improve the physical stability of the tailings dams.
- Provide positive drainage conditions that mitigate the potential for overtopping of dams and the potential for ponding of water on the cover.
- Provide capacity and erosion protection to withstand flows from applicable design storm events without failure.

The surface of TMA-2 was graded towards three drainage swales and a main central drainage channel, which are armoured with erosion protection (i.e., rip rap) and convey drainage out of the TMA footprint (Figure 1). The central drainage channel has a longitudinal slope of about 0.3%, a 3 to 4 m bottom width and side slopes of 4(H):1(V) or flatter. A secondary drainage system, comprised of ridges and three drainage swales, was constructed upstream of the central drainage channel within TMA-2. This secondary drainage system controls runoff over the cover surface by directing it to an armoured swale or channel over a short distance, thereby reducing the potential for rill and gully erosion by keeping watershed areas contributing to the swales/channels small and by limiting non-channelized overland flow to a maximum flow path length of 100 m. The three drainage swales have longitudinal slopes between 3.5% and 2.5% and with adjacent ridge side slopes graded at approximately 10H:1V. The surface slopes above the drainage channel and swales will range from 1% to 10%. The central drainage channel outlet has been sized to safely route a design storm event equal to a 1,000-year return period flood.

4.2 Soil Cover System

As part of the risk review process for the site, it was determined that the cover system over the TMAs needed to be upgraded to decrease the radon flux from the TMAs. The cover system concept that was designed and built to mitigate the release of radon gas is a sand-gravel-bentonite (SGB) cover system. This soil cover system consists of multiple layers with a 0.4 m thick performance (bottom) layer consisting of SGB material and a 1 m thick protective (top) layer consisting of granular material. The top granular layer protects the SGB performance layer from the potential damaging effects of freeze/thaw and wetting/drying cycles.

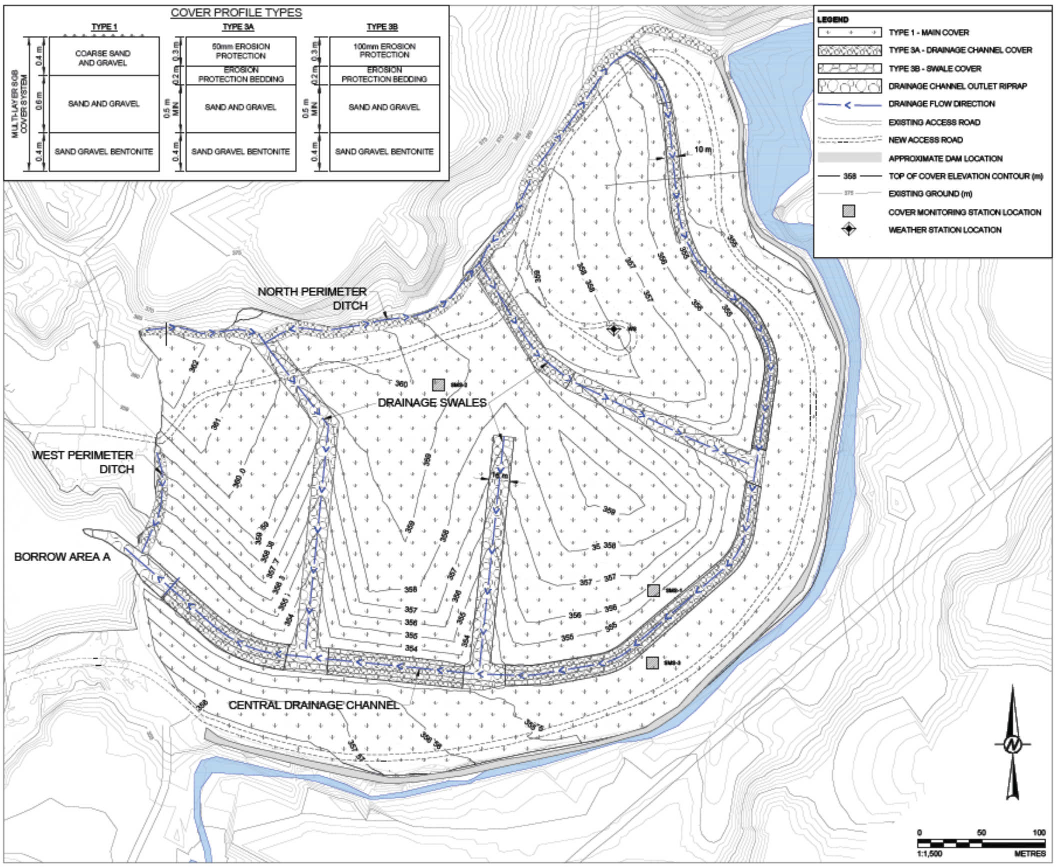

Figure 1 TMA-2 rehabilitation multi-layer soil cover plan

The overall depth profile of the SGB cover system reduces radon release from the tailings through increasing the length of the radon gas flow pathways. Radon gas exhaled from the tailings particles must travel through the network of pore spaces in the cover prior to atmospheric release. As the radon travels through the subsurface pore network, the radon in part decays into its progeny due to its relatively short half-life of 3.8 days. When radon decays into its progeny, it partitions from the gas phase into a solid phase through adsorption onto the soil particles. By increasing the length of the transport pathways between the source term and the atmosphere and/or increasing the tortuosity of the transport pathways, the cover system increases the residence time of the radon gas in the subsurface and allows for further decay of radon into its progeny prior to atmospheric release.

More importantly, the SGB performance layer reduces radon release by maintaining a high degree of saturation. The addition of bentonite to the sand/gravel material creates an SGB material that has enhanced water retention and low permeability characteristics. The bentonite in the SGB material hydrates upon exposure to water, which results in the bentonite swelling and filling void space between soil particles. The diffusion coefficient of radon has an inverse relationship with the degree of water saturation in a soil. Therefore, retaining a high degree of water saturation considerably reduces the radon diffusion coefficient, and therefore rate of radon migration through the cover system, by about two to three orders of magnitude. The granular protective layer above the SGB assists in maintaining a high degree of saturation in the SGB by significantly reducing evaporative losses.

4.3 TMA-2 Cover Construction

The construction of the TMA-2 rehabilitation design was completed over a three year period from 2015 to 2017. Drone images showing the year-to-year progress of the rehabilitation work are shown in Figure 2. In 2015, the construction started with clearing and grubbing the TMA surface to remove trees and other vegetation. Once the vegetation was removed, the existing granular cover materials were stripped, placed and compacted as fill underneath the new cover system. The bulk excavation activities were advanced in phases during each of the three years of construction to cut in the central drainage channel and three drainage swales. Some of the excavated tailings and existing cover materials were placed as compacted fill into the ridges to assist with building the drainage swales and achieve the overall subgrade surface shape. Tailings with suitable characteristics that were excavated from TMA-2 were hauled to TMA-1 and stockpiled for future use as part of the paste backfill program (Figure 3a,b). The construction of the SGB cover system also advanced using a phased approach and followed the excavation activities in areas where the subgrade was approved for cover placement.

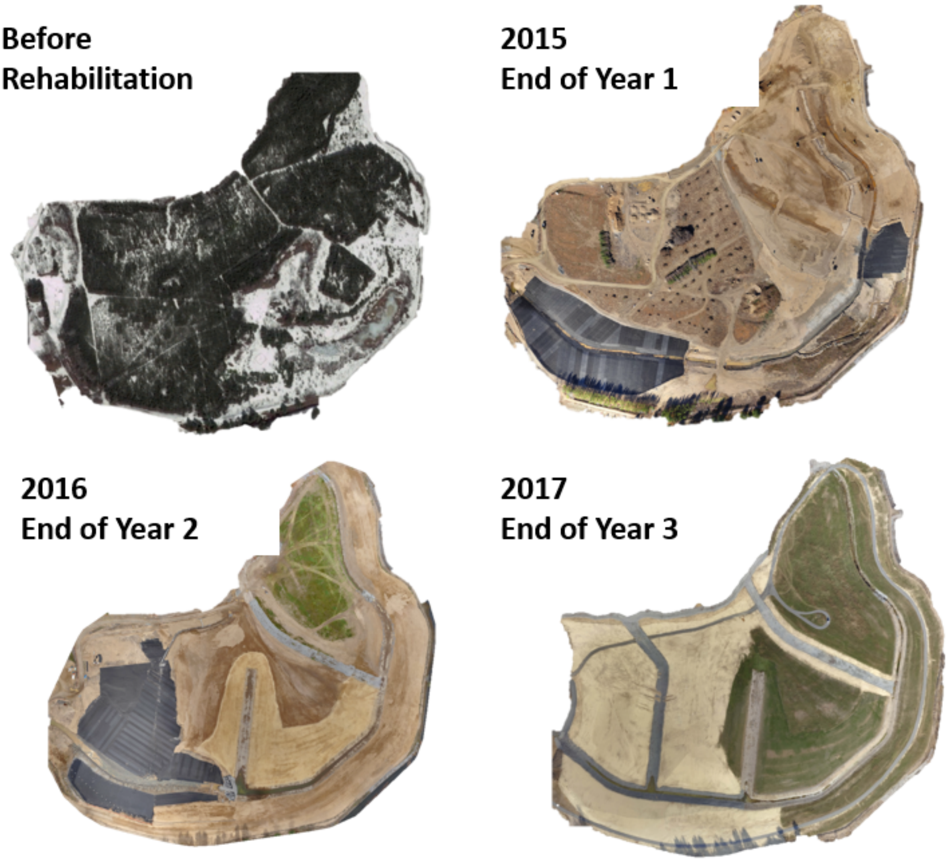

Figure 2 Aerial imagery showing the advancement of the TMA-2 rehabilitation work

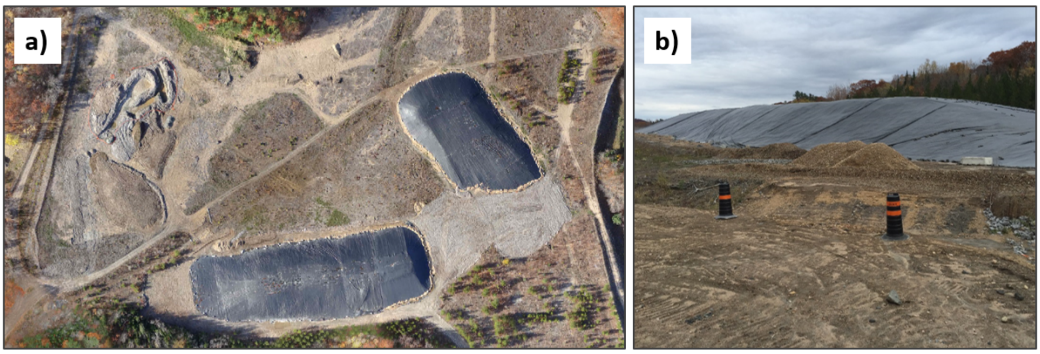

Figure 3 Photos showing the tailings stockpiles on TMA-1; a) drone image showing overhead photo; b) photo of side profile of a tailings stockpile

The SGB material was produced by mixing bentonite with granular materials that were sourced from borrow areas located within the site property boundaries. The granular materials were screened and stockpiled within the borrow areas and then hauled to the mixing operation to produce the SGB materials. Bentonite was sourced from commercial suppliers and imported into the site in 1 m^3 totes and was blended into the granular materials by using mechanical mixing equipment (i.e., pug mill) (Figure 4a,b). The SGB material was hauled to areas of TMA-2 where the subgrade had been approved and placed/compacted in two 0.2 m lifts in accordance to the technical specifications (Figure 4c). Once the 0.4 m SGB layer was constructed in an area, a layer of granular material was then placed and compacted over the SGB layer in three lifts to achieve a total thickness of 1 m. GPS-guided dozers were programed with the design grades and were used to shape the subgrade, and top surface of each of the cover layers. The GPS-guided system provided superior grading control and accurate construction of the drainage system (Figure 4d).

Figure 4 Photos showing the cover material construction methodology: a) overview of pugmill mixing equipment and stacker creating a daily stockpile of SGB material; b) close-up of the hopper and pugmill mixing equipment; c) spreading and compacting SGB material; d) spreading erosion protection within a drainage swale using a GPS-guided dozer

5 Crown Pillar and Stope Rehabilitation

5.1 Paste Backfill Rehabilitation Concept

Stability assessments indicated that seven stopes have associated crown pillars with a likely failure mechanism related to gradual degradation and unravelling of the crown pillar over longer periods of time (>50 years). The current void space that exists directly below these crown pillars is such that a gradual unravelling failure would result in a surface impact (i.e., failure of crown pillar to surface) rather than a sudden crown pillar failure (i.e., plug failure). The rehabilitation option selected for these near-surface crown pillars is to reduce the void space below the crown pillar by backfilling the underground stope voids. Since the void space below the near-surface crown pillars is connected to other lateral/vertical mine workings, a cemented backfill will be required in order to minimize the risk of long-term movement of this fill material. There is a glory hole associated with one of the stopes that requires rehabilitation; the glory hole will also be backfilled with paste. The most readily available and suitable raw material for making bulk void filling material is onsite-stored tailings. The tailings material will be used for the majority of the void backfilling material in the form of lightly cemented paste tailings. The paste tailings will be made from a mixture of tailings, water, and binder material (i.e., cement). When first mixed, the paste tailings are designed to be a high viscosity, flowable material that is suitable for filling inaccessible void spaces far from the insertion point. After the cement cures, the paste tailings becomes solid and provides the necessary strength to mitigate the potential hazards associated with the crown pillar over the longer term.

Fill barricades will be placed in areas where the stope connects with the greater underground workings to prevent the paste backfill from flowing where it is not required prior to the cement curing. In all cases, the fill barricades need to be placed in areas where human entry is not possible due to a lack of underground access. Therefore, a low-slump paste tailings/aggregate fill barricade will be placed through boreholes from surface to constrain the high slump bulk fill material and keep it where it is needed until it solidifies. The bulk paste backfill will also be placed through gravity placement or pumping through boreholes.

Expanding foam will also be used to assist with the construction of the fill barricades. The use of expanding foam is expected to be limited to special circumstances where connections to the underground workings pose challenges for the set-up of low-slump paste barricades. An example of this is where there are vertical raises that connect the stope to other stopes (or workings) further underground; these areas would be difficult to close using only the low-slump material alone. The foam, however, is to be used only as an initial means of creating a form work for placing low-slump paste over the form to create a bulkhead with appropriate strength.

5.2 Paste Feedstock

The most significant synergistic aspect between the TMA and stope rehabilitation work is the sourcing of tailings for the purposes of paste feedstock. A coordinated effort was required between the tailings geotechnical engineers and the paste engineers to identify areas within the TMAs that contain suitable tailings for paste feedstock. The tailings for paste feedstock need to meet specific grain size and moisture content requirements, which can be a challenge given that the properties of the tailings at the site vary considerably. From the TMA rehabilitation perspective, the desire is to minimize the amount of material movement effort needed to attain the final design surface of the tailings subgrade. As such, design adjustments were made, where appropriate, to increase excavation areas (e.g., central drainage channel and swales) where tailings were identified to be suitable for paste feedstock. Furthermore, the cut-to-fill in the TMAs was designed to be flexible to allow for the quantity of fill placed in the TMAs to vary. In particular, the cut-to-fill design allows the volume to be reduced, as needed, to account for the 'loss' of tailings that would be used as paste backfill. During the construction of TMA-2, careful monitoring and approval of tailings for stockpiling was needed as the physical characteristics of the tailings varied as the excavation program advanced. This was particularly the case for the excavation of the central drainage channel, where the tailings became finer at the upstream end of the channel (Figure 5a,b,c).

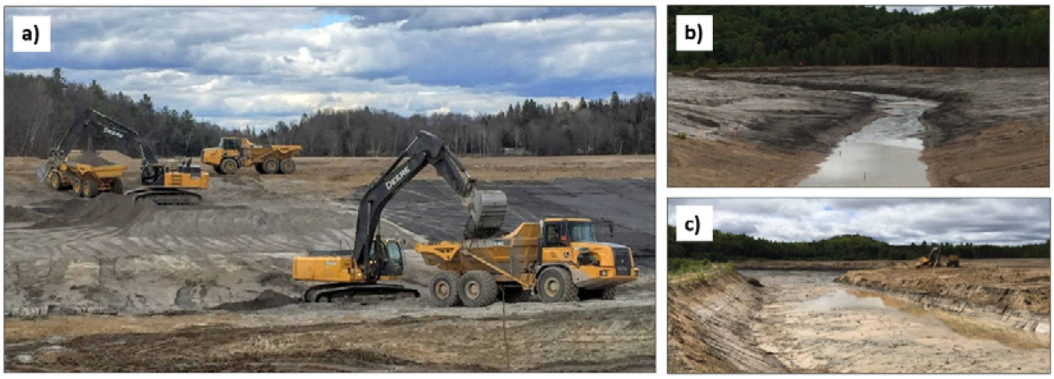

Figure 5 Photos showing the central drainage channel excavation: a) tailings for paste feedstock being loaded into rock trucks for hauling to the TMA-1 stockpiles; b) downstream section of the excavated central drainage channel where tailings grain size is relatively coarse; c) upstream section of the excavated drainage channel where the tailings grain size is relatively fine

5.3 Paste Backfill Construction Planning

The paste backfill program is currently planned to start in 2018 and backfill six of the seven stopes. The remaining stope will be backfilled in 2019. A figure showing an example of one of the subsurface stopes and the associated paste production site is presented in Figure 5a,b.

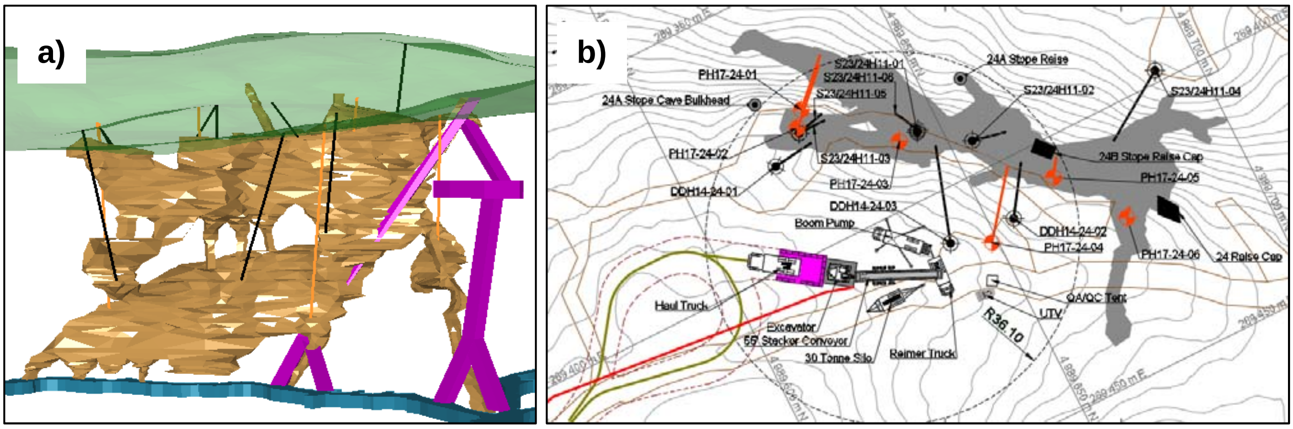

Figure 6 **Typical Stope Area: a) Longitudinal view of stope; b) Surface plan of paste production site**

As discussed in Sections 4.3 and 5.2, and as shown in Figure 3a,b, tailings for use in the paste backfill are stored in two stockpiles located in TMA-1. One stockpile consists of mostly coarse tailings and the other of mostly finer tailings. Prior to the start of the paste backfill production work later in 2018, the coarse and fine tailings stockpiles will be uncovered and set-up for use. The two tailings stockpiles will be put through a screening plant to remove oversize debris, including organics and large clay slabs. Blending of the fines and coarse tailings stockpiles will be required to achieve a particle size distribution within a specified range for paste backfill production. The blending system will be set up on TMA-1, and will be completed in conjunction with the screening process. The target ratio is expected to be near 3:1 coarse to fine; this target can be optimized depending on the observed performance during placement of the backfill.

A production site has been prepared at (or near) each of the stope to be rehabilitated. Prepared tailings feedstock will be loaded into rock trucks and hauled to the paste production sites. The tailings feedstock will be placed into daily stockpiles at the production sites. Binder will be sourced from a commercial supplier and stored in a 100 tonne cement powder storage silo. The binder will be delivered to the production site where is will transferred into a 30 tonne portable silo, which will be positioned next to the mixer truck. The tailings and binder will loaded into the mixer trucks along with water, as required, to achieve the desired paste recipe. At full operation, it is estimate that an average of 900 m^3 of paste backfill will be produced per day when two plants are in operation.

6 Conclusions - Integrated Design-build Approach

The integrated design-build approach that is being implemented to rehabilitate the TMAs and crown pillars is providing added value to this project. The key example of this is related to the use of tailings as feedstock, where a plan is in the process of being executed to source tailings from the TMAs that meets the paste backfill specifications. The sourcing of materials needed to consider the rehabilitation design for the TMAs, including minimizing material movement and TMA subgrade preparation efforts. Other examples where there is added value due to design-build approach is the development and execution of the health and safety plan, incorporating permitting and environmental drivers into the design, constructability challenges, water supply logistics, and overall execution planning.

In the case of this project, the design-build approach has led to a more efficient transition from the design phase to the implementation phase due to efficient communication of information and resource sharing between disciplines, early identification of potential constructability and environmental issues, and upfront incorporation of the permitting constraints into the overall project schedule. Furthermore, resolution of conflicts and/or decision making associated with challenges encountered in the field due to unforeseen field conditions is completed in a timely manner. This is in part due to the development of solutions that are practical and flexible to change and the incorporation of contractor input into the design during the early stages of the project.

5. Mine flooding, balancing of groundwater deficits and pit lakes

Long-Term Effects after Closure of Hard Coal Mines, The Netherlands

A Biesheuvel *Witteveen + Bos, The Netherlands*

FJR Denys *Ministry of Economic Affairs and Climate Policy, The Netherlands*

M Heitfeld *Ingenieurbüro Heitfeld-Schetelig GmbH, Germany*

P Rosner *Ingenieurbüro Heitfeld-Schetelig GmbH, Germany*

JH Spaans *Witteveen + Bos, The Netherlands*

FG Versteegen *Witteveen + Bos, The Netherlands*

Abstract

Commissioned by the Ministry of Economic Affairs and Climate Policy, a Dutch/German project group has carried out a study on long-term effects of closure of hard coal mines in the Netherlands.

In the southern part of the Netherlands and in adjacent areas in Germany, coal mining took place until the 1970s. Large abstraction of groundwater in the Carboniferous coal seams provided dry working conditions in the mines. Since several decades, these abstractions have been terminated and subsequently the mine water level has risen. The rise of the mine water has still not finished. A study was carried out to identify the potential risks of the long-term-effects and proposals were made for monitoring ground movement, mine shafts, groundwater quality, groundwater quantity, and mine gas. An integrated risk analysis was conducted and concepts for necessary measures and monitoring were developed. The risk of mine water rise for shallow groundwater levels was evaluated with groundwater models and the effects on groundwater quality were evaluated using a hydrogeochemical model and a solute transport model. Secondary effects of changes in groundwater levels on housing, infrastructure and nature were evaluated.

The results of the study have been published end of 2016. Subsequently an expertise centre is being set up in the Province of Limburg and monitoring systems for the effects of rising mine water on groundwater quantity and groundwater quality in the relevant groundwater bodies are being implemented. A programme for the remediation of historical shafts has been implemented by the municipality of Kerkrade. The present paper gives an overview of the results of the research project and the progress made concerning the implementation of recommendations.

Keywords: *mine closure, rising mine water, long-term effects, groundwater model, monitoring, risk analysis*

1 Introduction

In 2014 IHS (D) was assigned to conduct a systematic and comprehensive study that assesses all future safety relevant long-term effects related to hard coal mining in South Limburg (NL) and shows necessary measures. Under the lead of IHS the comprising scope of work was executed by a consortium consisting of Witteveen+Bos (NL), AHU (D), TU Delft (NL), GeoControl (NL), DMT (D) - Projectgroup "Na-ijlende gevolgen van de steenkolenwinning in Zuid-Limburg" (projectgroup GS-ZL).

An inducement for the study was the growing public concern about potential damage related to mining as well as a spectacular sinkhole incident in Heerlen in 2011.

Based on an extensive archive research, all relevant mining documents have been compiled and digitised (i.e. mine maps, documents on shafts, data on the pumping of mine water), hydrogeological data has been compiled (geological model, groundwater data), and a groundwater model has been set up.

The outcome of the comprehensive study is a risk and measurement plan for both capturing and dealing with future risks. In December 2016, the comprehensive study has been published and the recommended measures have been initiated.

2 Geology and mining in the project area

The South Limburg hard coal mining district is located in the province of Limburg in the south eastern part of the Netherlands. To the east it is directly adjacent to the German Aachen hard coal mining district; the Belgian "Kempens-Mijngebied" is adjacent to the west. All three hard coal mining districts are part of a coherent Subvariscan hard coal belt in the north of the Eifel and the Brabant Massif. Starting from the Dutch/German border region near the cities of Kerkrade (NL) and Herzogenrath (D), the former Dutch mining region extends about 30 km to the northwest to the Meuse; in SW-NE direction the mean extension of the district is about 12 km (Figure 1). The city of Heerlen is located in the centre of this district.

In the south eastern border region (city of Kerkrade), the tightly folded hard coal bearing strata crops out beneath a thin overburden. There, first hard coal mining activity took place in the 12th century. The historic mining activity spread over an area of about 2 km² under the (today) densely populated urban area of Kerkrade. To the northwest, the hard coal bearing strata submerges under an overburden of increasing thickness. At the Meuse, the overburden attains a thickness of about 400 m. Outside of the historical mining area, deep mining activity started in the end of the 19th century for the most part.

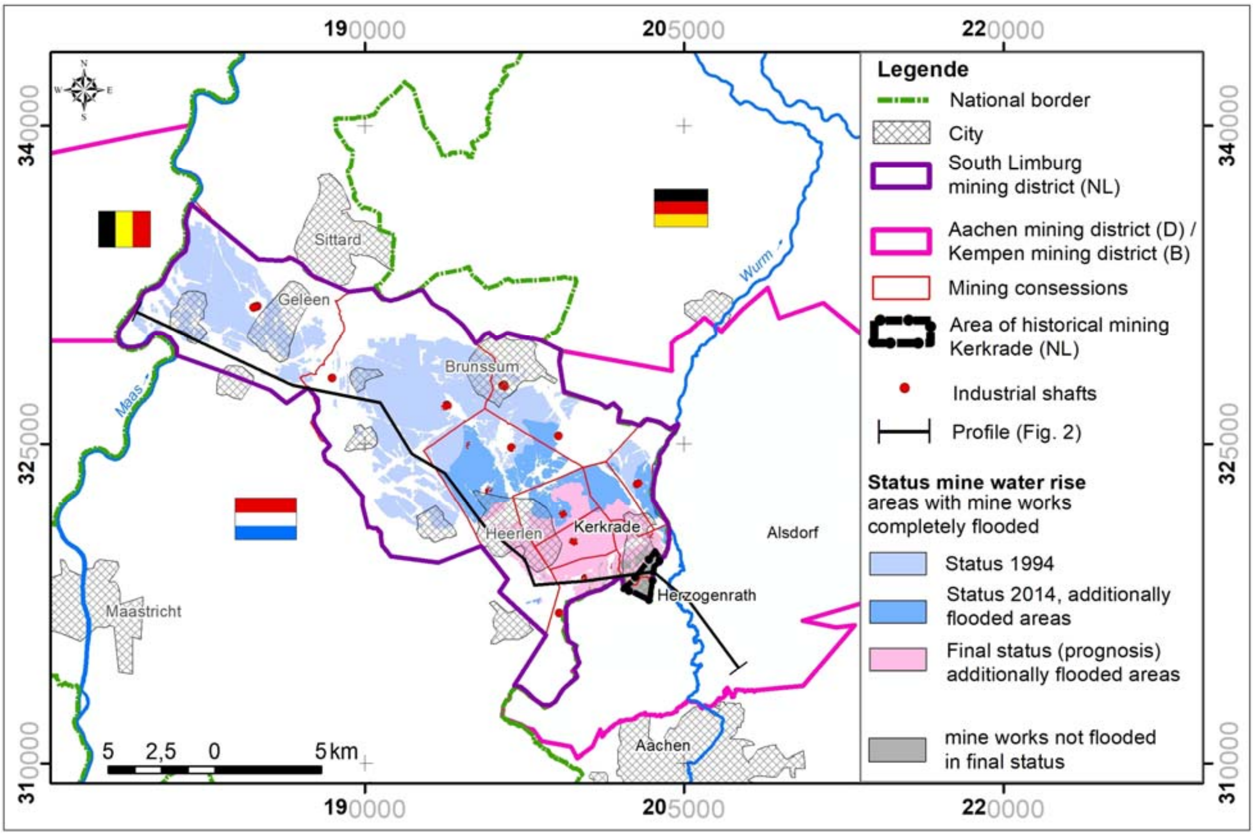

Figure 1 Mining area of the South Limburg mining district with different flooding scenarios

The South Limburg mining district is located in the transition zone between the Limburg Chalk platform and the Tertiary subsidence trough of the Lower Rhine Embayment. In this area, the bedrock subsides successively toward the Lower Rhine Embayment at two NW-SE striking tectonic main faults (Heerlerheide fault and Feldbiß fault). In the south western part of the mining district, the overburden features Cretaceous sand-/silt and limestone deposits; in the north eastern part Tertiary sediments are predominant (Figure 2).

The mine workings of the different coal mining concessions are spreading across the whole mining district. In dependence of the in-situ situation a maximum mining level of approximately -800 mNAP was reached. In the main areas of mining activity, the cumulated mined thickness attained about 15 m. As a result of this, mining related subsidence of 10 to 15 m occurred. Active near-surface drainage measures were not necessary in areas of mining subsidence of the South Limburg mining district due to the morphological conditions.

The mines of the South Limburg mining district were interconnected during the whole operational phase. However, water intake to the individual mines varied widely; in many places, strong influxes of overburden groundwater occurred. Hence, the hydraulic heads in the basal overburden aquifers were reduced. In the last operational phase, mine pumping rates for dewatering the whole mining district were about 48 m³/min. In general, mine water was comparatively low mineralised. For the most part, the pumped water featured chloride concentrations between approximately 100 and 3,000 mg/l (c.f. Rosner, 2011).

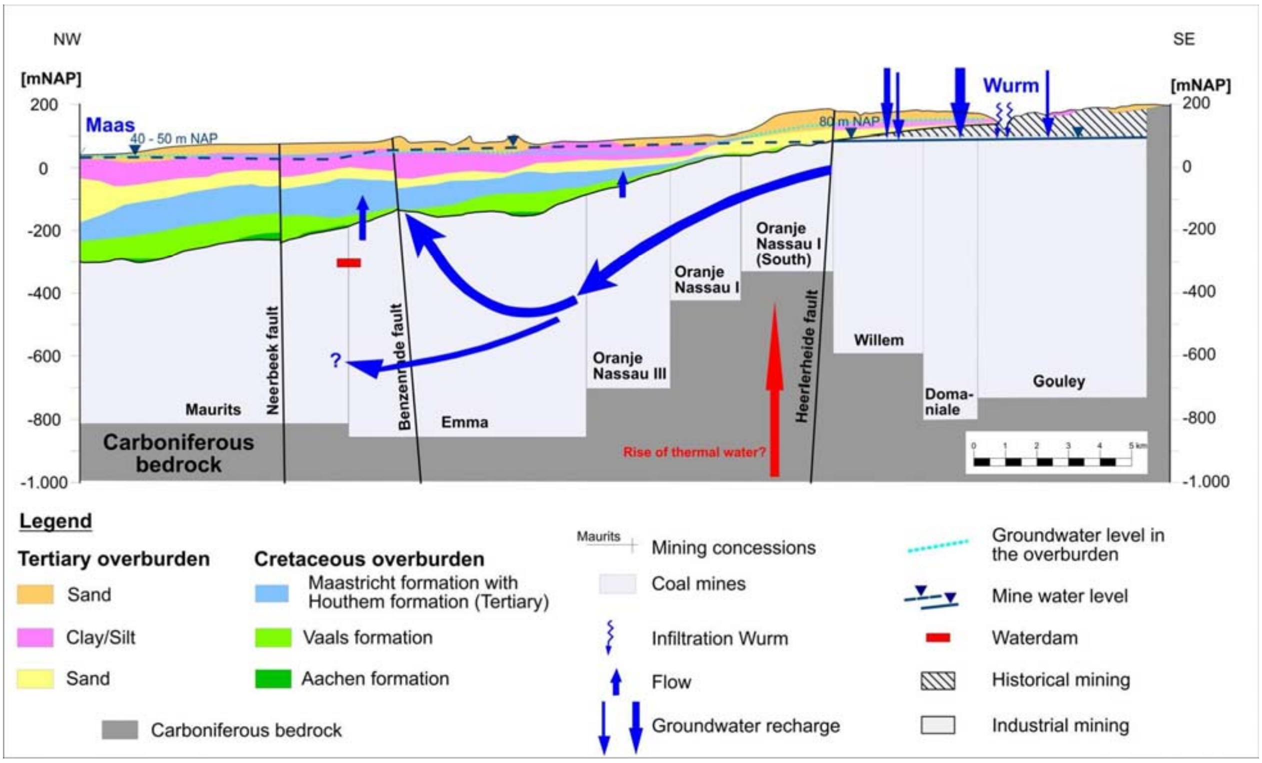

Figure 2 Geologic-hydrogeological cross section through the South Limburg mining district

In the context of the successive mine closure between 1967 and 1974, a partial rise of mine water was initiated. In 1974, mine pumping was resumed by the German mine association EBV GmbH for protecting the German hard coal mines. But it was not until after the abandonment of the last German coal mine in 1992 that mine pumping in the South Limburg mining district was terminated completely. Meanwhile, the mine water head reached a uniform level across all mines; in December 2017 the level was between 25 and 50 mNAP. Currently, the mean rate of rise is about 2 to 3 m/a. Hence, with the exception of a small area in the southeast, the mine workings have already been flooded to a larger extend; pressure heads have risen to the level of the overburden (Figure 2).

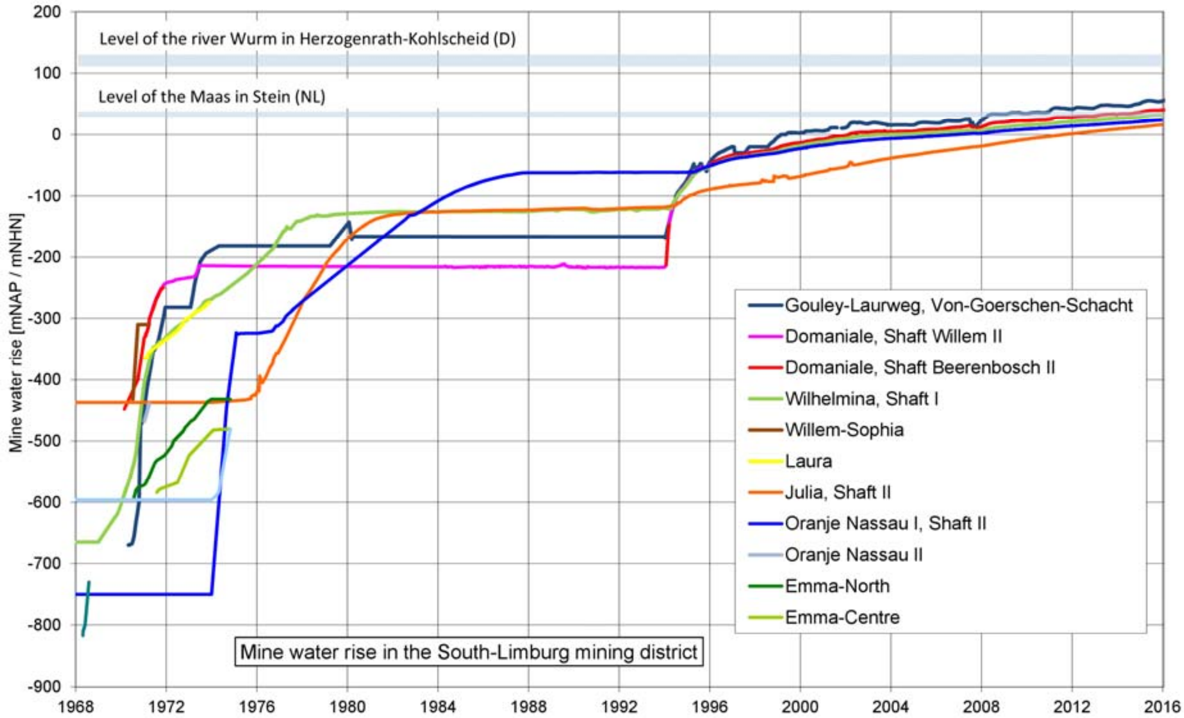

Figure 3 Progression of mine water rise in the single basins of the South Limburg mining district

Based on a groundwater model, the further rise of mine water is expected to be about 40 m; in the south eastern part of the historical mining area (Kerkrade) the final level will be about 80 mNAP at maximum. Therefore, the pressure head is not going to reach the level of the natural receiving water in the outcrop area of the hard coal bearing strata. It is expected that the further rise of mine water is going to extend over a period of 20 years at least.

3 Effects of rising mine water

3.1 Ground heave

For capturing ground movement that occurred in the context of mine water rise since the 1960s, TU Delft compiled and assessed all available levelling data as well as satellite data (InSAR) for the whole project area as well as for the adjacent Belgian and German areas. An overview of ground movement that occurred in the context of mine water rise between 1974 and 2014 is shown in Figure 4.

Time series analyses yielded a good correlation between the progression of mine water rise and the development of ground heave. Ground heave took place evenly and over a large area during the rise of mine water. However, three main areas of ground heave evolved in those areas that were former main areas of mining activity. The most distinct ground heave takes place in the central and in the north western part of the mining district (Ground heave zone 1 and 2, Figure 4); there, mine workings have been flooded prior to 1994 for the most part (ground heave 0.30 to 0.35 m). In the south eastern part of the mining district, where the mine water level has not reached the bedrock surface yet, ground heave is less distinct (about 0.10 to 0.15 m at maximum, Ground heave zone 3, Figure 4). Basically, ground heave is confined to the area of the coal mining concessions; the values of ground heave subside successively beyond the edges of mine workings.

The capture of the already undergone ground heave was crucial for identifying potential risk areas that feature differential ground heave. It turned out that a significantly increased gradient of ground heave only emerged in the north eastern border region of the mining district where the edges of mine workings are predefined by the tectonic main faults (Heerlerheide fault and Feldbiß fault). A detailed analysis of both the temporal and spatial development of ground heave in the areas of tectonically predefined edges of mine workings revealed that ground movement develops in a mostly continuous manner beyond the tectonic fault zones, albeit without developing a significant, potential damage relevant area of discontinuity. However, considering the sparse measuring point density, the local development of discontinuities cannot be excluded entirely. Damage related to differential ground movement could not be observed yet.

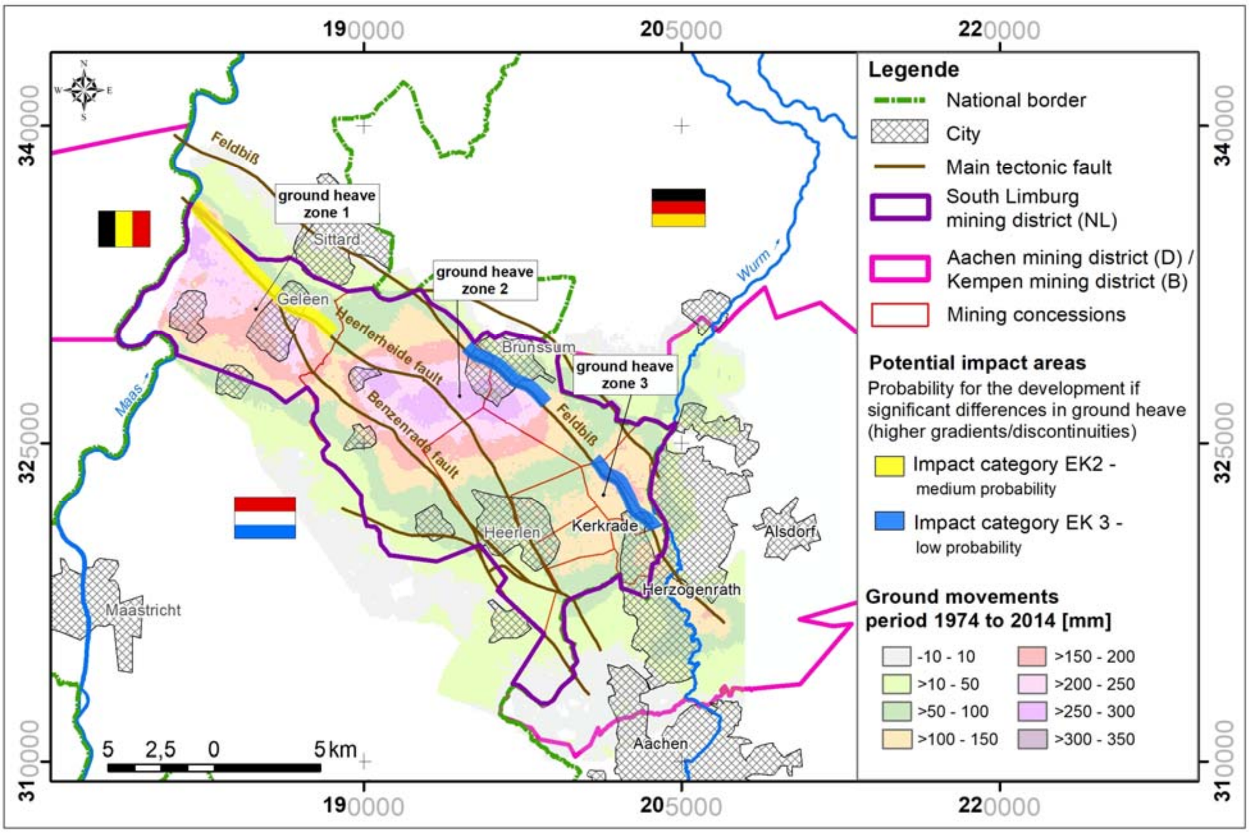

Figure 4 Ground movement in the South Limburg mining district; period from 1974 to 2014 with the potential impact areas of differential ground heave

Based on the prognosis on the further rise of mine water and the further development of the hydraulic heads in the overburden (groundwater model), a further prognosis on to-be expected ground heave was elaborated. According to this prognosis, further ground heave in the order of about 0.15 m at maximum have to be expected. Hence, ground heave related to the rise of mine water in the South Limburg mining district would add up to maximum values of 0.5 m. These values correspond to about 4 to 5 % of the maximum subsidence that took place in the main areas of mining activity.

Although the larger share of ground heave has already taken place, future damage related to differential ground heave cannot be excluded entirely. Experiences from other German hard coal mining districts show that discontinuities only develop where very specific hydrogeological and mining situations apply. For the assessment of the future impact potential an approach was used that was developed for the Ruhrgebiet area (Germany) in the last years (Heitfeld et al., 2014). This approach comprises a three step classification according to the probability for the occurrence of discontinuities which might damage buildings (with impact category EK1 meaning a high and impact category EK3 meaning a low probability of occurrence).

Based on this approach for the South-Limburg mining district three potential impact areas of impact category EK2 and EK3 were defined in areas where the main tectonic faults delimit the main centres of mining activity (Figure 4). Here too, substantial damage to buildings is not being expected. Outside these areas, no damage relevant differential ground movement is being expected.

For the defined impact areas, a detailed monitoring on the basis of representative geodetic measuring profiles in the fault areas has been recommended. The large scale surveillance of ground movement shall be carried out based on satellite data (InSAR).

3.2 Potential impacts on the groundwater in the overburden

In comparison with the natural conditions, the hydraulic system was altered substantially by the impacts of mining activity. In the level of the hard coal bearing strata between the groundwater recharge area in the southeast (valley of the Wurm river) and the north western part of the mining district spacious hydraulic connections have been created (Figure 2). At the points where the hydraulic head of mine water exceeds the overburden groundwater head, mine water can infiltrate into the overburden strata and impact groundwater conditions in the Cretaceous and Tertiary overburden.

The potential impacts of mine water rise on the overburden groundwater conditions were determined on the basis of a modified overburden MODFLOW-groundwater model (TNO, 2007); the hard coal bearing bedrock was integrated into this model as an additional model layer. Based on the prognosis on the hydraulic head of mine water, an impact area was defined in the central part of the mining district, where mine water might rise up to the overburden (Figure 5).

For this area, the potential alteration of groundwater quality has been simulated using a transport model (MT3D) and hydrogeochemical model (PHREEQC). Especially in the Cretaceous limestone aquifer in the area between the Heerlerheide fault and the Benzenrade fault increasing chloride- and sulphate concentrations have to be expected due to rising water from the Carboniferous formation. This area features groundwater extraction plants that could be affected by the alteration of groundwater quality as well. The alteration of near-surface groundwater heads as determined by groundwater modelling is in the order of decimetres; for local valley areas wetting cannot be excluded (Figure 5).

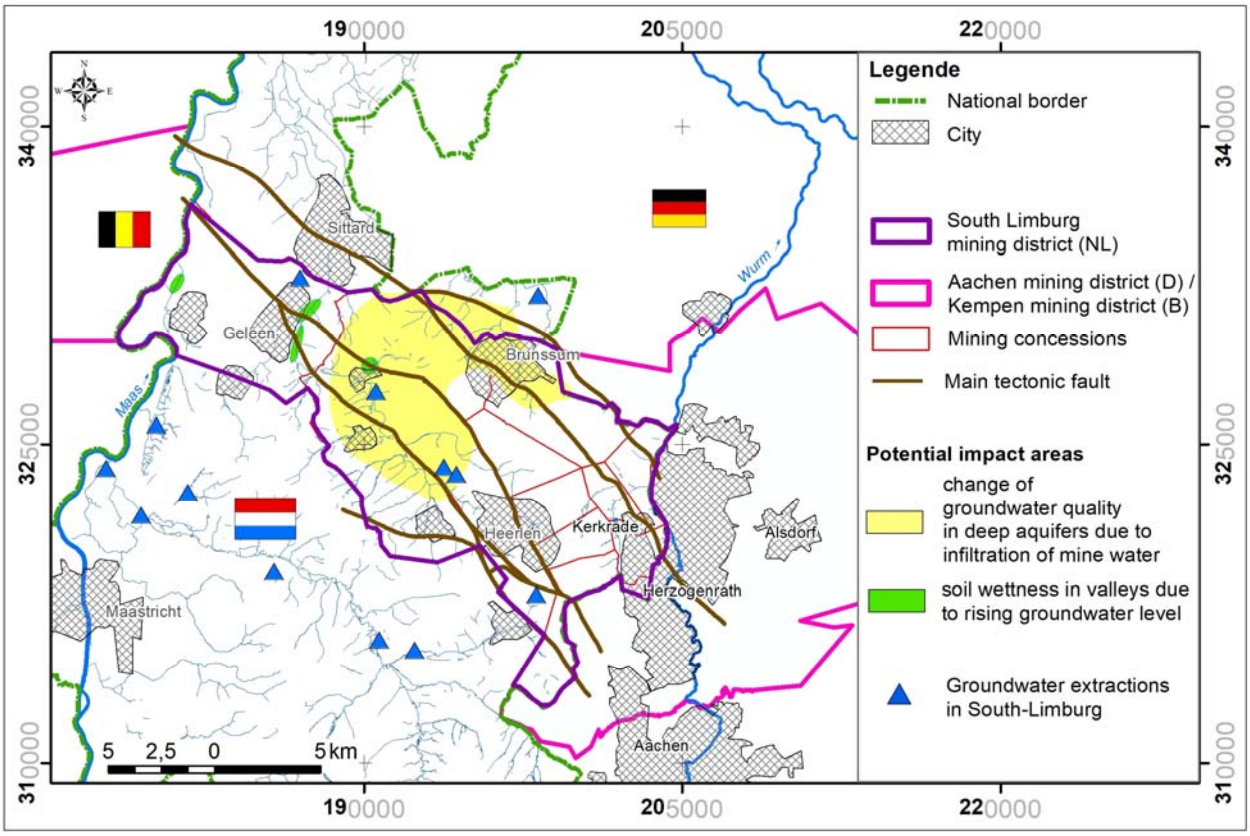

Figure 5 Potential impact areas were wetting in valleys or change of groundwater quality in the deep aquifers might occur

3.3 Seepage of mine gas

In the future, seepage of mine gas is possible only in a spatially limited area in the south eastern part of the mining district where the underground mine workings have not been flooded entirely yet (Figure 1). There, mine gas features increased carbon dioxide content (around 10 vol.-%); methane content is insignificant. Hence, the main risk related to the accumulation of mine gas in enclosed spaces is the depletion of oxygen and the related danger of suffocation. Risk areas might develop where zones of disintegration, drillings, or shafts provide preferential pathways for mine gas. This applies especially to the area of historical mining around the city of Kerkrade. As well, one has to consider the risk of sudden degassing during drilling work.

For the area of Kerkrade it has been recommended to perform an inventory of all buildings that are located near mine shafts with regard to the formation of cracks that might be pathways for mine gas. On this basis, a mine gas monitoring shall be developed. For the sewer system in Kerkrade, a combination of regular sewer inspections and gas measuring has been recommended. If necessary, a gas drainage system for new buildings should be considered.

3.4 Small earthquakes

Under the impression of the massive damage caused by induced earthquakes related to the extraction of natural gas in the Groningen area, a respective assessment of the earthquake risk had to be undertaken for the area of rising mine water. A further background for assessing this topic was the occurrence of two seismic events at a tectonic fault in the south western border region of the South Limburg mining district in 1985-1986 and in 2000-2002. It was investigated to what extend underground mass changes related to the rise of mine water and/or reduced shear strength in the fault zone could have triggered these swarm earthquakes. However, a significant causal correlation could not be found. A result of the assessment was that the natural earthquake risk that is present in South Limburg has not been changed by the rise of mine water.

4 Risks from mine shafts and near-surface mining

In the historical mining area (Kerkrade), impact areas were defined for 59 shafts; in these areas, sinkholes or depressions cannot be excluded. Taking into account the land use in the defined impact areas, a priority list for further remediation measures was elaborated. Risks from historical mine shafts have to be taken into account in future construction projects. In total, the risk from sinkholes caused by near-surface mine workings is estimated to be low; until now, no major damage was observed. It has been recommended to consider the potential impacts from mining in future land development.

In the area of industrial deep mining, 39 shafts are documented; most of these shafts were shut down in the 1960s and 1970s by installing a cohesive concrete plug in the level of the bedrock surface. The performed safeguarding measures were assessed against the current state of the art. For some shafts further investigations and remediation measures have been recommended.

In the city of Heerlen in 2011 a sinkhole developed above a mined coal seam in an area that features a 80 m thick overburden built of Cretaceous limestone and Tertiary sands and silts; as a consequence, a shopping centre had to be demolished partially (KLÜNKER et al., 2013). At this point, the coal seam was mined close to the Carboniferous bedrock surface; mining cavities have survived in the underground. The overlying limestone strata is karstified; the Tertiary sands on top of the limestone are flowable. The sinkhole developed because of this special situation. In the context of the project numerous areas could be identified that feature similar conditions; those areas were defined as potential risk areas. Currently, a risk area of this sort is being investigated in detail to gain more specific insights for a risk assessment. These risks have to be considered in future construction projects.

5 Integrated risk analysis

In a risk analysis the individual identified impacts were evaluated with regard to the probability of occurrence of a harmful event; based on this, measures were derived and formulated. Eventually, an integrated risk analysis was conducted for the different subjects that are potentially affected by the impacts of mine water rise. According to the threat level of the associated impacts each measure was assigned to scoring factors. In the evaluation approach, knowledge gaps were filled with plausible unfavourable assumptions. The necessary measures (e.g. remediation, extension of the monitoring network) were then prioritised using an evaluation matrix. To integrate the effectiveness of the individual measures with the overall rating, a cost-benefit analysis was conducted. On the basis of the integrated risk analysis, a prioritised catalogue of measures was elaborated; furthermore, a monitoring was conceptualised that is optimised for different requirements.

The effectiveness of the proposed measures was evaluated with the aid of a decision matrix using the factors "Usefulness" and "Costs". Five assessment categories can be differentiated (Cat. 0 - "No regret" to Cat. 5 "inadequate for the time being"). For the eventual recommended measures (Cat. 0 to Cat. 2) a detailed plan of action was elaborated.

On behalf of the Dutch Ministry of Economic Affairs and Climate Policy the outcomes of the study were evaluated by the British Coal Authority. In this way, a comparison of proportionality and completeness of the recommended measures with the comprehensive expertise in Great Britain should be archived. The British Coal Authority has approved the catalogue for monitoring and measures in principle and pointed out the need for preservation and creation of local competences in handling the long-term effects of hard coal mining (The Coal Authority, 2016).

6 Monitoring long-term effects on groundwater quantity and groundwater quality

To monitor the effects of rising mine water on groundwater levels and on groundwater quality, a monitoring network is designed. The following goals for the monitoring network have been established:

1. To provide insight in current groundwater levels and the change in groundwater levels over time, both in phreatic aquifers as in deep aquifers (Cretaceous limestone, Carboniferous formation).
2. To provide insight in hydrogeological parameter values of the Carboniferous layer such as permeability, connectivity between mined areas and existence of "hydraulic windows" between the Cretaceous limestone and the Carboniferous formation, in order to improve current groundwater modelling tools.
3. To increase insight in groundwater quality and changes in groundwater quality over time, to evaluate the impact of mine water rise on the ground water resources (mainly in the Cretaceous limestone aquifer).
4. To gather information which can be useful to make better estimations on other effects of rising groundwater levels, such as induced seismicity.

Next to these insights the results obtained by the monitoring network will form the basis on which risk management will be executed.

Designing the monitoring work was carried out in three steps. First, the potential impact areas were determined with a groundwater model. Figure 5 depicts the areas where changes in shallow groundwater levels which can cause wetting of brook valleys and where changes in groundwater quality in the Cretaceous overburden are expected. Additional, worst-case calculation were made to identify adjacent areas where impacts on groundwater levels and groundwater quality might occur and monitoring might be useful.

Secondly, existing monitoring wells areas were evaluated, on their usefulness to meet the monitoring goals. From all available monitoring wells a selection has been made based on the following criteria:

- Monitoring wells latest measurements/data should be no older than 2015.
- Monitoring wells must have a filter/screen in the overburden (phreatic aquifer) or in the deeper aquifers (Carboniferous limestone or Carboniferous formation).

- The spatial distribution of the monitoring wells is evaluated, such that trends in groundwater levels and quality can be detected, in areas where effects are expected (Figure 5) and adjacent areas, where effects cannot be excluded.

These monitoring wells have been selected to be part of the monitoring network (Figure 6).

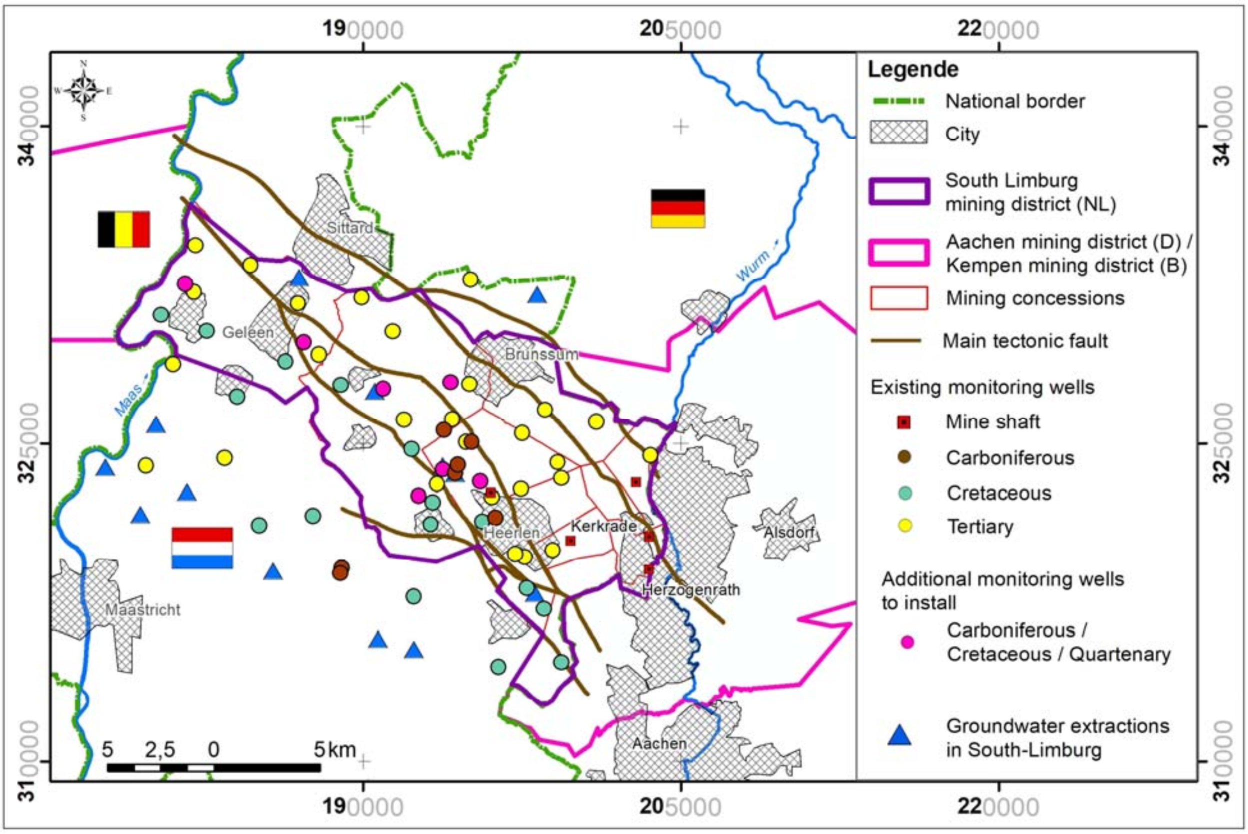

Figure 6 Existing monitoring wells selected to be part of the monitoring network and additional monitoring wells to be installed

Thirdly, based on the selected, existing monitoring network, data gaps were identified. To fill in these gaps, seven new, deep monitoring wells will be drilled (Figure 6). Each of these wells will be equipped with three filter screens (Tertiary aquifer, Cretaceous limestone aquifer and Carboniferous formation). Groundwater levels and groundwater quality will be measured regularly. Signaling values, both for levels and for quality have been defined, above which action should be taken to reduce risks for current water resources.

7 Conclusions

In the context of a comprehensive inventory of the mining related fundamentals of the South Limburg mining district as well as based on the capturing of the already undergone impacts of mine water rise about 40 years after abandonment of coal mines a broad basis for the assessment of future risks and required actions has been created. Based on an integrated consideration of all risk an extensive programme of monitoring and measures was elaborated. After project completion, all documents have been published.

Currently, the recommended measures are taken in cooperation between the Ministry, the provincial government, and the municipalities that are affected by the impacts of hard coal mining. For this purpose, among other things, a local expertise centre was established by the provincial government.

A groundwater quantity and quality network is designed and will be implemented. Signaling values, both for levels and for quality have been defined, above which action should be taken to reduce risks for current water resources. The elaborated findings and the realisation of recommendations will provide important impulses both methodically and with regard to content as well as new evaluation approaches for future risk management also in other mining districts.

Acknowledgement

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Mining Subsidence in a Partially Flooded Abandoned Mine: Aseismic Ground Movement and Consequences for Post-Mining Risk Management

I Contrucci *Ineris, France*

C Balland *Ineris, France*

J Kinscher *Ineris, France*

E Klein *Ineris, France*

Abstract

In the Lorraine area of eastern France, decades of iron-ore mining from 1850 to 1997 have left vast underground cavities beneath or near urban areas. Several major collapses occurred in the southern part of this iron-ore basin in the 1990s, after the mine closure and the flooding of underground mine workings. Following these large-scale collapses, the French government initiated a strategy of post-mining risk management to prevent and control risks associated with these ground failures. The high-risk zones are secured either by reducing the vulnerability while the moderate risk zones are monitored for public safety purposes by using in situ monitoring. This monitoring relies mainly on real-time microseismic systems, to detect precursors to a rapid large-scale collapse. Data recorded are processing automatically, and may generated alarm in case of abnormal evolution, in terms of number of event as well as in energy. A cell of expertise can be mobilized to analyse the situation and inform the local authorities of the evolutions of the situation. Evacuation can be triggered in case of danger for public safety.

After the progressive closing and then flooding of the northern iron basin ending in 2008, subsidence was observed in a town of the Lorrain basin in autumn of 2009. However, this local subsidence, with a low velocity of few centimeters per month, was not clearly detected by the borehole microseismic monitoring station located nearby. Only some microseismic events were recorded, which could not be unambiguously related to the beginning of the subsidence event. To better understand this lack of microseismic precursor a geophysical investigation was launched. A calibration blast experiment was carried out from a remaining old underground access in order to characterise the wave propagation properties in this context.

The results of this study show strong anelastic attenuation of the seismic waves though the monitored overburden most likely related to the extensive fault system intersecting the study site. Moreover, robbed pillar extraction and flooding of the site have induced a reduction of the mechanical properties of the overburden. These observations, added to a slow kinetics subsidence mechanism (~ cm/months) with little seismic energy release, may explain the lack of detected microseismicity during the subsidence event. In addition, low frequency microseismic events associated with the very slow subsiding movements might have not been detected by the used high frequency recording instruments, designed initially for rapid collapses (~ cm/hours).

Keywords: *microseismic; monitoring; post-mining risk; subsidence; anelastic attenuation; mine closure*

1 Introduction

In the Lorraine area in eastern France, decades of iron-ore mining from 1850 to 1997 have left vast underground chambers and pillars beneath urban areas. These residual voids are estimated to be 500 million m^3 in total size. Several major collapses occurred in the southern part of this iron-ore basin in the 1990s after the mine closure (Didier, 2007). These events happened a few months after the progressive rise of the water level in the underground workings, which was caused by the pumping stoppage of the mine water. Major and brutal collapses were provoked by the failure of residual abandoned underground pillars. Surface subsidence could reach two meters like in the Auboué area. More than five hundred buildings have been damaged due to these disorders and many had to be destroyed (Deck, 2002).

Following these large-scale collapses, the French government and the local authorities initiated a strategy of post-mining risk management to prevent and control the risks associated with these ground failures. By this strategy, first hazardous zones are identified, which is assessed by defining ranks according to their vulnerability and exposure of human infrastructure and activity. Then, the high risk zones are secured either by reducing the hazard or by surveying the hazard by means of microseismic monitoring (Bennani et al., 2003) The potential of the microseismic monitoring was assessed and validated in the geological context of the Lorrain basin by means of locally provoked small scaled mining collapses during the "Terres Rouges" experiment in 1997 (Couffin et al., 2003; Senfaute et al., 2000). Calibration blast were performed in the iron ore Lorrain basin to calibrate microseismic monitoring system (Contrucci et al., 2010) to adjust geophysical parameters.

So far no significant microseismic activity was recorded in the monitored areas that could be associated with the origin of a mining collapse. Nevertheless, a significant subsidence event was observed in a monitored town in the fall of 2009, located in the south-western edge of a flooded, abandoned chamber and pillar mining sector. For confidentiality reasons, the name of the site will remain anonymous. This local subsidence, with a velocity of several centimetres per month, was not fully detected by the microseismic monitoring station located nearby (Groseilliers station, Figure and Figure), only few events were recorded. We were then questioned about the reasons that led to this situation by undertaking thorough investigations on all of the measuring system and on microseismic wave propagation conditions on the site. No technical failure was highlighted by these investigations. However, the hypothesis of a gradual subsidence releasing low energy densities during the time became plausible based on results of the wave propagation modelling. Note that the area, affected by mining subsidence, is no longer accessible because of flooding of the area in late 2007. Among the hypotheses that may explain the lack of microseismic precursor and, given the kinetic of the phenomenon on several months, one is based on a large aseismic deformation of an overburden already deconsolidated. A second hypothesis is based on the local geophysical and geomechanical conditions affecting the effectiveness of the microseismic monitoring, like the faults corridor identified on the monitored area. A third hypothesis is based on an improper installation of the microseismic sensor in the borehole, and a bad coupling of the probe with the ground.

To explain the causes of this situation, a program of geophysical investigations was launched with a series of complementary operations to provide elements of response to the lack of microseismic detection. Calibration blasts were carried out from the eastern part of the accessible mine workings and additional sensors were deployed at the surface. This experimentation was carried out in September 2010. The aim of the experimentation, according to the hypothesis listed before, was to answer to the following questions: (1) What is the velocity and wave attenuation field? (2) What is the minimum source power that can be detected by the sensors? (3) What is the impact of the geology, the faults corridor and the integral pillar extraction zone on the wave propagation field ?

2 Context and Methods

The site shows many normal faults forming a corridor with an average orientation of about N45°. The main discontinuity of this system is a fault which is the northwest edge of the mine. The site has two areas of hazard (Figure), classified as risk of progressive subsidence. The iron ore layer was exploited with a recovery factor of about 47%. Operated by room and pillar method, mine workings are now flooded at the NGF level of ~ 208 m, and are located at about 160 m below the surface, with a dip of approximately 2.5° (NO). This configuration prevents to access to the area located directly below the collapsed region and below the Groseilliers microseismic station (Figure).

Cracks observed in the houses of the inhabitants of the town were observed in October 2009. This led to the establishment of a monthly levelling follow since December 2009 (Figure). The measured displacements reveal the formation of a basin whose maximum amplitude was 66 cm in April 2012. This basin is located south of the hazard zone. For this blast calibration experiment, different acquisition systems have been installed both on the surface and at bottom, in the mine, in addition to the permanent microseismic monitoring network stations named Lilas, Groseilliers (Figure). Two temporary geophones lines connected to two acquisition units were located at the surface. A temporary seismic network was installed inside the mine, consisting in two stations, each equipped with a geophone, a microphone, an hydrophone, a 3 components 1 Hz seismic station and a dynamic piezometer.

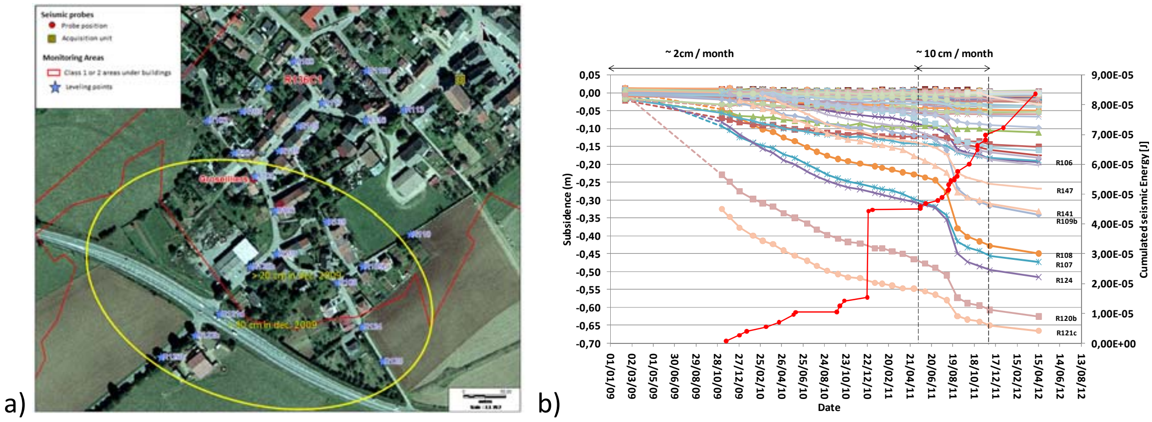

Figure 1 **a) zoom on the subsided zone and location of the leveling points. Red line marks the limit of the risk zone, yellow line represents the extension of the surface subsidence (GEODERIS); b) leveling measurements since January 2009 until August 2012 (BRGM-DPSM) of the points located in figure a. Red curve represents the cumulative sensor energy of the microseismic events recoded during the period.**

Figure shows the location of the different acquisition systems, blasts and rock falls performed for the experiment. The blasts were made in drilling of 5 meters depth and 60 mm of diameter. The explosive used was EURODYN 2000 dynamite type. These blasts were mainly located at the east of Lilas and Groseilliers stations, because of the mine flooding, although the basin subsidence is located to the South-West. Rock falls experiment (10 drops a weight of 500kg) was performed in the Louise gallery primarily to calibrate seismic and acoustic monitoring network located in the mine.

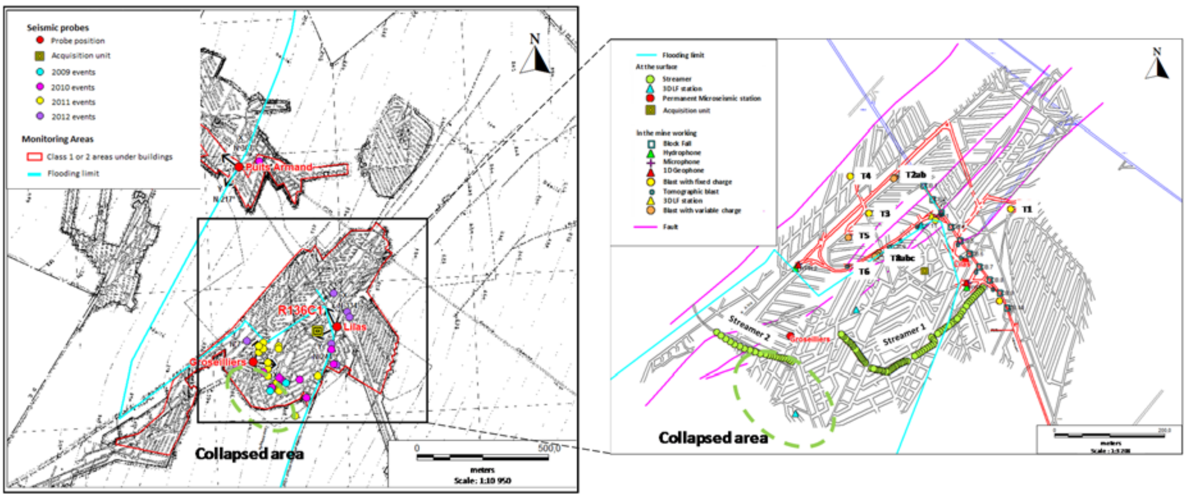

Figure 2 **left map: mine workings of the iron ore grey layer of the site and location of the risk zone (red lines) and the permanent microseismic network (red points). Right map: Location of the different acquisition system and the blast superimposed to the grey layer mine workings (BRGM-DPSM)**

To estimate the velocity field, two tools were used. The first tool is called SYTMISvel (Contrucci et al., 2010). It is able to build isotropic multilayer 1D velocity model by inversion. For the inversion input data are: P wave and/or S wave first arrival time, incident wave angle measured at 3 components seismic stations, number of geological layers, blast location and errors on arrival time picking and on angles. The second tool is called TOMSIS (software 2D seismic tomography (Balland et al., 2009)). In this case, the strata are not predefined. The propagation medium is discretized, which can account for the anisotropy of velocity. The anelastic wave attenuation was calculated by the spectral ratio approach (Sain et al., 2009; Toksoz et al., 1979). The spectral amplitude ratio was considered for collinear seismic rays of P waves with quasi vertical incidence angles emitted by weight drops of 500 kg, located just below the Lilas station.

3 Results

3.1 Velocity field

The first method of velocity estimation of the geological layers (Table 1) clearly shows a first low velocity layer of ~ 1900 m/s and ~ 30 m thick, which is located over a layer of ~ 3100 m/s of ~ 90 m thick. The third layer is ~ 30 m thick with a higher velocity of 3700 m/s. The last layer represents the mined layer with a velocity of ~ 3400 m/s. The first layer may be associated to both the altered layer and alternating marl-limestone while the second may be associated to the Bajocian limestone. Finally, the third layer is associated to marl of Charennes. Note that the velocity measurement integrates widely layers of smaller thickness as the layer of marl (19 m) located between two limestones, which give an idea of the limitations of the methods for estimating the seismic velocity in this context. Velocity observations are broadly consistent with what has been observed at other sites of iron basin (Contrucci et al., 2010; Tastet et al., 2007).

Table 1 : summary of the velocity characteristics of the model on the site.

Site		Surface	Bajocien	marl of Charennes	Iron layer
4 layers model	thickness [m]	27	89	33	40
	velocity [m/s]	1867	3137	3695	3398
	Uncertainty	373	198	208	56

The anisotropic velocity measurements shows a remarkably velocity increase with the dip (**Figure**). Usually, sedimentary interfaces produce an inverse anisotropy direction (Oberti et al., 1979), indeed waves propagate faster in the horizontal plane of the layers and more slowly perpendicularly through the layers. Here, in our case, highest velocities are observed for sub-vertical rays. However, full range of dips could not be sounded, because of site constrains. The lowest velocity is at a dip of about 35° associated with an azimuth around 220° (**Figure**).

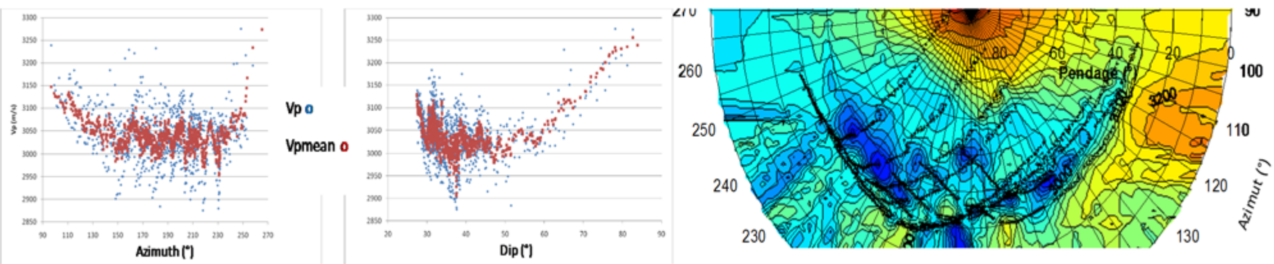

Figure 3 P-wave velocity as a function of azimuth (top), dip (middle) and stereographic representation (bottom).

As for other sites (Ikeda et al., 1981), the origin of this anisotropy is likely to be related with the presence of faults. The NE-SW faults orientation observed underground in the mine (Figure) coincides with the anisotropy velocity field. The most likely hypothesis is that waves which propagate in the fault plane axis encounter "crushed" areas with lower mechanical properties and lower velocities. The influence of faults can also explain the anisotropy inversion due to the stack of sedimentary layers. Without fault on the site, we would probably measure horizontal anisotropy as usually observed in a sedimentary terrain. The effect of faults on velocity is probably underestimated.

3.2 Tomography

The tomography image (Figure) shows a structure of the velocity field that can be divided into three large units that seem to be following the horizontal direction corresponding to the stratigraphy. The first unit located near the sensors has a low velocity (< 2500 m/s) of about 50 m thick. The second unit is 50 to 75 m thick with a high velocity (> 3500 m/s). And the third unit is the most heterogeneous, with velocities of around 3000 m/s.

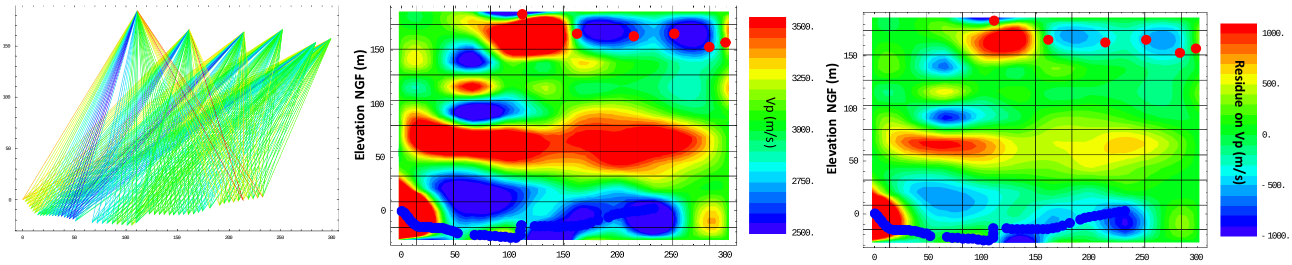

Figure 4 left: 2D seismic ray coverage of the tomographic plan located between shots and streamer 1. Center: tomographic inversion, and right: associated residues. Red points represent the location of the blast and blue points the location of the streamer sensors.

3.3 Sources detectability

The environment of the Groseilliers station has no particularly significant attenuation compared to the Lilas station. This observation is confirmed by the record of an equidistant blast to both stations with maximum amplitude almost identical on both 3 components probes (Figure 5). This shot suggests that the two probes are well coupled to the ground. The minimum explosive source detected by the probes is less than 200 g of explosive at 250 m from a 3 components probe. On the other hand, rockfall on the floor in the gallery Louise (500 kg dropped from 2 m) were detected by Lilas station and this regardless of the hypocentral distance (up to 150 m). Transmission of waves generated by rockfalls is probably advantaged by the strong low-frequency content of the source. The rockfall efficiency must also be better than explosive. Indeed, a significant amount of explosive charge is converted into heat and plastic strain.

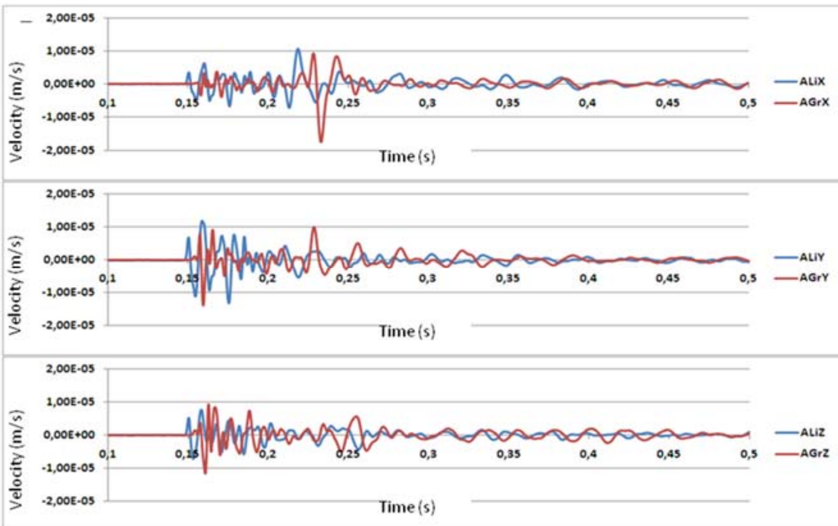

Figure 5 signal representation: (top) X sensor, (middle) Y sensor, and (bottom) Z sensor of a blast (1kg) equidistant from the microseismic stations Lilas and Groseilliers.

3.4 Field attenuation

Signal spectrums of 1DZ and 3DZ seismic sensors of the Lilas station, as well as associated spectrum ratios of weight drops carried out below Lilas station, are showed on Figure . Spectral ratios are quite noisy (Figure -b and d), nevertheless those calculated from the P-wave arrival times are smoother (Figure -d). These spectral ratios show a weak increase of the slope until 250 Hz, and then a decrease. This tendency is clearly visible on the mean spectrum. Several linear regression fittings were tested on spectral ratios in a frequency range between 0 and 250 Hz. From these tests, we observe weak Q factor values. These values are ranging between 5 and 15, because of the data variability (Figure -b and d). Values greater than 20 are likely not possible despite this variability.

Thus, the Q factor for this site can be reasonably estimated at Q = 15 ± 5 on a frequency band ranging between 10 and 250 Hz. These calculations confirm that the anelastic attenuation is significant on the site despite P wave velocities in the order of magnitude of 2900 m/s. In the literature we can observe low Q value factors for velocities between 3000 and 4500 m/s, when the overburden is faulted and fractured (Barton, 2007; Sjogren et al., 1979). Velocities are less sensitive to fracturing of the medium than the Q factor. Indeed, on a site located in similar geological formation (Cerville-Bussoncourt, France), where an underground cavity collapse was triggered, it has been observed that a 10 % velocity change can correspond to a 50 to 70 % variation of the Q factor value (Kinscher, 2015; Marot et al., 2014).

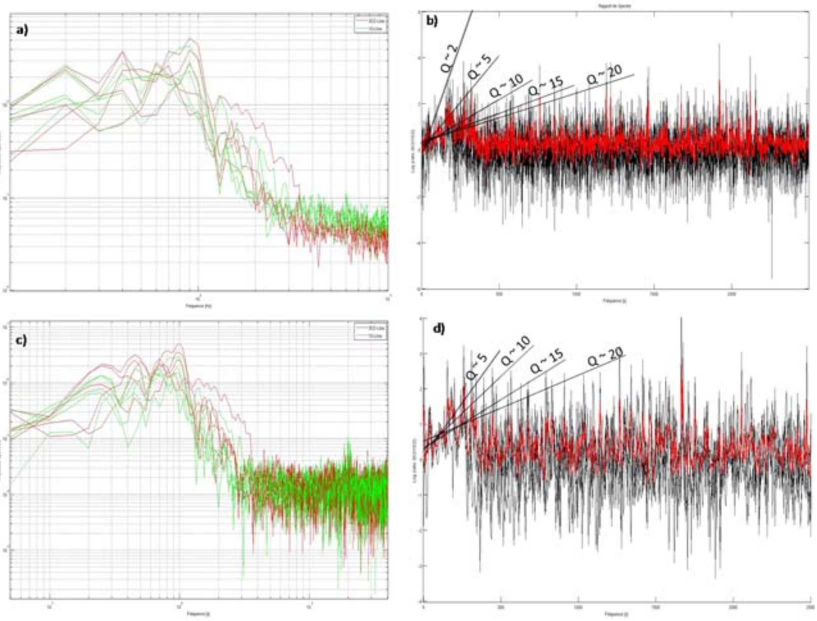

Figure 6 amplitude spectra and spectral ratios of signal from block drops carried out just below the Lilas station, a) considering the entire signal, in green 1DZ sensor and in red 3DZ sensor. b) Spectral ratios with several possible linear regressions and the corresponding Q values, in red average spectrum. c) spectra of the P-wave first arrival and d) associated spectral ratio, in re, average spectrum.

4 Discussion

The low level of seismic signals detected by the Groseilliers station during the subsidence seems to be mainly due to the high seismic attenuation of the site, as shown by this study, as the possibility of a sensor failure is excluded. However, this attenuation phenomenon is likely coupled with very weak seismic sources and/or with very low frequency (< 10Hz). In addition, the collapsed pillars were not probably healthy and may have already been damaged by the old total pillar removal area nearby (robbed pillar area, Figure 14). Moreover the flooding of the area since 2007 has certainly weakened the existing mine workings, because water accelerates crack propagation and thus increases rock damages (GISOS, 2007).

In addition, the uncertainty of the underground galleries positions relatively to the surface, allows considering a location of the maximum surface subsidence from 10 to 30 m further south. This observation could move the collapsed zone in the robbed pillar area, at the border of the healthy gallery. Then, pillars involved in the collapse would have been already damaged by total pillar removal operations, and pillars located nearby have been also fractured. Then the seismogenic (energetic) fracture has certainly occurred prior the installation of the Groseilliers station. We can therefore consider the existence of damaged pillars before the collapse of November 2009. The formation of fractures and/or microcracking in the volume of the pillar would produce a rheology capable of inhibiting large, fast and energetic seismic ruptures. This rheology only would allow slow transient deformation (aseismic slip on fracture planes, and or plastic behavior in the volume), possibly with small seismogenic ruptures, infra-metric, so too weak to be recorded by the Groseilliers station.

Moreover, secondary faults, to the main fault, have been identified in mine workings at the N-W and S-W below the Groseilliers stations (Figure). These faults may have been remobilized during robbed pillar operation of the exploitation located at the SW of the Groseilliers station. This damage zone may also prevent the transmission of the seismic wave generated by subsidence. Therefore the subsidence occurred in areas that already had low mechanical properties due to the robbed pillar extraction method or located inside the area, aggravated by flooding. In addition, many faults have been observed on the site. This causes strong anelastic seismic attenuation, which is not favourable for seismic signal transmission. Figure resume all the hypothesis mentioned in the discussion.

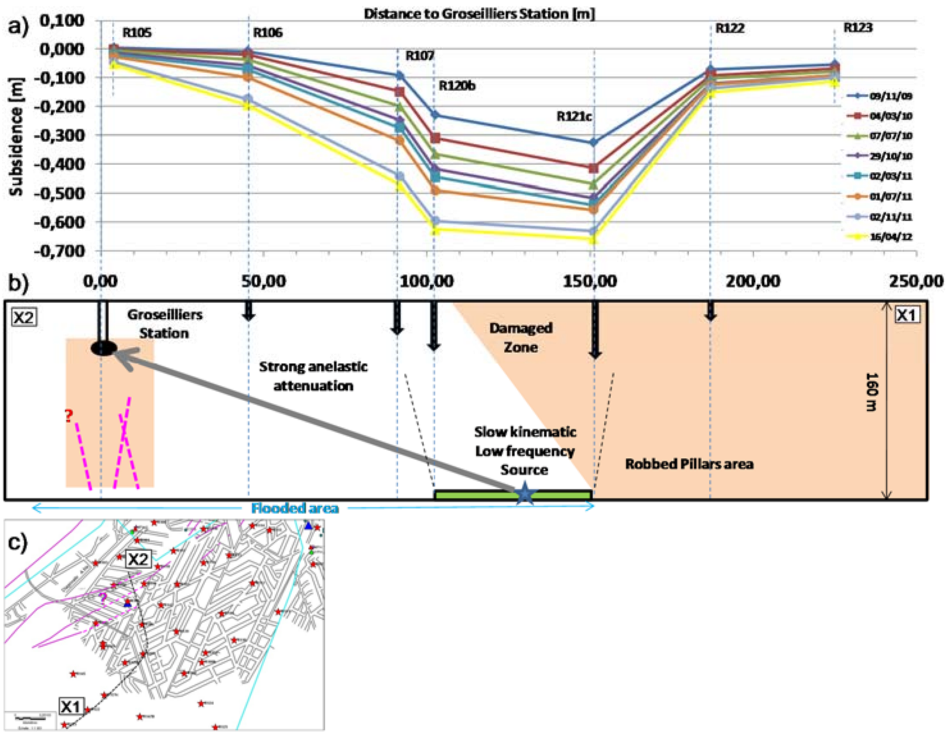

Figure 7 **summary of the hypothesis to explain the lack of detection of the seismic precursory of the subsidence. a) subsidence profile of points along a cross section located between X1 and X2 of the c) figure. b) schematic cross section between X1 and X2 and interpretation.**

5 Conclusions

These investigations helped to highlight an apparent attenuation of the mine overburden, both in terms of intrinsic characteristics. This strong reduction is probably related to the extensive faulting that intersect the mine. This attenuation could explain the non-detection of microseismic events of low energy related to the long term subsidence observed by levelling. Subsidence showed a quasi-linear rate between November 2009 and August 2011, where the average velocity of 2 cm / month. This indicates a slow and steady release of the seismic energy. If, as it was the case for brutal subsidence which occur in 1996 and 1997 at Moutiers and Auboué sites, where most of the energy (about 70 to 80%) was released during few weeks, microseismic events would normally have been recorded. The microseismic monitoring network deployed in the Lorraine iron ore basin is rather design for the detection of rapid subsidence mechanisms. Following this experiment, a differential GPS was installed on the site to follow this progressive subsidence, as it is done for seismological monitoring based on both seismic and geodetic networks.

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Closure Water Balance Model to Support Closure Designs for a Mine in Laos

BR Luinstra *SRK Consulting (Australasia) Pty Ltd, Australia*

JT Chapman *SRK Consulting (Australasia) Pty Ltd, Australia*

A Hendry *SRK Consulting (Australasia) Pty Ltd, Australia*

A Watson *SRK Consulting (Australasia) Pty Ltd, Australia*

R Staines *SRK Consulting (Australasia) Pty Ltd, Australia*

J Rowntree *MMG Limited, Australia*

D Noonan *MMG Limited, Australia*

Abstract

SRK Consulting (Australasia) Australia Pty Ltd (SRK) are currently assisting with the development of closure plans for portions of a mining Development Area located in Central Laos. To support closure planning, it is important to identify which pits and dumps represent significant contaminant sources, and to understand how effectively contaminant release can be mitigated as part of the closure design.

A catchment delineation process was undertaken in which flow paths and catchment areas were defined to reflect the Life of Mine (LOM) topography, landforms and features within individual precincts. A closure water balance model (CWBM) was constructed to allow assessment of impacts for closure options at the precinct, sub-catchment and catchment scale.

Stochastic rainfall was developed based on the available climatic data for the years 1994-2015 and showed good correlation with long term averages. Runoff from natural (i.e. non-mining) areas for the CWBM was developed using the Australian Water Balance Model (AWBM). Unique calculations of hydrologic fluxes were conducted within GoldSim for mine pits, backfilled pits, water management structures, waste rock landforms and non-mining areas. Within the CWBM, flows from natural areas and precincts were aggregated at nominated water quality assessment points to provide flow estimates for water quality predictions.

In general, pit voids and water management structures follow a distinct seasonal pattern, with ephemeral outflows during the wet season, and no outflow during the dry season. The assessment predicts that this seasonal pattern will be maintained after closure, such that the pit voids and water management structures maintain perennial lakes through the dry season, and overflow during the wet season. In addition, most pit lakes will be gaining water bodies, i.e. receiving significantly more seepage from groundwater than they are losing to groundwater and will spill.

Keywords: *Hydrology, Hydrogeology, water quality, water balance*

1 Introduction

The subject mine (the site) is an open cut gold and copper mining operation located in Central Laos. Mining operations comprise several gold and copper open pit operations, with the gold operations currently in care and maintenance. Figure 1 shows the site layout comprising open pits, waste rock dumps, and water management structures.

For the purposes of closure planning, the operations have been separated into three distinct areas, based on geographical location and operational status. The current assessment primarily deals with the Western and Central Development Areas which comprise a series of open pits and waste rock dumps for both copper and gold operations, that fall primarily west of the main river that passes through the site. The other two areas comprise the tailing storage facilities (TSF) and a copper open pit operation that includes the process plant and other infrastructure.

The assessment formed part of a multi-disciplinary approach to support development of overall closure designs (the overall approach is described in a companion paper, Chapman et al. 2018).

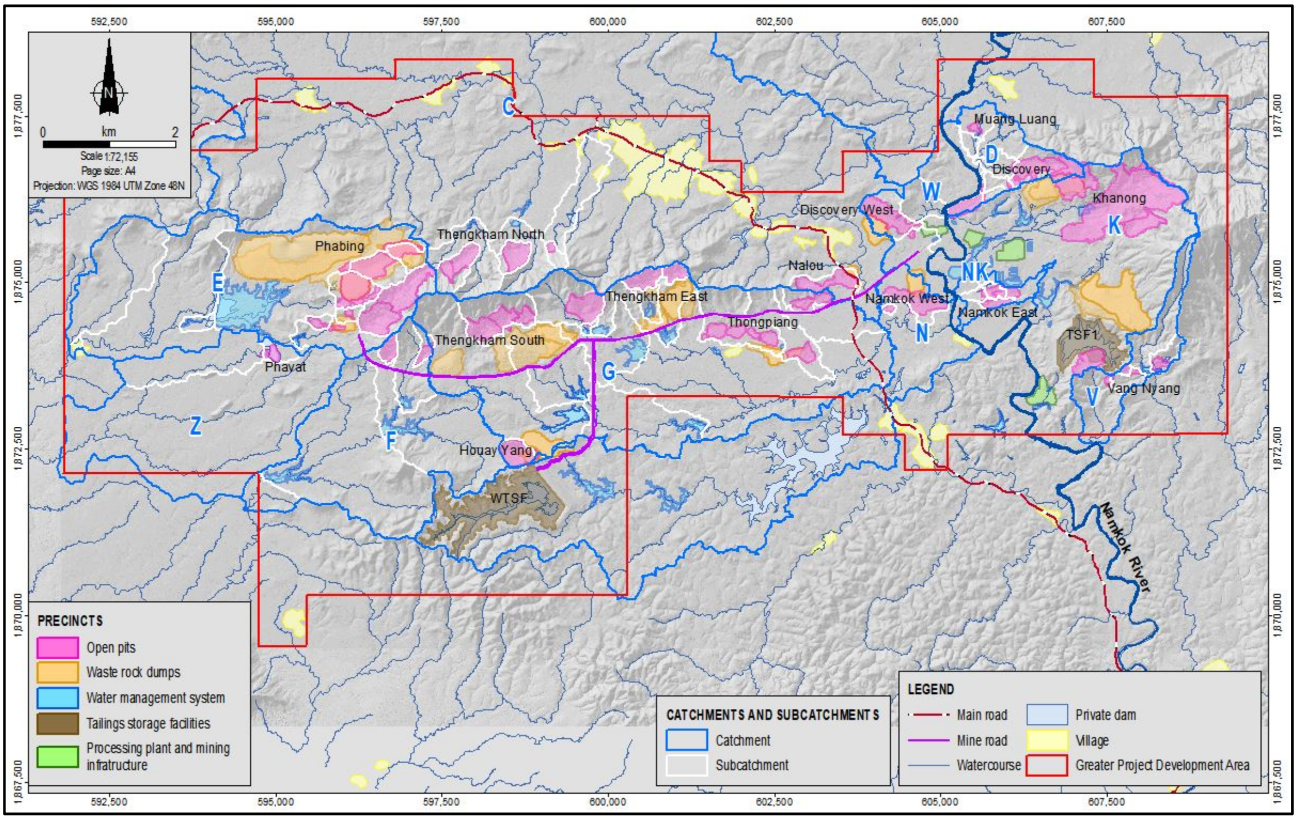


Figure 1 Subject Mine site – general layout

2 Climate

The site is characterised by a tropical climate, with a distinct dry season (October to April) and wet season (May to September). Daily rainfall and evaporation data have been collected since 1994, and monthly average values are summarised in Figure 2.

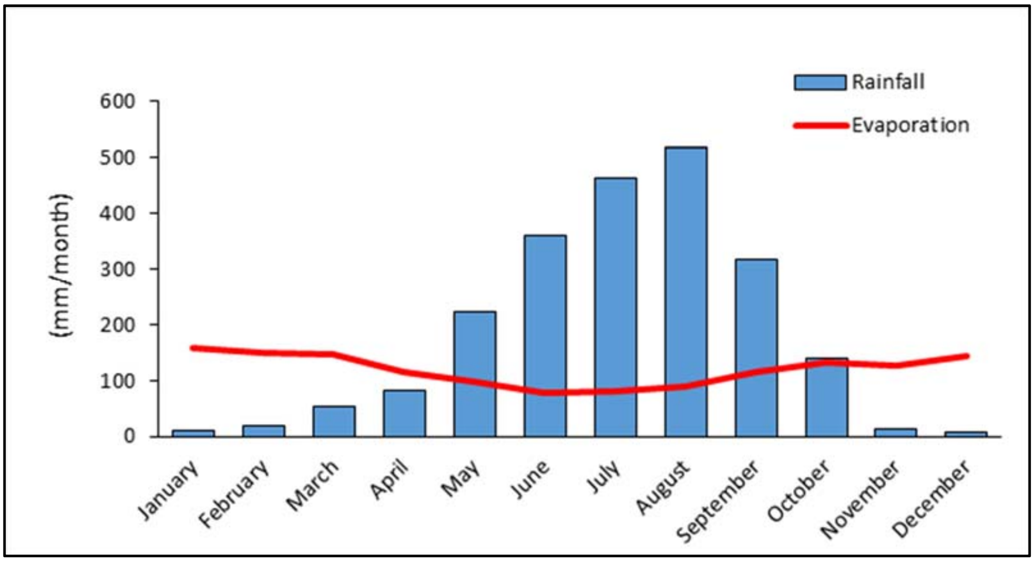


Figure 2 Measured monthly rainfall and evaporation (1994 - 2015)

The mean annual rainfall for the region is approximately 2,250 mm/year, of which up to 80% occurs in the wet season. Mean annual evaporation in the region is approximately 1,450 mm/year. The site has a net positive water balance (i.e. rainfall>evaporation), most evident during the wet season from May through September. During the dry season (November through April) the site has a net negative water balance.

3 Hydrology

The Project area drains into the Namkok and Xe Noy River systems. The site was additionally divided into smaller catchments (see Figure 1) of which C, D, G, N, NK, V, Wand Z discharge into the Namkok River, while catchments E, F and Z drain into the Xe Noy River towards the west. The catchments generally form headwater streams, i.e. first and second order streams before joining the Xe Noy and Namkok Rivers.

Due to the distinct dry and wet seasons, significant seasonal fluctuations occur in streamflow. During the dry season headwater streams are considered ephemeral. Larger reaches of streams (i.e. the Namkok and Xe Noy rivers) receive significant baseflow during the dry season and are considered perennial.

4 Water Balance Model Development

4.1 Approach

A Dynamic Systems Model (DSM) developed in GoldSim (version 11.1.5) has been used to simulate the flow of water for the various hydrologic components, including non-mining areas, pits, waste rock dumps and sediment management ponds.

The objective of the model was to develop a post-closure water balance for the site to evaluate the effects of closure options for mine infrastructure and larger catchments on water quality. The model included:

- Flow estimates for individual components, including runoff and recharge to the groundwater system.
- Flows from contributing natural areas.
- Combined flows from both natural areas and identified mine infrastructure at identified water quality monitoring or water quality evaluation points.

4.2 Stochastic Rainfall and Evaporation

Variation in rainfall is the primary source of uncertainty in the development of the closure water balance model (CWBM) for the Project Area. GoldSim allows the water balance to be simulated for many realizations incorporating stochastic rainfall data to develop probabilistic results. The stochastic rainfall generation module allows day to day rainfall patterns to vary, while maintaining consistent seasonal rainfall patterns.

Evaporation was calculated based on monthly average site data for the period 1994 to 2015. A pan factor of 0.8 was adopted for natural water surfaces (pit lakes and sediment ponds).

4.3 Life of Mine Flow Logic Development

Prior to development of the CWBM, a catchment delineation process was undertaken to develop a flow logic tree for the final closure catchment configurations. For each catchment, the topography was updated to reflect the Life of Mine (LOM) landforms and features. This updated LOM topography was then analysed within a GIS environment to develop updated surface water sub-catchments. Non-mining impacted areas, were separated from mine impacted areas and infrastructure to allow the assessment of water quality impacts from mixing and/or diversion of natural runoff with mine-impacted water. Surface areas for individual precincts and undisturbed areas in each catchment were calculated within the GIS environment and tabulated for use in the CWBM.

Within the CWBM, flows from natural areas and relevant precincts were aggregated at the nominated Assessment Points to provide flow estimates for water quality predictions used to assess the closure options for the site. Flows from individual precincts, as well as from Assessment Points, were utilised in the solute loading calculations provided in Linklater et al. (2018).

4.4 Runoff from Natural Areas

An Australian Water Balance Model (AWBM) module (Boughton, 2004) was developed within the GoldSim model to simulate runoff from non-mining impacted areas. The AWBM is a commonly-used catchment water balance model method which simulates storage within a catchment to simulate the variable nature of catchment morphologies. Overflow from the surface stores, when rainfall exceeds their capacities, is routed to a further two storages which allow generation of both baseflow and surface runoff components which feed stream flow. Values for surface storage capacities and factors for partitioning between surface flow and baseflow are ideally generated through calibration with gauging data from catchments within the study area.

4.5 Waste Rock Dump Runoff and Seepage

The battery limits for this study include 13 waste rock dump (WRD) landforms, not including backfilled pits. Runoff from the WRDs and seepage into the groundwater system were calculated for each landform within the CWBM using a waste rock dump module that was based on a curve number approach. Runoff is generated when daily rainfall exceeds initial abstraction (*Ia*) for the waste material. In order to account for the effect of consecutive rainfall days, initial abstraction was reduced by 90% if the rainfall on the preceding day exceeded 20 mm. The curve number adopted for backfill material was 60 and applied to all WRDs. All WRDs were initially assessed as uncovered and unvegetated landforms

Seepage from WRDs was established at 15% of the annual rainfall. A portion of the seepage was assumed to daylight as toe seepage, and was directed into the surface water system, while the remainder was directed to the deeper groundwater system (referred to as basal seepage). For the initial iteration of the CWBM, toe seepage was assumed to occur at every WRD and was set to 30% of total seepage from the WRDs. Storage within the WRDs was not simulated in the CWBM. In some instances, percolation can be delayed by extended time periods, which would result in solute loads from the WRDs lagging behind peak runoff flows. The current approach may therefore not be conservative and calculated dilution ratios may be higher than would occur in reality.

4.6 Pit Water Balances

A total of 42 pits were included in the battery limits for this study. Two fundamental closure options have been identified for the pits: backfilling or flooding. Conceptually the groundwater level is expected to rebound to elevations similar to pre-mining elevations for backfilled pits, with the backfill above the water table resembling WRDs (with similar options for closure, i.e. reshaping, covers, etc). Open pits are expected to form lakes due to the positive water balance and, as dynamic systems, required simulation of inflows, outflows, and changes in water storage over time.

Interaction of pit lakes with groundwater is also expected post closure. Water quality within pit lakes and overflow data is discussed as part of the geochemical assessment (Linklater et al. 2018).

The water balance for pit lakes was as follows:

$$\Delta_{water\ volume} = P_{precip} + Q_{inflow} + R_{wall\ runoff} + R_{Natural\ runoff} + GW_{seepage} - E_{pit} - Q_{outflow}$$

(where Δ is a change in volume, *P* is precipitation, *R* = runoff, *GW* is groundwater, *E* is evaporation and *Q* is volume in consistent units). Pit wall runoff was calculated using a pit runoff factor. Runoff was assumed to occur only once rainfall exceeds 5 mm. For rainfall less than 40 mm, the runoff coefficient was set at 20% of daily rainfall, unless there was more than 5 mm of rainfall the preceding day, in which case the runoff factor was increased to 65% of daily rainfall. For daily rainfall above 40 mm, the runoff factor was set at 65%.

Outflow to groundwater from the pit lake, or inflow from groundwater, is proportional to the difference in head between the pit lake elevation and the surrounding groundwater table.

To facilitate development of an analytical solution to estimate flows both into, and out of, the pit lakes, flows were calculated within the CWBM by adding the results of a derivation of the McWhorter and Sunada (1977) equation for flow into a cylinder and out of a cylinder.

4.7 Sediment Management Pond Water Balances

Included in the battery limits for this study are twenty (20) sediment management ponds. The sediment ponds were assumed to be perched, and seepage was calculated as the footprint surface area (m^2) × hydraulic conductivity ($m.s^{-1}$). Hydraulic conductivity was assumed to be 1.0×10^{-7} $m.s^{-1}$.

4.8 Groundwater Recharge and Discharge

Groundwater recharge, including recharge from natural areas and seepage from all precincts, was aggregated for each catchment, or sub-catchment, as applicable. A primary assumption was that, under steady-state conditions, all recharge within a catchment will be returned to the surface water system at the discharge location of the given catchment (i.e. assuming no inter-catchment groundwater flow). To account for potential additional losses, inter-basinal flow, changes in aquifer storage and the potential for redirection of groundwater via karst features, a groundwater discharge factor was incorporated into the model (set at 0.5 in the CWBM).

Groundwater discharge was separate from the baseflow estimated as part of the AWBM runoff calculation. The AWBM baseflow represents transient storage within shallow soils, subsoils or alluvial materials associated with streams, whereas groundwater discharge represents outflow from catchment-scale aquifer systems.

4.9 Modelling Scenarios

Two scenarios were developed as follows: a) base case scenario whereby WRDs and above-grade backfilled pits remain uncovered; and b) mitigated case whereby WRDs and above-grade backfilled pits are covered. In order to simulate flows for the mitigated case, adjustments to the WRD basal seepage, toe seepage and curve numbers were incorporated into the model, as outlined in Table 1.

Table 1 Runoff factor adjustments for waste rock dumps for base case and covered scenarios

Scenario	Seepage factor (percentage daily rainfall)	Toe seepage (percentage daily rainfall)	Curve Number
Base case (uncovered)	10%	5%	60
Mitigated case (Covered)	5%	1.75%	75

5 Results

The model was used to simulate flows on daily time steps for an initial period of 10 years. A total of 100 realizations using stochastic rainfall data were run to develop a probabilistic assessment of flows within the model. Pits with lakes and water management structures were assumed at full capacity on commencement of the simulation period. The results of the simulation are compared with the mean monthly rainfall data for 1994 to 2015 in Figure 2 and suggest a reasonable correlation with observed data. The probabilistic rainfall as presented in Figure 3 shows that the highly seasonal precipitation patterns persist.

Probabilistic monthly storage volumes (in m^3) and outflow rates (m^3/month) for a typical pit lake are provided in Figure 8 for closure. In general, pit lakes follow a distinct seasonal pattern, with ephemeral outflows during the wet seasons, and no outflow during the dry season.

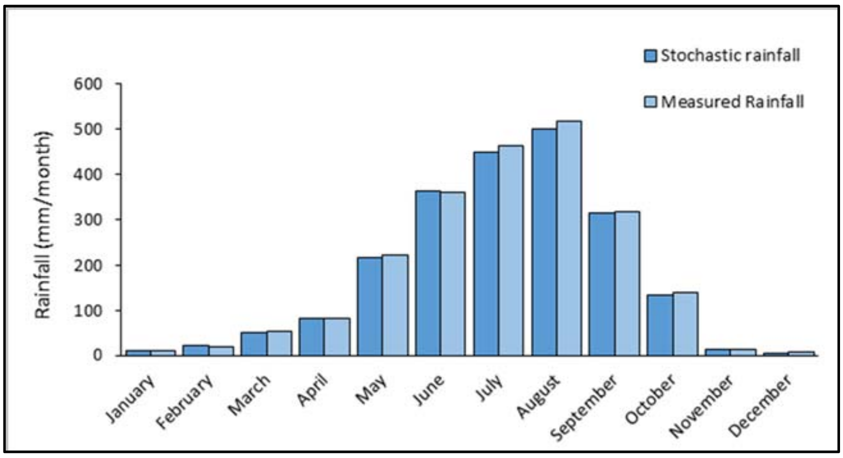


Figure 3 Comparison of measured (1994-2005) and (2015–2025) stochastic rainfall from the CWBM

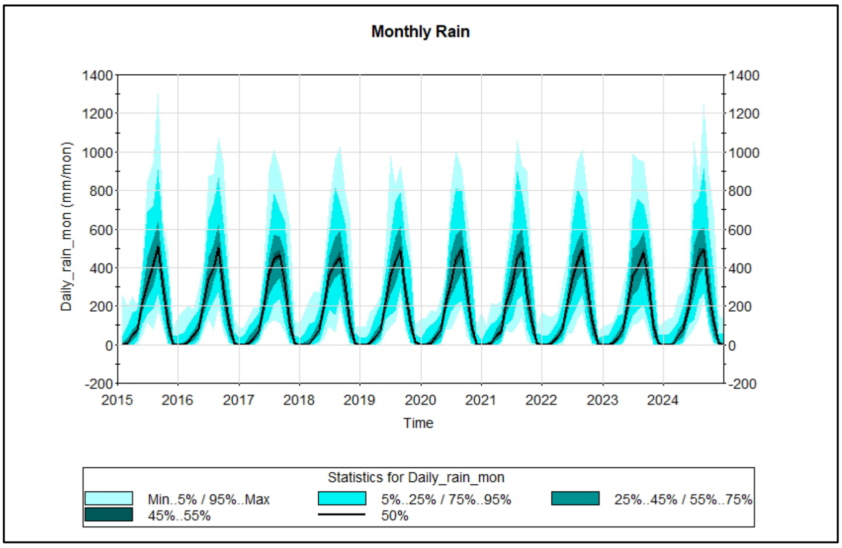
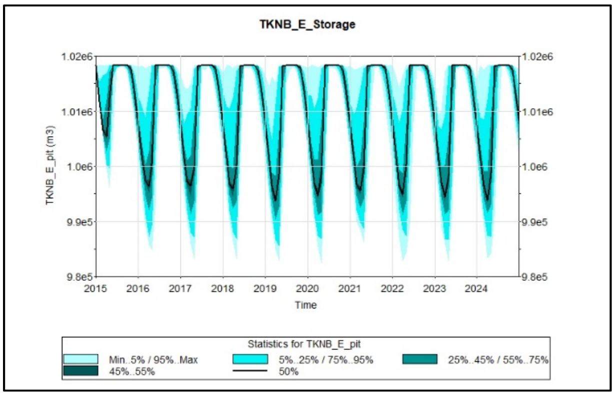
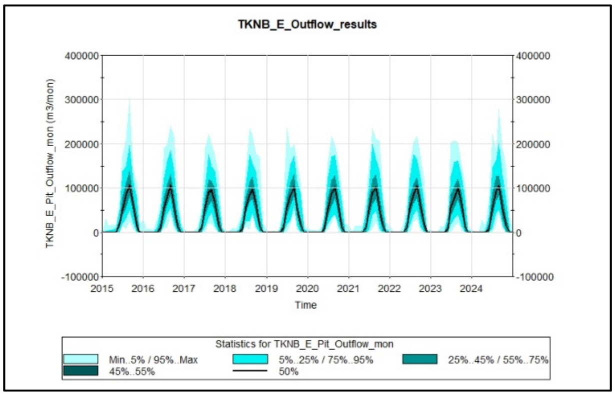


Figure 4 Probabilistic rainfall results from the CWBM

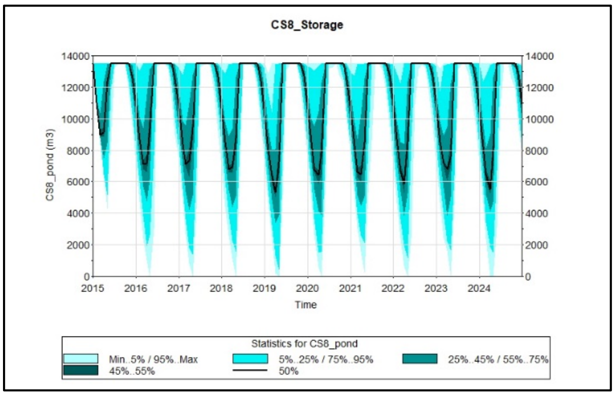
Based on the probabilistic results developed from the CWBM, even during the driest years, pit lakes will persist and will spill during the wet season. Similarly, during the wettest years, the water levels in the pits are reduced during the dry season with no outflow during the dry season. The sediment ponds are shown to follow a similar pattern (see Figure 5). Runoff from waste rock landforms also match seasonal rainfall patterns as shown in Figure 6, with flows expected during the wet season, and very low to no flows anticipated during the dry season. The probabilistic assessment for a representative WRD does not show any deviation for the typical seasonal runoff patterns for either the base case (uncovered) or the mitigated (covered) case. Runoff at Assessment Points (and from natural areas) also follows seasonal patterns, as demonstrated by the flow patterns predicted for Assessment Point CMN1 (Figure 6).



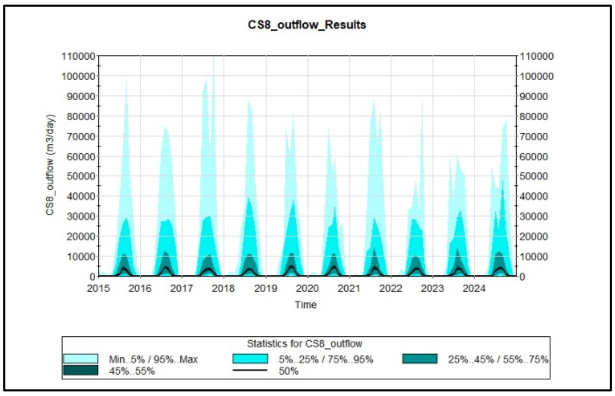
Pit Lake Storage Volume



Pit Outflow

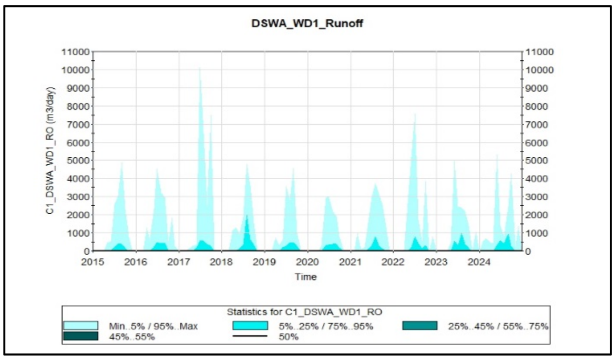


Sediment Management Structure Storage

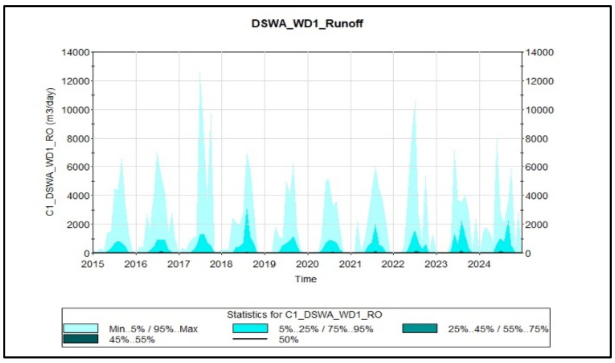


Sediment Management Structure Outflow

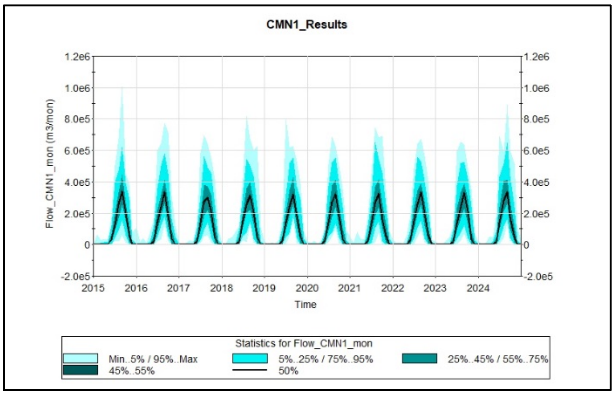
Figure 5 Representative probabilistic CWBM results for Pit s and Sediment Management Structures



WRD Runoff – Uncovered case



WRD Runoff –Covered case



Assessment Point CMN1 Runoff

Figure 6 Representative probabilistic CWBM results for Waste Rock Dumps and Assessment Points

6 Conclusions

Results of the water balance modelling indicated the following:

- The influence of the extreme seasonality of rainfall patterns is noted in all aspects of the model. Runoff from mine infrastructure and natural areas is unevenly distributed throughout the year, with very high flows in the wet season, and little to no flow during the dry season. Water volumes in storages, including pit lakes and sediment dams, vary significantly between wet and dry seasons.
- All pits form perennial lakes which overflow during the wet season.
- A majority of pits represent gaining water bodies, i.e. receiving more seepage from groundwater than they are losing. Groundwater mounding, which would be expected in an area with a positive water balance, is limited since in most cases spill points for pits are at or below the near-field water table elevations.
- Due to the scale of the assessment a large proportion of flows is derived from natural areas. This is primarily a function of the dispersed and small scale nature of mining at the site. This may have limitations on the suitability of the water balance results when considering precinct-scale closure options for future iterations of the closure plan.

The model is necessarily limited to use as a tool for evaluating closure options. The lack of available flow data for calibration of the model does add uncertainty to the results of the runoff and values; however, the predominant driver of runoff is the seasonal rainfall patterns, and uncertainties in runoff estimates are within the range of probabilistic results from the CWBM.

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STAMS[7]: New Tools for Monitoring Flooded and Non-flooded Mine Shaft

M Al Heib *Ineris, France*

O Alvarez *grupo hunosa, Spain*

J Alvarez *Universidad Carlos III, Madrid, Spain*

M Bedford *University of Exeter, GB*

FM Fernandez *grupo hunosa, Spain*

A Jardon *Universidad Carlos III, Madrid, Spain*

F Hadj Hassan *Mines Paris, France*

S Lafortune *Ineris, France*

Z Lubosik *GIG, Poland*

C Satterley *The Coal Authority, UK*

K Siever *dmt-Group, Germany*

B Schoen *dmt-Group, Germany*

R Terroba *grupo hunosa, Spain*

A Werna *GIG, Poland*

A Winkler *SRK, Poland*

Abstract

In European coalmines, there are many unequipped, abandoned shafts (in Poland, Germany, France, Spain, UK and other countries) in which the long-term stability is a cause of concern. The need for continuous assessment and monitoring of the stability of abandoned shafts present a real challenge particularly for deep shafts. The European STAMS research project (Long-term STability Assessment and Monitoring of flooded Shafts), subsidized by the Research Fund for Coal and Steel programme (RFCS), is addressing this issue. The objective of the STAMS project is to implement Periodic Inspection Modules, and to design permanently installed monitoring systems, to achieve periodic and long-term continuous monitoring and condition assessment of flooded mine shafts. The project proposes solutions to monitor and to assess the stability and the conditions of flooded shafts, including the non-flooded portions of partially flooded shafts, for long periods of time. The Multi-functional Monitoring Module is able to make periodic measurements in order to assess the stability of a flooded shaft. The Ultrasonic Inspection Module allows the detection of lining deformations with high precision between periodic inspections of shafts. In addition to monitoring, a modelling approach has been developed to assess the long-term stability of shafts during and after flooding by coupling the hydro-mechanical behaviour with the chemical reactions which occur between the mine water and the shaft lining components. A database of the flooded shafts has been established. Laboratory and trials tests are carried out by the partners of the project to check the tools and to test them under real conditions. This paper presents and describes the developed modules and the first obtained results.

Keywords: *Shaft, lining, flooded, inspection, damaged, monitoring*

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[7]Partners of STAMS (http://stams-rfcs.eu/): INERIS and ARMINES (France), UK Coal Authority, University of Exeter (UK), DMT (Germany), GIG, PGG and SRK (Poland), Hunosa and UC3M (Spain).

1 Project rationale and objectives

In European coalmines, there are many unequipped shafts, which are mainly upcast ventilation (exhaust) shafts and, less often, intake shafts (Lecomte et al., 2012). In the Polish hard coal mining industry alone there are around 50 active shafts of this kind (Bock, 2014). Complementary to this, in France and the UK, there are more than 150,000 recorded mine entries, which may require inspection. The impacts are significant and vary from local scale (e.g. collapse) to mesoscale, where the extensive hydraulic interconnectivity of mine workings must be taken as a fact of life (Figure 5). Most European countries have problems with and are trying to deal with these issues.

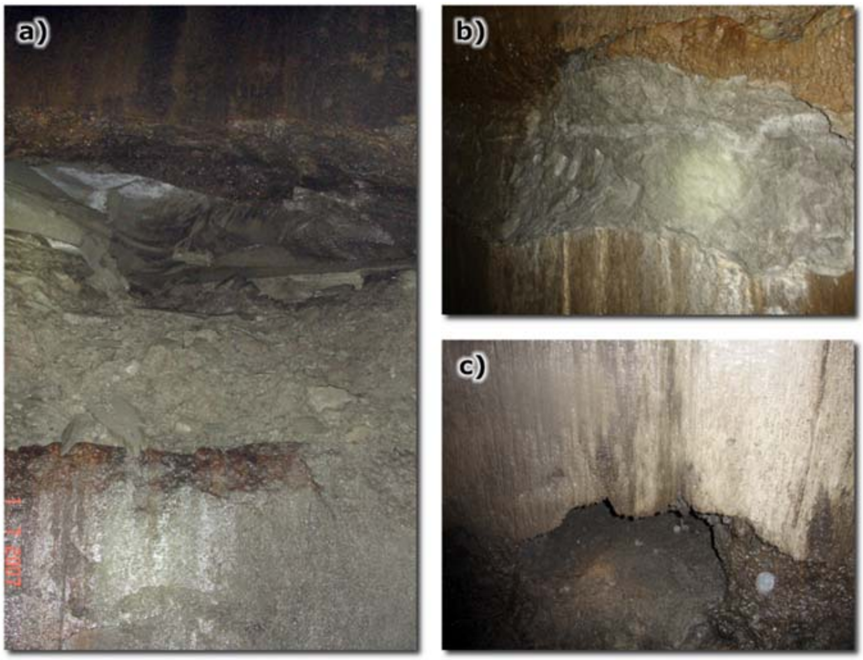

Figure 5 Examples of deep lining damage (Bock, 2014), a – very wide and deep lining loss throughout the entire thickness, with rocks visible behind the former lining b – deep lining damage (to a depth of approximately 20 cm), c – wide and deep lining damage

Depending on the context, the concrete lining of shafts may require periodic inspection and continuous monitoring to assess its condition and stability. However, in most ventilation shafts serving active mines, and in pumping stations using submersible pumps, there is no personnel access equipment installed. This makes it practically impossible to perform direct inspections on the lining of even the non-flooded portions of the shafts, because there is no safe means of access. In Poland, there are currently 30 active shafts which are partially flooded, whose lining must be evaluated every five years according to legislation. However, given the technical limitations (lack of proper equipment), even when limited inspections are possible, they are carried out only on the upper, non-flooded shaft sections. It should be emphasized that in such cases the full assessment of shaft lining stability is impossible using currently available techniques. Similarly, in the UK, there are an estimated 1,000 – 5,000 flooded open coal mine shafts and a legal obligation to ensure their safety (Whitworth, 2002).

Although existing technologies used in other industries (e.g. oil and gas borehole logging) can work at depths of 1500 m, as required for this application, monitoring flooded mine shafts poses unique challenges that are not addressed in other industries.

Another particularly big issue is the necessity to lower an instrument to the proper depth before starting the appropriate underwater inspection. That is because the water level in many flooded shafts is located at a depth of several hundreds of meters below the surface. To avoid entanglement with shaft infrastructure in the non-flooded section of the shaft, and to allow a single module to be used both above and below the water surface, monitoring and inspection modules must incorporate some inspection capability above the water level. This requires a unique combination of existing dry shaft inspection techniques and technologies relevant to the underwater environment.

The objective of the project is to develop technologies to assess the condition of shafts that are partially or completely flooded now, and of those that will be flooded in the future. Such an assessment is essential in order to take action to avoid the detrimental effect associated with the deterioration of disused mineshafts. The need for continuous assessment and monitoring of the stability of abandoned shafts will increase in the following years. The project contributes to the future urban development of coalmine districts in European coalfields.

2 Flooded shafts characterization

In order to better understand the monitoring requirements, 23 Polish coalmine shafts were analysed (Figure 6). The data obtained shows that, in most cases, the depth of the shafts is between 500 and 700 m. Only two shafts were deeper, but even then, the depth was less than 800 m. The water level in many flooded shafts is located at a depth of several hundreds of meters below the surface. The diameter of shafts of the most cases (69%), is between 4 and 6 m. The practical implications of the data obtained is that the inspection devices should be able to operate in shafts with a diameter between 4 and 8 m. The collected data shows that significant access limitations result from the size of the access opening. The minimal values (0.60 - 0.75 m) occur in 6 of the 23 shafts. However, the size limitations have a larger impact on the dimensions of the inspection modules. In some cases, it should be assumed that a reconstruction of the shaft opening may be required. The most typical lining in the analysed shafts is concrete with thickness between 0.5 and 0.75 m.

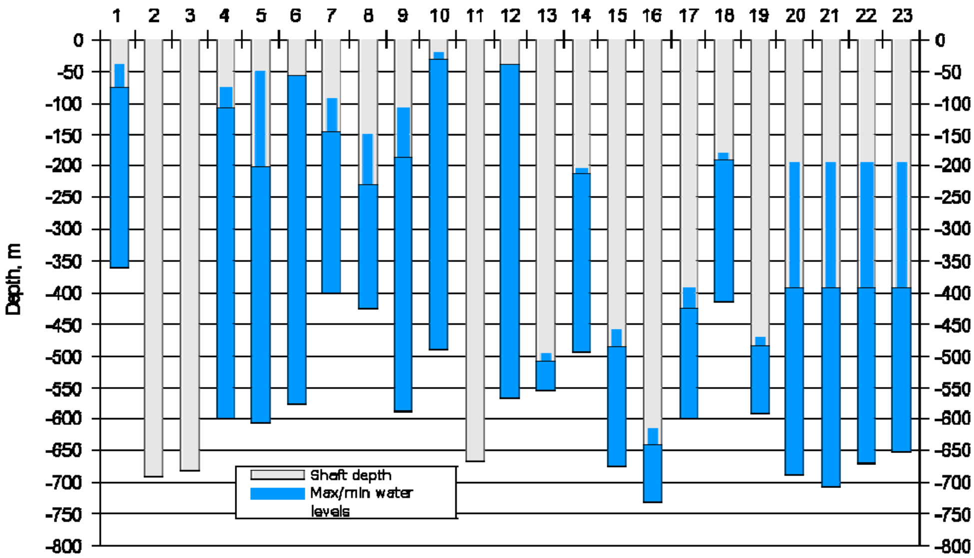

Figure 6 Range of Shaft Depths in Analysed Shafts

3 Periodic inspection system

3.1 Overview

A periodic inspection system has been developed to evaluate the state of flooded shafts. The periodic shaft inspection system of the STAMS project comprises two different periodic measurement modules (PMMs)- the **U**ltrasonic **I**nspection **M**odule (UIM) and the **M**ultifunctional **M**easurement **M**odule (MMM) - and the **R**eference **P**oint **I**nstallation **M**odule (RPIM) which is used for fitting reference points that will subsequently be detected by the inspection modules (Figure 7). The PMMs have been designed and developed to withstand an external water pressure of 150 bar which corresponds to a depth of 1500 m.

In order to minimize development cost and equipment cost for the end user, a decision was made to use certain common sub-modules as illustrated in *Figure 7* and described in the following paragraphs.

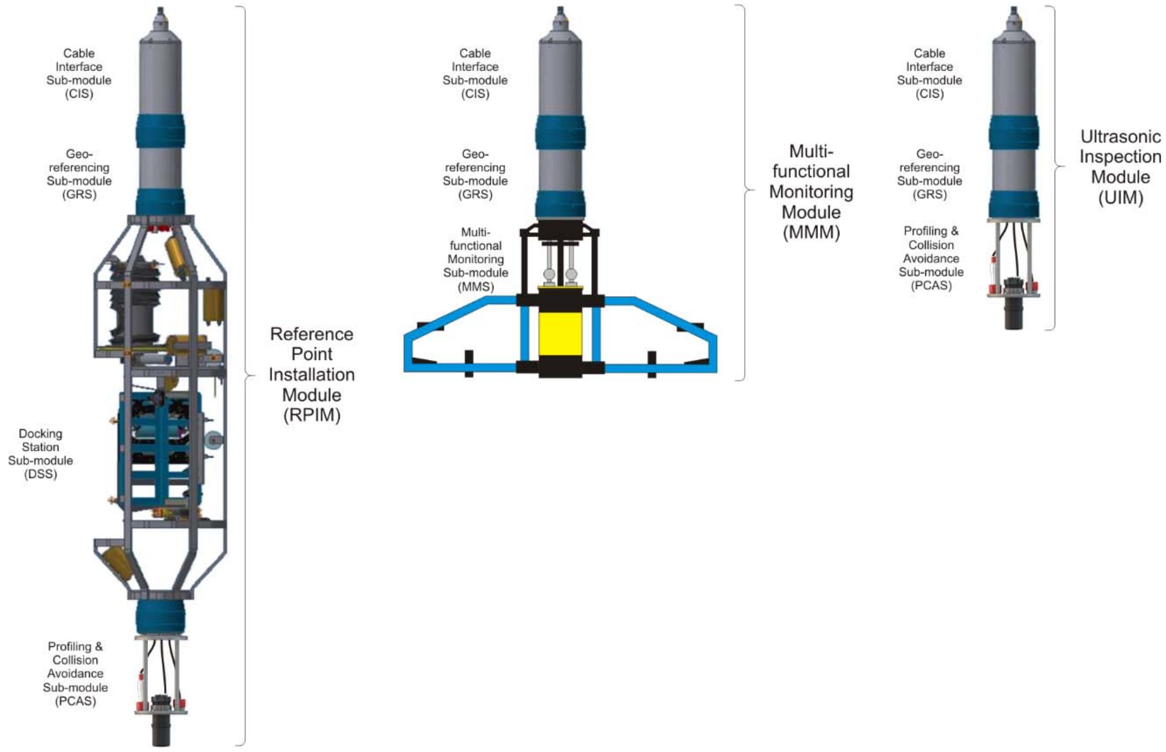

Figure 7 Periodic measurement modules (PMMs)- the Ultrasonic Inspection Module (UIM) and the Multifunctional Measurement Module (MMM)

The Geo-referencing Sub-module (GRS) contains an inertial measurement unit (IMU). This allows the orientation of a PMM with respect to north and its position within the cross-section of the shaft to be determined, so that unintentional motion during winching operations can be corrected. Sensing of the fixed reference points is also an important element of geo-referencing but this is achieved using the same sonar instruments that are used to measure the shaft's profile which is external to the GRS. The Cable Interface Sub-module (CIS) provides a power supply and communication facilities, plus the mechanical interface between the module and the wireline. The PCAS (Profiling and Collision Avoidance Sub-module) provides the Obstacle detection, above the water level is achieved using a downwards looking CCTV camera while this functionality is achieved below the water level using a sonar altimeter. The PCAS is also used in the Fixed Reference Point Installation Module.

3.2 Multi Monitoring Module (MMM)

The MMM provides a suite of instruments, mostly for conducting tests on the properties of the water in flooded shafts and carrying out microscopic inspections, but with the addition of some rudimentary ultrasonic capability. The capability of the MMM is extended by the addition of a full scanning sonar capability, including both profiling and possibly also imaging. It was considered that this change would be much more cost-effective, for those users who require a full shaft characterisation including water sampling and ultrasonic surveying, than if two separate PMMs had to be used. The Multi-Functional Monitoring Module (MMM) has the following components:

- Cameras with 1/3 in CCD Sensor, wide angle and low underwater distortion and light sources working to the depth of 6000 m (producer Deep Sea);
- Transmission and power modules compatible with Fixed RPIM;
- Car trailer and winch components will be used to inspection zone of the flooded shaft.

3.3 Ultrasonic Inspection Module (UIM)

The Ultrasonic Inspection Module (UIM) is one of two Periodic Measurement Modules (PMMs) that have been developed in the project. Its purpose is to carry out ultrasonic inspections of the lining of flooded portions of shafts where visual inspection would not be possible due to the turbidity of the shaft water. In particular, the output of a scanning exercise is a series of shaft profiles, from which a 3D model can be built, that can be compared with the output of previous scans to detect changes which could indicate damage to the lining and, hence, possible imminent collapse.

Ultrasonic scanners (sonars) take one of two forms as illustrated in **Fehler! Verweisquelle konnte nicht gefunden werden.**: (1) A profiling scanner has a narrow sonar beam which intersects with the surface being scanned at right angles. It records either the first or the strongest return signal. Multiple measurements are made by use of mechanical scanning – through 360 degrees in the case of a shaft – and when this is combined with the vertical movement of the unit down the shaft by winching, a geometrically accurate 3D model of the shaft is obtained.

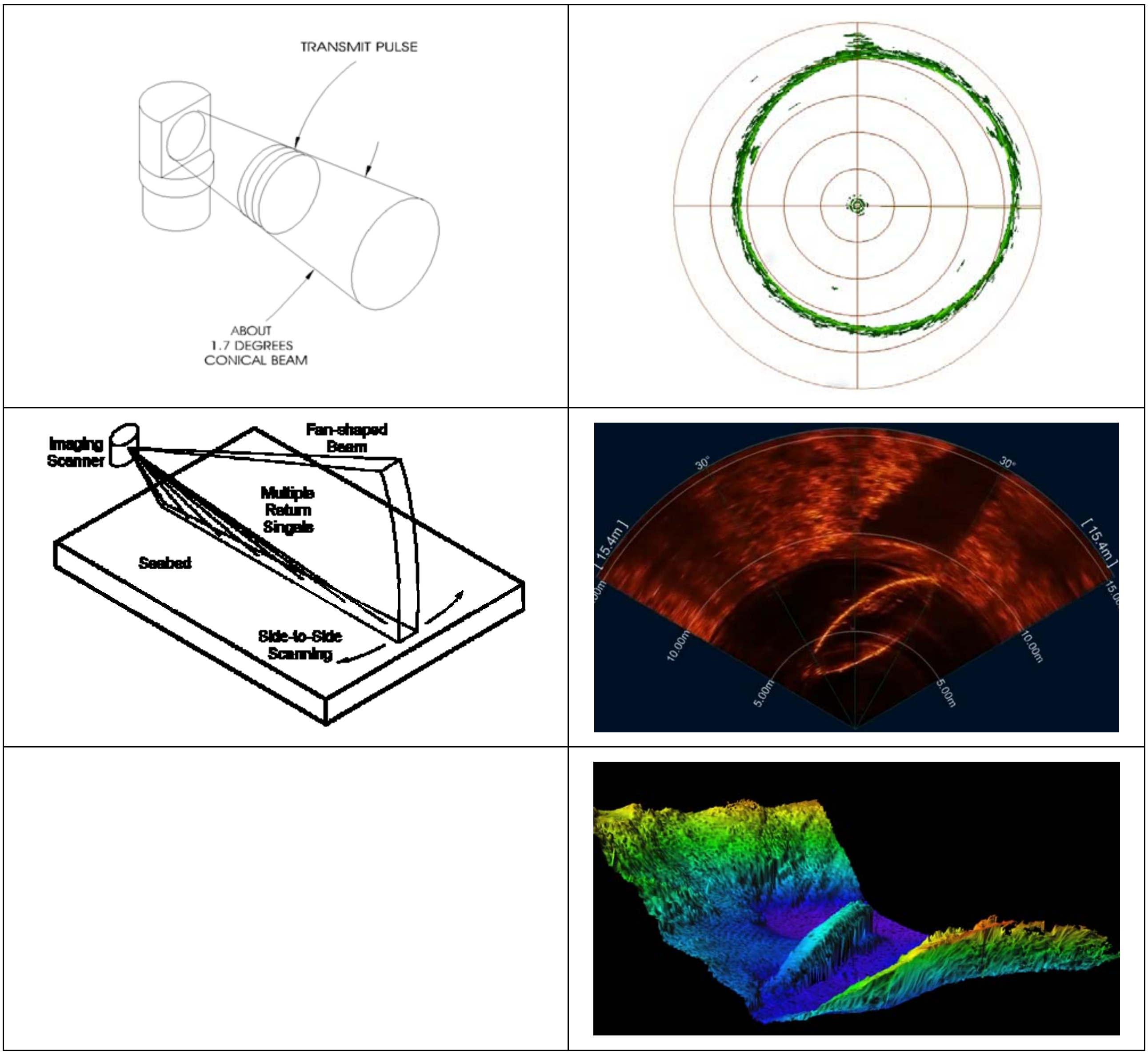

Figure 4 Comparison between Profiling and Imaging Sonar Top-left: Profiler beam characteristics, Top-right: Typical profiler output (mine shaft), Middle-left: Imager beam characteristics for typical seabed application, Middle-right: typical imager output (ship on seabed), Bottom-right: Waterfall display generated from profiling output (feature on seabed)

(2) An imaging scanner has a broad fan-shaped beam which intersects the surface being scanned at an oblique angle. Multiple return signals are recorded, corresponding to different distances from the scanner. Again, rotational scanning occurs and, since the amplitude of the return signals provides density information about the target, this allows an image to be created that is similar to a visual image.

In this application, it was initially considered that a novel combination of the two types of sonar would provide accurate measurements from the profiler while the imager would assist in the identification of features. It was decided early in the project, however, that a major differentiator between the two PMMs should be one of cost, allowing end users to choose either a low-cost unit with basic facilities (the UIM) or a higher-cost unit with a broader range of facilities (the MMM), depending on their budget. For this reason, it was decided to include only a profiling sonar in the UIM but to allow the display of a software generated waterfall display (see **Fehler! Verweisquelle konnte nicht gefunden werden.**) which will offer many of the perceived benefits of an imaging sonar but without the incremental cost of the additional hardware. The sub-module that achieves the UIM's main purpose of measuring the shaft's profile is the Profiling and Collision Avoidance Sub-module (PCAS). As the bottom-most sub-module in the UIM, the PCAS also includes instruments for detecting obstructions below the UIM which could pose a collision risk. All the instruments in the PCAS are off-the-shelf instruments. The profiling sonar, selected from candidate instruments from four manufacturers, is the Tritech Super Seaking Profiler.

3.4 Reference Points Installation Module (RPIM)

The main function of the Reference Point Installation Module (RPIM) is the installation of the so-called Reference Points (RP) along the shaft wall. The Reference Points will serve to correct the estimated position of the sensing modules: as these RPs are placed in known positions, a map will be created through which the modules can correct their position by obtaining their relative position with respect to the Points of Reference. Reference, applying an algorithm of SLAM (Simultaneous Localization and Mapping), similarly to (Gomez et al., 2004, Lefebvre et al., 2009). The RPIM will be hung along the shaft through the common cable to the rest of the modules, through which it also transmits information. For the installation of the points, a submarine mobile robot (ROV, for its acronym in English) is used, which carries with it the tool for fixing reference points. During the descent, the ROV will go inside a cage (Docking Station Sub-module, DSS), which will protect it from possible impacts (see Figure 1 and Figure 2). Once the desired height for the fixing of Reference Points has been reached, the RPIM will stop and the ROV will navigate autonomously or teleoperated out of the cage towards the desired fixing point. Once the fixing process is finished, the ROV will return to the cage and continue the descent of the RPIM. The RPIM will place said RPs only in the flooded section, since the dry section would require additional machinery. The design criteria for the RPS requires passive units, to avoid the use of batteries or electrical wiring, in order to minimize the need for maintenance, which would be challenging and potentially costly in the flooded shaft.

To accomplish this requirement two possibilities have been considered. First, the use of RFID (Radio Frequency Identification) tags. Taking into account that the water of the mines presents a high conductivity, the dispersion of the magnetic fields is very high (inversely with the cube of the distance (Domingo, 2012, Meybodi et al., 2011)), requiring work in the low frequency spectrum (LF, 120-150 kHz) to minimize this effect. These frequencies, however, would require very long antennas, and, therefore, very large reference points. Due to the practical issues and potential costs of installation of large reference points the possibility of benchmarking using RFIDs was ruled out. The second possibility seeks to take advantage of the acoustic technologies available. Bearing in mind that an ultrasound scan of the shaft wall will be carried out, the Passive Reference Point will consist of a three-dimensional volume easily distinguishable from the medium. The final dimensions of the RPs have been adapted to the sonar resolution.

The final design, as shown in (Figure 8), is a triangular prism of 10 mm high and 130 mm side, since the Profiling Sonar has more precision of depth than lateral. The selection of the size of the reference points has been taken according to the minimum dimensions that the Profiling Sonar can detect in the worst case: that is, when the distance between the sensor and the wall is maximum. It has been considered that this maximum distance is 5 m considering that it is the maximum radius found in the shafts of the mines studied in this project (see Figure 8).

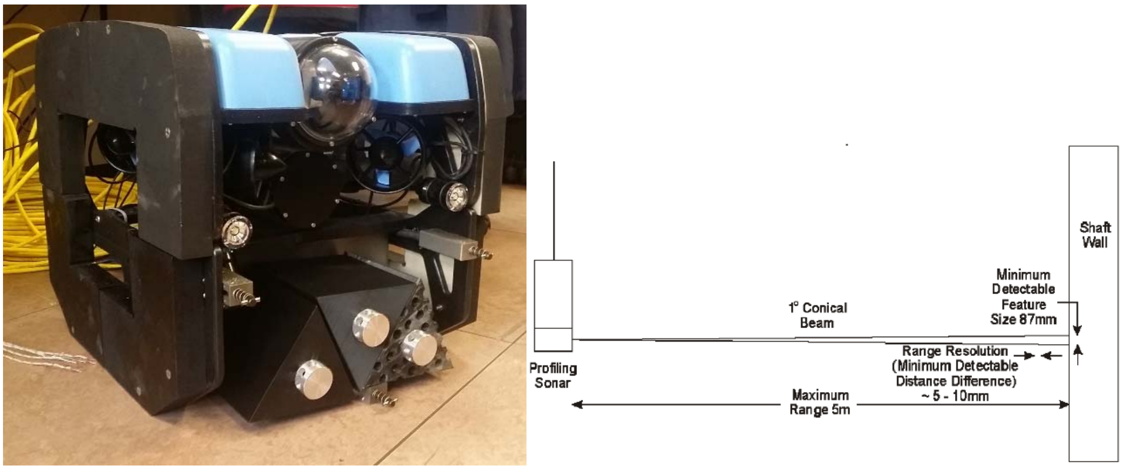

Figure 8 **Design of the triangular reference points, arranged in the housing of the fixing mechanism, the minimum size of an element on the wall that the Profiling Sonar can detect is 87 mm when the distance between the sensor and the wall is 5 m.**

Remotely operated vehicle (ROV) Autonomously Operated Vehicle

Due to the novel conditions that the flooded mines represent for underwater inspection, the use of a simulator is required to predict the possible behaviour of the submarine vehicle and the sensors before real-life tests. The UWSim or Underwater Simulator, is a simulator of open-source submarine vehicles, which includes the necessary sensors for navigation, such as IMUs, sonar for obstacle avoidance, RGB cameras, depth sensors, force sensors, etc. It also provides an interface with ROS (Robot Operating System (Quigley, 2009), which allows acquisition and processing of this data, or send commands to the actuators through ROS nodes. This allows simultaneous operation of the underwater vehicle and the simulator. A sensor model has also been developed that emulates the behaviour of a Profiling Sonar, including the characteristics of commercial sensors. The data will be acquired through the UWSim and will be processed with the Point Cloud Library (PCL).

The ROV used for this project is the BlueROV2 (Figure 8). Given that in the worst case the conditions of visibility will be zero, the rest of the available sensors (Profiling Sonar, IMU) will be used to implement a sensorial combination that allows obtaining of the position of the ROV with the minimum possible error. With this, an algorithm will be implemented that makes the ROV autonomous, with the possibility of teleoperating it when necessary. It will therefore have both management functions: teleoperated (ROV) and autonomous (AUV). All these algorithms will be developed in the simulator first, to later implement them in the real robot.

Fixation tool

The methods of fixing the Reference Points that have been studied are bonding, drilling and direct fixing. The possibility of bonding was discounted due to the high amount of dirt or suspended solids present on both the walls of the mine and in the water, as this would require a complicated pre-treatment of the surface. The drilling thrust depends on the geometry of the drill (diameter, point angle, lip length, evolution of the cutting angles along the edges, etc.), the cutting conditions (cutting speed, feed rate, lubrication, etc.) and on the material's properties. The influence of the material's properties on the cutting thrust is characterized by the hardness or by the coefficient which depends on the shear flow stress.

It was observed that overall the thrust was linear with hardness, in other places the variation of thrust was not necessarily regular and linear, in particular for iron-carbon alloys. Parameters related to the material, other than hardness, can modify the cutting thrust level. It is recognized that the presence of oxide and sulfate inclusions in the slim form leads to a cutting force reduction. Reduction of adherence between chip and tool results in a reduction of the cutting thrust. In a wet hole or unconsolidated material, it will be necessary to feed the hammer slowly to sufficiently clean the hole as the hammer is advanced. A rotatory drill is obtained with a hammer action. The hammering action provides short hammer thrust to pulverize relatively brittle material. These drill strings work in torsion an experiences axial and torsional vibration. Those high and complex forces and torques would be very difficult to compensate by the ROV, which leads to this possibility being discounted in this case.

Another possible approach is using tools for direct fastening. In these tools, the fastener driving power is generated by a power load of combustible gas or compressed air. They are self-centering, and used for deep holes, providing high cutting speeds. The bits use a rotary motion similar to a twist drill, but the bits are designed with bearing pads that slide along the surface of the hole keeping the drill bit on the center. They can work in both steel and concrete. Other advantages of this system for the application of the RPID, are its simplicity, the no need of electric powder and its high speed. As such, direct fastening is the method of choice, because advantages such as self-centering, concrete or steel applicability. Moreover, there is no electric power consumption, due that firing is activated electronically and the power provided by the internal powdered cartridges.

3.6 Communication module

The Figure 9 represents the main modules and the communication protocols that each one has with the central station via CIS (Cable Interface Unit):

- The RIPM is formed by the DSS, the AUV with the fixation device and the PCAS. The AUV is connected with the DSS via Ethernet, and then the DSS transmits the information via RS 232, GPIO, and analog Video /HDMI.
- The Ultrasonic Inspection Module (UIM) collects sensor data from Profiling Sonar and GRS. Those data are sent to the CIS via RS 232.
- The Multifunctional Monitoring Module (MMM), similarly to the UIM, collects sensor data and sends it uphole. The images from the CCTV are sent to the CIS via RS-485.

All those modules will work concurrently, but the operation of all of them will be managed by a common modular software. This software will facilitate the operation of the corresponding hardware device.

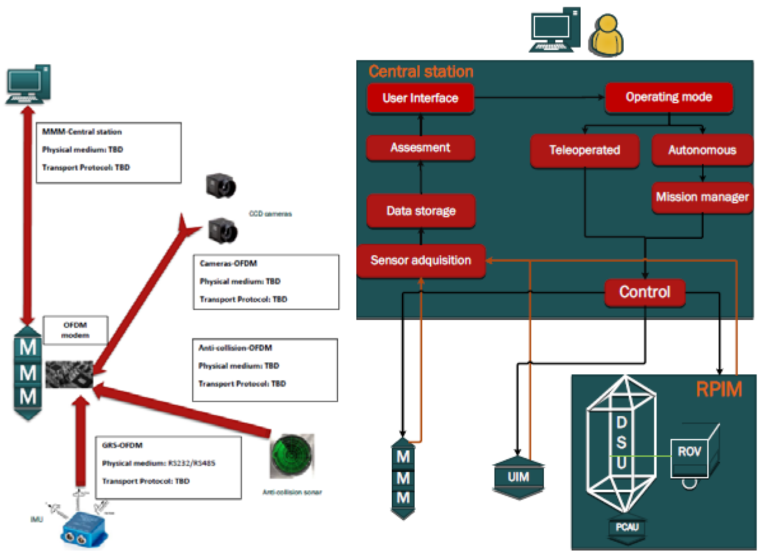

Figure 9 Communication modules and the communication protocols

4 Continuous Monitoring

4.1 Introduction

While the Periodic Inspection Modules allow detailed inspections and measurements to be made on an infrequent basis, the complementary continuous monitoring regime has been designed to make a more restricted range of measurements but to allow them to be made on a continuous basis. The system includes two elements – a tube bundle system and an electronic sensor system – so that end users may choose to implement one or both, depending on their budget and the requirements of a particular shaft. In the event that both elements are installed, a degree of redundancy is provided. So long as the electronic sensor string and the tube bundle are widely separated within the shaft's cross-section, it is considered likely that any incident that damages one element would probably not affect the other so a degree of continuous monitoring would remain operational.

4.2 Tube Bundle System

The tube bundle system works on the same principle as the tube bundle systems that are often employed in working mines, mostly in Australia and China, but with some limited use in European mines. The method of working involves drawing samples of the atmosphere from different parts of the mine, using a pump, via different sample tubes within the bundle, for chemical analysis at the surface – see (Zipf *et al.*, 2013) and (SIMTARS, 2015). It is envisaged that very similar surface equipment to that used in working mines could be used, to sample air in the dry portion of abandoned shafts, although a special tube bundle has been designed to withstand the hostile conditions that could be encountered in an abandoned shaft. This takes into account the fact that the underground elements of the continuous monitoring systems must be considered "fit and forget" systems that are capable of operation for many years or decades without the option of maintenance. Initially, consideration was given to also using the tube bundle for water sampling in the flooded portion of a shaft but this was abandoned because the submersible pumps that would be required would not meet the requirement of a long operating life without the option of maintenance. This decision also embodied the philosophy of using each of the continuous monitoring systems for the environment and application for which it is most suitable.

Conventional tube bundles employ several sample tubes surrounded by an outer layer but, for this application, a novel three-element tube bundle was designed to meet the requirement of increased resilience to impacts. It is shown in Figure 10. The three elements are (1) the sample tubes which are made of polyethylene, (2) an intermediate yielding layer, designed to absorb impacts, made of thermoplastic polyurethane, and (3) an outer layer made of PVC with an anti-static additive.

Figure 10 Prototype of Extra-resilient Tube Bundle

Tests, involving dropping weights onto pieces of the tube bundle prototype, demonstrated a good degree of resilience. In particular, a weight of 64kg, dropped from a height of 2m, resulted in abrasions and some tearing on one side and a cut on the other of the outer layer, although neither was full depth. No damage occurred to the intermediate layer, and moderate flattening and lateral crush marks occurred to the sample tubes, although they were still completely airtight. Although more severe incidents, such as segments of cage rails or steel pipes coming loose and hinging into the tube bundle, would undoubtedly destroy the tube bundle, indeed it would be prohibitively expensive to provide protection against such severe incidents, it is considered that the bundle will survive a large proportion of possible in-shaft incidents.

Unlike the situation with active mines, where joint boxes allow sample tubes to be directed to a large number of different areas of the mine in a tree-like structure, in this application it is necessary only to provide a means by which a single sample tube can be extracted from the bundle at a small number of depths in the shaft to allow atmospheric sampling. To achieve this, a so-called breakout box has been designed and prototyped. Attention has also been given to support for the tube bundle because it will often be installed post-closure, so there will be no opportunity to attach it to the shaft lining at regular intervals, as would be the case in a working mine. Support is achieved using a synthetic 16mm double braided rope with a Dyneema core and a polyester outer cover. The tube bundle is clamped to the rope at regular intervals and also immediately above and below each breakout box as shown in *Figure 11*.

Figure 11 Breakout Box Fitted to Tube Bundle with Support Rope Attached

4.3 Electronic Sensor System

The electronic sensor system can be used in both the dry and the flooded section of a shaft even though, in most cases, different sensors would be used in these two regions of the shaft. Several initiatives have been developed to reduce the cost of installing an electronic sensor system and to achieve the aim of providing a "fit and forget" solution. This will make implementation more attractive to the end user, thereby increasing the number of systems that may be installed, and increasing the system lifetime to achieve the required long-term monitoring capability.

One of the most innovative technologies to be developed, for reducing installation cost and increasing long-term reliability, is a scheme for the contactless transfer of power and data between the sensors and the line. A previous version of this type of telemetry system was developed for use in transport tunnels (European Commission, 2008), but there has been no known similar development for use underwater.

In the scheme developed for abandoned shaft monitoring, each pod of sensors (known as an out-station) is contained in its own pressure-proof housing and receives power by inductive coupling to an external line carrying a low frequency alternating current. The same line carries data, which is modulated on a low frequency carrier, and which is also coupled inductively, allowing bi-directional data transfer. Typically, each out-station would be polled in turn by a master control unit, and asked to upload its data or to report its status.

The single power/data line comprises a braided stainless steel core cable with a thick polypropylene outer cover, which may in principle be several kilometres in length. The significant feature of the system is that there are no direct connections to the out-stations. Connectors for submarine housings – or 'penetrators' as they are known – can be extremely expensive. The absence of penetrators, coupled with a simple design of pressure-proof housing capable of withstanding 200 bar, helps to achieve significant cost and reliability benefits. An additional feature that contributes to the cost-effectiveness is that the housings are designed to fail 'safe'. As the water level rises in the shaft, the housings under the most pressure stress can fail without affecting the integrity of the rest of the system.

The out-stations contain a high-quality piezo-resistive pressure sensor, to allow them to measure water depth, as well as sensors for temperature, accelerometer (for detecting motion in the water that could be indicative of shaft stability issues) and water conductivity. The ends of the pressure-proof housing are metal and the body is plastic, so this allows a simple two-terminal resistance measurement. In theory, the housing could be adapted for a four-terminal measurement, which is more reliable in conditions of high conductivity.

This project has also looked at the scope for contactless conductivity measurement and at methods for correlating conductivity (and temperature) with pH value.

Internally, the most obvious method of providing power is from a small rechargeable battery, charged via the inductive coupling. However, such batteries do not have a long lifetime, especially when trickle-charged on a continuous basis, which was the original intention. It has therefore been necessary to include a power management utility in the software, and to consider the use of super-capacitors as an alternative to conventional batteries. There are several possible inductive coupling topologies, the simplest of which is the toroid. However, a toroidal coupling is difficult to assemble in the field, especially if one wants to avoid breaking and re-joining the cable. Other topologies such as a loosely-coupled bobbin have been investigated.

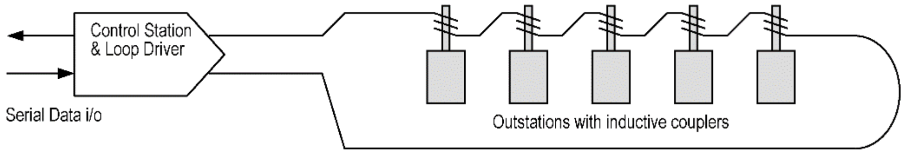

Figure 12 Block Diagram of Underwater Transmission Scheme The control station features a high-stability trans-conductance amplifier and bridge driver. The communications line couples inductively to the outstations and transfers power and data.

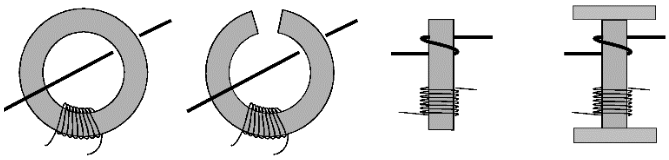

Figure 13 Examples of Inductive Coupling A toroid has practical disadvantages. However, other arrangements, as shown, result in only loose coupling. The bobbin (right-most figure) is considered the most practical configuration.

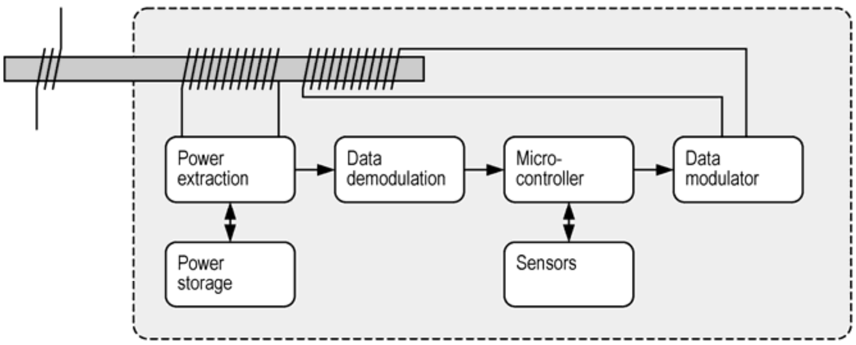

Figure 14 Block Diagram of an Out-station

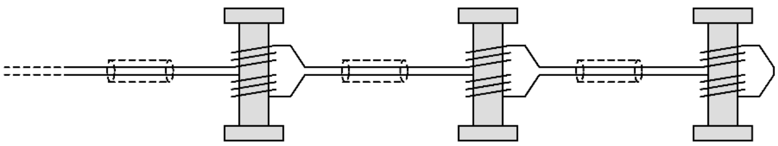

Figure 15 Common-mode Noise Reduction using a Paired Line

5 Long term stability modelling

Shaft long-term stability after its closure is mainly governed by the behaviour of its lining which is generally composed of concrete or brick/masonry. Tubbing mainly with cast iron is sometimes used when crossing aquifer formations particularly for very old shafts. Shaft stability becomes critical during the flooding phase where lining is attacked by highly polluted water with aggressive minerals such as sulphates and chlorides. This leads to lining weakening and its potential failure, inducing thereafter the risk of shaft collapse.

The flooding phase involves three kinds of loadings applied on the lining (Corvisier et al., 2010). The first one is mechanical and is linked to shaft sinking and lining installation (permanent stress regime). The second loading is hydraulic and is related to water table regime (water pressure). The last loading is due to corrosion and chemical reactions which occur between mine water and lining materials (loss of thickness and degradation of mechanical properties). Hence, to deal with long term stability of a shaft, it is necessary to examine the risk linked to each one of these three loadings and to couple them at the end for a reliable assessment.

The mechanical behaviour of shaft and lining may be studied by classical approaches (either analytical or numerical) using the convergence-confinement method to evaluate properly the loading within the lining. This requires of course knowledge of the geological and geotechnical properties of the host rocks, the geometrical data of the shaft (depth and diameter), the lining properties (composition along the depth, thickness and mechanical properties) as well as the procedure of lining installation. For the hydraulic aspect, both the hydrogeological data of the grounds and the lining hydraulic properties are required. Numerical hydromechanical models can then be used to forecast the excess of loading brought on the lining by the water table regime.

The chemical loading needs more detailed data especially at the lining level. The composition of the material as well as the mine water which will be in contact should be known. This operation is done commonly by in-situ sampling and by laboratory measurements (optical microscopy, electron probe microanalyser and X-ray diffraction for lining material and pH, conductivity and chemical composition for mine water). Batch leaching tests can be also carried out and their results analysed in terms of solution composition as well as solid phase. Based on measured properties, the potential chemical reactions and pathologies are evaluated and dedicated numerical models coupling geochemistry with transport are implemented to study the durability of lining. These models consider the thermodynamics and kinetics of the materials in aqueous solutions and the reactive transport to estimate the altered thickness of the lining during the considered period.

At the end, shaft stability is evaluated by calculating a safety factor which is defined as the ratio of the lining material strength by the active stresses. For the hydraulic and mechanical aspects, coupling is classical and the evaluation of the safety factor is obvious provided using consistent assumptions in numerical modelling and reliable mechanical and hydraulic properties. However, for the chemical aspect, full coupling is not easy. The proposed approach is simple and consists of simulating the chemical reactions and estimating the degraded width from each lining side (internal face inside the shaft and external face rockmass side). This degraded width is supposed to be totally ineffective and lost and therefore lining thickness is reduced from each side by this width. The remaining part of lining is assumed to preserve the initial mechanical properties of the material without any weakening effect. Stability can be therefore assessed by establishing charts giving the variation of the safety factor for a given thickness and strength of the lining material and given conditions of the shaft (geometry, mechanical and hydraulic loadings). Within the project, this approach was applied at three different levels: first, illustrating its principle on three French shafts lined with concrete and cast iron where sufficient data were available on the required characteristics of the rockmass, lining and mine water. Two Polish shafts which have collapsed by lining failure were then back-analysed to demonstrate the capability of the approach to reproduce observed behaviour. Finally, the long-term stability of selected shafts from partner's sites was assed using the available data. An illustration of the modelling results on two French shafts lined with concrete is given by Figure 16 and 24.

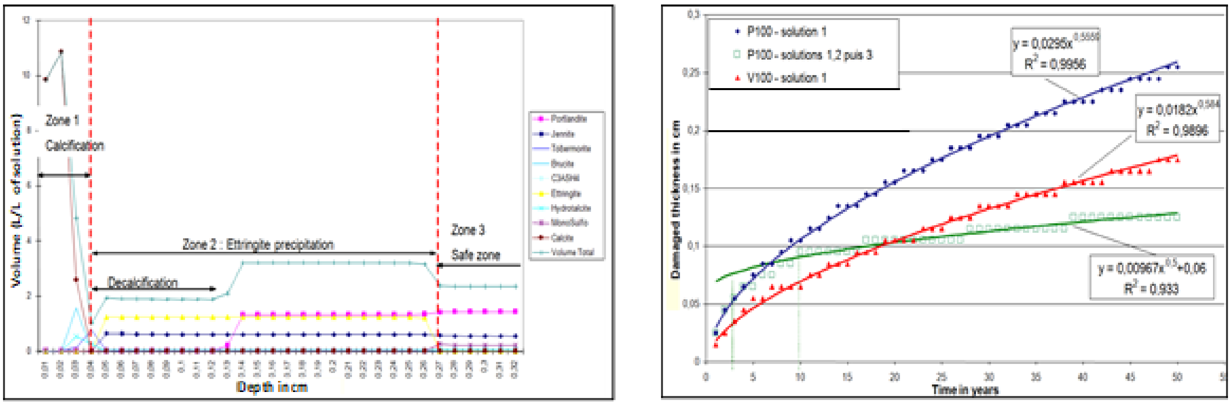

Figure 16 Illustration of chemical attack of concrete lining by mine water and progress of the degraded front with time

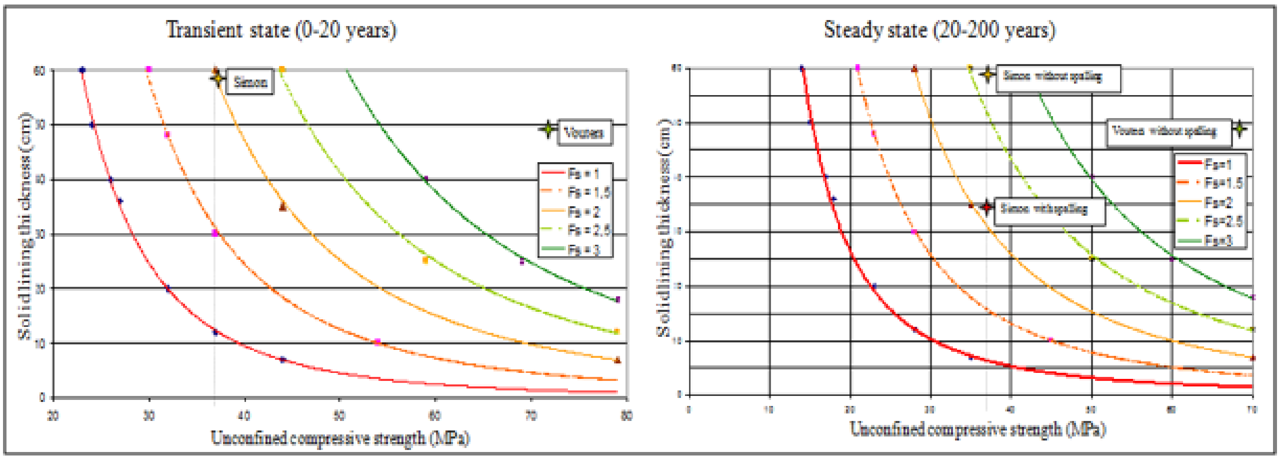

Figure 17 Stability conditions of the two shafts for the transient and steady phases

Parallel to the modelling work, a testing programme was set up on concrete samples submitted to different water solutions. Concrete was selected at it represents the most common shaft lining material in coal mines. The aim of the tests is to validate the parameters assumed in modelling particularly in relation with the chemical and mechanical aspects.

6 Conclusion

The stability of abandoned mine shafts is a major cause of concern, because of the risk to life and property in the case of collapse. For this reason, there is significant interest in being able to inspect shaft linings for signs of damage. Significant work has been carried out into developing inspection methods for dry mine shafts but flooded shafts pose a greater problem. Because most shafts will, eventually, become at least partially flooded, the STAMS research project is developing inspection technologies for flooded, abandoned mine shafts.

Instruments, which will be winched down the shaft from the surface, have been developed for carrying out periodic inspections. The Multi-functional Monitoring Module will carry out an extensive range of measurements, including video inspection, sonar investigations and water analyses. The Ultrasonic Inspection Module is designed for end users with a lower budget, and allows for accurate cross-sectional details to be recorded via sonar. Major differences in the results obtained during consecutive deployments is indicative either of damage or deterioration of the shaft lining.

To augment detailed periodic inspections, techniques for more limited monitoring, but on a continuous basis, have been researched. First, a tube bundle system has been designed for sampling the atmosphere at various depths in the dry portion of a shaft. This operates in the same way as similar systems in working mines but the tube assembly has been designed to withstand the harsh conditions in abandoned shafts to provide long-term, maintenance-free monitoring. Second, various technologies for implementing a system of electronic sensors, for use above and below the water lever, have been researched. Key techniques include a method of contactless power and data transfer, and a means of ensuring that any sensors that fail do not jeopardise the complete system. Both ensure low-cost installation and long-term operation.

Chemical reactions between mine water and lining materials, and the resulting alteration, may weaken the stability of the lining and induce failure. The risk of failure is greater with more critical initial stability conditions before flooding, and with acidic mine water. The uncertainties about the many types of data, required to carry out coupled modelling to assess the long-term stability of mine shafts, highlight the importance of monitoring and the need to implement innovative inspection and monitoring tools.

Acknowledgement

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Realising Beneficial End Uses for Pit Lakes

CD McCullough *Mine Lakes Consulting, Australia*

M Schultze *UFZ-Helmhotz-Centre for Environmental Research, Germany*

J Vandenberg *Golder Associates, Canada*

Abstract

There is growing recognition that pit lakes can represent significant liabilities at mine closure. With over ½ century of open cut mining demonstrated in most countries, pit lake legacies have been shown to present long-term and significant health, safety and environmental risks difficult to resolve.

However, pit lakes also present opportunities to provide significant regional benefit and even address residual closure risks of both their own and overall project closure, and, if properly planned, can offset the environmental costs of mining by creating new end uses. The following end uses have been realised: passive and active recreation, nature conservation, fishery and aquaculture, drinking and industrial water storage, greenhouse carbon fixation, flood protection and waterway remediation, disposal of mine and other waste, mine water treatment and containment, and education and research.

We reviewed published pit lake closure studies (both successful and not) combined with our own collective experiences to determine what lessons might be gleaned to improve closure practice. As with many mine closure outcomes, examples of end use development as a closure strategy are rarely published; and even more so when they are not successful.

We found beneficial end use type and outcome varied dependent upon climate and commodity; but equally important social and political dynamics that manifest as mining company commitments or regulatory requirements. We also found that initial optimism about likelihood of end uses being successfully realised often failed to meet stakeholder expectations.

Common attributes and reasons that led to successful closure outcomes as end use developments are discussed. Recommendations are given for all stages of mine closure planning to realise successful pit lake closure with beneficial end uses.

Keywords: *pit lake, closure, planning, end use*

1 Introduction

Mine pit lakes are created, intentionally or otherwise, when open cut mine voids fill with water (Castro & Moore 2000). When voids extend below regional groundwater levels, groundwater inflows may be the dominant contribution and controls to final lake volume and depth respectively (Werner et al. 2001; McCullough et al. 2013). Where surface water flows are significant into and/or out of the pit lake then this water source may be more important in defining pit lake hydrology and quality (McCullough & Harkin 2015; McCullough & Schultze 2015).

There is growing recognition that pit lakes can represent significant liabilities at mine closure; particularly to the environment (Doupé & Lymbery 2005). With over ½ century of open cut mining demonstrated in most countries, pit lake legacies have been shown to present long-term and significant health, safety and environmental risks that are difficult to resolve (Vandenberg & McCullough 2017).

However, pit lakes are one of the few closure landforms that concurrently present opportunity that may address residual closure risks of both their own and overall project closure (McCullough et al. 2009a). The following end uses have been realised: passive and active recreation, nature conservation, fishery and aquaculture, drinking and industrial water storage, greenhouse carbon fixation, flood protection and waterway remediation, disposal of mine and other waste, mine water treatment and containment, and education and research (McCullough & Lund 2006).

In this paper we provide examples of existing pit lake end uses and some collective insights from our work across three continents, and internationally, as to what end uses have been successful; and why.

2 Approach

We reviewed published pit lake closure studies (both successful and not) combined with our own collective and international experiences for a range of pit lake historical, current (undergoing closure) and planned outcomes. Collectively, this comprised a database of 226 separate pit lakes (221 existing lakes, 5 proposed. Pit lakes were tagged their end uses.

As previous studies have found (Castendyk & Eary 2009), most pit lakes were located in Australasia, Europe and North America. Although, the higher number of pit lakes in these continents is most likely an artefact of the authors' locations in addition to where most publishing activity has occurred, we focused on lakes from these continents where there was a greater knowledge base (Table 1). When these three continents were only concerned, most pit lake lakes included in the database were in Canada (45), USA (29), Czech Republic (26), and then Australia and Germany (24 lakes each).

2.1 Reviewed pit lake locations and physical characteristics

Database pit lakes ranged in depth from 2–400 m with a mean of 45 m (n=152). Lake surface areas ranged from 0.028–1,935 ha with a mean of 152 ha (n=153). The mined commodities are summarized in Table 1.

Table 1 Number of pit lakes by continent and country (>n=1)

Continent	Coal	Au	Sand	Aggregate	Fe	Cu	U	Pyrite	S	Pb	Limestone	Zn	Total
Europe	81	1	14	1	0	0	0	4	3	0	1	2	**107**
North America	39	14	0	1	6	4	5	0	1	3	0	0	**73**
Australasia	15	5	0	5	1	1	0	0	0	0	1	0	**28**
Grand Total	**135**	**20**	**14**	**7**	**7**	**5**	**5**	**4**	**4**	**3**	**2**	**2**	**208**

3 Realised end uses

Our review identified a number of end uses that pit lakes were being used for (Table 2). Key end uses were defined as follows.

1. Wildlife: Planned or otherwise providing significant wildlife habitat for aquatic and/or amphibious ecology.
2. Fishery: Used as either an incidental, planned or stocked fishery; or for the purposes of aquaculture. Fin fish, crustacea or otherwise.
3. Recreation: Active recreation such as swimming, boating, water skiing and SCUBA diving. Also including passive recreation of water-oriented amenity such as picnic areas and walking/biking trails around the lake.
4. Source and storage of water: Providing a water source for either potable, irrigation (agriculture or horticulture) or for industrial purposes and storage space for regional water management including flood protection.
5. Waste storage and treatment: Used as a waste storage receptacle. Either mine wastes or unrelated wastes such as from nearby industries.

Table 2 Key pit lake end uses (n>1)

Country	Fishery	Wildlife	Recreation	Source	Waste
Australia	6	7	8	2	2
Canada	22	6	2		5
Czech Republic	7	11	18	11	3
Germany	2	2	10		2
New Zealand		2	1		
Poland	5	13			1
Spain			1		2
USA	10	9	1	2	
Total	52	50	41	15	15

Examples of successful realisation of these end uses are demonstrated by the following case studies.

3.1 Wildlife

The presence of endangered species of plants and animals has been recorded in a number of sandpit lakes in the Třeboň Basin of the Czech Republic after discontinuation the sand mining (Kriváckavá et al. 2006).

The sandpit lakes afford an area for new populations of water and marsh plants that are found locally and also regionally within Central Europe. 14 tree species and 59 herbaceous plant species with a minimum cover of 5% were documented on the 11 monitored sandpit lakes. The sandpit lakes were classified as important biotopes according to the European Union guidelines. Endangered species of vascular plants occur in many sites in the sandpit lakes such as *Illecebrum vercillatum*, *Lysimachia thyrsiflora* and *Lycopodiella inundata*.

Similarly, these littoral flora have been found as an important component of the waterbird environment. Forty two species of water birds were recorded in the sand-pit lakes belonging to 10 orders (Rajchard et al. 2006). Sand-pit lakes were found to represent biotopes that can serve as refuges for the endangered species occurring in the Třeboň Basin Biosphere Reserve: little bittern *Ixobrychus minutus* and great reed warbler *Acrocephalus arundinaceus* and potentially for other bird species that may not be as endangered.

3.2 Fishery

Beneficial socio-economic development of the Chabařovice pit lake in Northern Bohemia, Czech Republic initially led to high densities of cyprinid fishes resulting in eutrophic water conditions (Peterka et al. 2011). As a result, lake management has featured an extensive stocking and harvesting ecosystem biomanipulation management programme since 2005 focussing on lower densities of fish, dominated by piscovores. For example, larger individuals of the traditional game fish pike *Esox lucius*, zander *Sander lucioperca* and wels catfish *Silurus glanis* perch is still the most abundant predatory fish in the lake. However, dying aquatic macrophyte vegetation as the lake fills means that there may be insufficient habitat for perch egg laying unless artificial habitats are used (Cech et al. 2010).

3.3 Recreation

Pit lakes have afforded local populations with both passive and active recreational opportunities.

New lake districts formed in the eastern part of Germany from lignite mining in the Lusatian and in the Central German lignite mining district (Schultze et al. 2013). For the majority of these lakes, recreation is one of the intended end uses, often the main one. Lake Senftenberg became rapidly a highly frequented destination for weekend recreation after its filling and neutralization in the 1970s since the distance to the city of Dresden (ca. 550 000 inhabitants) is only *ca.*60 km and there are very rare alternative options for water related recreation in that region. In the Central German lignite mining district, Linke & Schiffer (2001) found that the popularity of the lakes for recreational purposes is strongly related to the distance of the lakes to the two major cities in the region: Leipzig (ca. 580,000 inhabitants) and Halle (ca. 240 000 inhabitants).

Strong competition between sites and communities can develop in new lake districts. In order to avoid failure of investments in new infrastructure for recreational end use of the pit lakes, regional concepts and regional collaboration of all stakeholders is needed (Berkner 2005; Heidenfelder & Schneider 2005; Seifert 2005).

In Alberta, Canada, a number of open cut coal mine pits have been converted to pit lakes that are now used as recreational fisheries and as central features around which hiking trails have been created. Quarry Lake, an abandoned coal mine on the edge of the Rocky Mountains, is a popular destination for angling and hiking (Tourism Canmore 2017). For East Pit Lake (resulting from coal mining and filled primarily with groundwater), water-quality monitoring and habitat assessment demonstrated that the lake was suitable for establishing an arctic grayling recreational sport fishery. Alberta Environmental Protection awarded TransAlta a reclamation certificate for the lake in 1994 (Sumer et al. 1995).

Buzzacott & Paine (2012) reviewed 157 existing pit lake dive parks worldwide and argued for converting additional mine pits to inland dive parks. The main benefits of such dive parks are that they reduce pressure on sensitive dive sites, especially for diver training which can entail accidental contact with the substrate, and that they have a longer season due to warmer temperatures than the ocean in many locations, which enables divers to maintain their skills and social interactions in the off season.

3.4 Water Source and Storage

Pit lakes are infrequently used as a water source. Potable uses are typically limited by the presence of alternative, pre-existing water supplies, and by often low water quality resulting from elevated geochemical reactivity in void shell rocks and any mine waste backfill materials.

There are several anthropogenic lakes used as fresh water reservoirs in the Czech Republic, especially in large gravel sand mines in southern Moravia near Ostrožská Nová Ves village (Hrdinka 2007). Drinking water is also abstracted from bores immediately around the historic gold mine Wedge Lake pit in the Goldfields region of Western Australia (McCullough & Lund 2006). Pit lake and immediate surrounds groundwater is low in salinity, hardness and nitrates and is combined with groundwater from a bore field near the treatment plant.

3.5 Waste Containment and Treatment

The void of the former lignite mine Großkayna (Central German lignite mining district) was partially backfilled with industrial wastes. The wastes mainly consisted of ashes from lignite combustion. Waste materials from the production of nitrogen fertiliser were also deposited among the ashes leading to ammonia concentrations >300 mg/L in pore waters. A pit lake (Lake Runstedt; volume 54×10^6 m^3, area 2.33 km^2, maximum depth 33 m) was established on top of the waste material by deviating water of river Saale. By controlling neighbouring pit lakes water levels decant of the lake and transport of fluids from the waste into groundwater is prevented (Fritz et al. 2001). Hypolimnetic aerators are used to enhance nitrification in the hypolimnion while denitrification was proved to occur in the littoral (Reichel et al. 2010).

Creation of water capped tailings or end pit lakes is also a strategy for permanent storage of fluid fine tailings (FFT) from oil sand processing (MacKinnon & Boerger 1986; Johnson & Miyanishi 2008; Vandenberg 2016). Both fresh and process-affected waters are used for filling. One function of such lakes is the passive bioremediation of toxic chemicals such as polycyclic aromatic hydrocarbons (PAHs) and naphthenic acids. Mixing between the MFT and the overlying water cap can be prevented by a sufficient depth of the water layer. Moreover, the lake must not recharge aquifers that are in contact with other sensitive water bodies. However, regulators have not yet approved this concept, and there are uncertainties how microbial metabolism and gas production will affect long-term water quality.

Springer Pit Lake is a mine pit at the Mount Polley Mine, a copper mine in B.C., Canada. The pit lake stored water and tailings after a tailings storage facility embankment breach on August 4, 2014. Storing tailings in a pit void was considered Best Available Tailings Technology for geotechnical stability (Morgenstern et al. 2015). Between August 2014 and August 2015, tailings supernatant water and mine runoff were diverted to the pit lake. Upon resumption of mining in August 2015, mill process water and tailings were also deposited in the pit lake. The pit lake was then used as the primary feed source for water discharge following treatment. After a few months, Springer Pit Lake provided sufficient passive water treatment for the active water treatment plant to be switched to “passive mode”, meaning that mechanical and chemical additions to the water treatment plant were switched off and only monitoring instruments were left active (Vandenberg 2016; Vandenberg & Litke 2017). Water quality in the pit lake followed predictable trajectories (Beddoes et al. 2016) and was suitable for discharge to the receiving environment, without active treatment. At present, the pit lake is being drawn down, and tailings are planned to be removed from Springer pit to allow mining to resume in the pit. At mine closure, approximately 15 Mt of potentially acid forming (PAF) waste rock will be placed into the pit, which is considered best practice in terms of mitigating acid and metalliferous drainage from the PAF waste rock (MEM 1998; Verburg et al. 2009) and is a regulatory requirement.

4 End use selection

We found beneficial end use type and outcome varied dependent upon climate and commodity; but equally important were social and political dynamics. We also found that initial optimism about likelihood of end uses being successfully realised often failed to meet stakeholder expectations over longer post-closure terms.

Mining company interest and willingness to engage in the repurposing of pit voids as pit lakes with beneficial end uses requires a view to innovation outside of typical day-to-day mining activities. Similarly, regulators must have views open to different closure outcomes than they may be used to and that regulation may permit (Jones & McCullough 2011); with some beneficial outcomes presenting higher risks than more traditional approaches to closure (backfill, fencing, etc.). Third parties; be they investors, community groups or research organisations may assist in this process (McCullough 2016).

5 Determinants of end use success

Our review has shown that there are general attributes of pit lake shape, location, type and their closure management that can lead to successful end uses becoming realised.

Some pit lakes have been shown to provide good habitat conditions for conservation of significant bird life and plant species. Unlike many natural lakes that are now eutrophied by human activities, many pit lakes, especially those from inert geological materials such as sand and aggerate mining, are oligotrophic which may help prevent out-competing periphytic algal from smothering the plants. Although sides may be steep relative to natural lakes, the low stability of their sandy host geology and shallow depth means that littoral areas may also will be extensive (Halír & Žižka 2008).

Water quality is often the limiting factor to establishing wildlife values in a pit lake; low pH and elevated metals may make both in lake fisheries and aquaculture using offtake water unsuccessful or higher risk than acceptable for a commercial venture (Stephens & Ingram 2006). Conversely, good pit lake water quality may be deteriorated in ultra-oligotrophic and unproductive pit lakes by nutrients from uneaten fish food and from fish waste in in-lake aquaculture operations, or by high nutrient concentration discharge (Kumar et al. 2016).

Although water quality is key to a successful pit lake fishery; habitat and food availability/quality are also necessary for a successful sustainability (Lund & McCullough 2011). For example, substrate for egg spawning (Cech et al. 2009) or woody and rocky debris for protective shelters (McCullough et al. 2009b). The shoreline slope, length and slope angle are also recognised as important. With micro-topography of the benthos such as varied depths advised to create more habitat opportunities. Shallow wetland areas can also be constructed near inflow areas to mitigate nutrient inputs into the main lake body (Svoboda et al. 2007).

Even if fisheries are able to become established, then contaminant uptake by fish must be thoroughly assessed (Miller et al. 2013). Nonetheless, in locations where the potential for contaminant uptake is high but fish health is maintained, sport fishing or ornamental fish farming can still be employed. Contaminant accumulation can also be reduced through shorter duration fish cultivation (i.e., using fast-growing fish species) and artificial feeding (Otchere et al. 2004).

Recreational In addition to water quality, in particular in case of direct water contact, recreational uses of lakes will be primarily defined by location and access to human habitation. Exceptionally low turbidity due to low phosphorus availability and, thus, very little plankton growth can make pit lakes very attractive sites for diving. Dive parks and other water-based recreational uses may be more valuable in regions that do not already have natural lakes in which to recreate or where existing lakes are limited in their recreational opportunities e.g., by size, shape and depth; or by competing uses such as wildlife values.

Pit lakes can only be successful as a water source if the lakes are of sufficient volume and water quality appropriate to the end use (Hrdinka 2007). Water volume and quality may be inter-related in high net evaporation areas where higher water quality/volume end uses may be unsustainable (McCullough et al. 2013). Water balance and associated water quality modelling can be useful in determining the long term success of these end uses (Vandenberg et al. 2011).

Waste deposition requires conditions not permitting contaminants transport into other components of the environment. Atmosphere, biota, down-stream/gradient water bodies (surface and underground). Sealing the mine void shell and capping of the waste and hydrological control may ensure the required conditions.

6 Conclusions

As with many mine closure outcomes, examples of end use development as a closure strategy are rarely published; and even more so when they are not successful. We collated information on geographic and physical attributes and pit lake end use outcomes to determine what lessons might be gleaned to improve pit lake closure practice and outcomes.

Common attributes and reasons that led to successful closure outcomes as end use developments included; early planning and incorporation of closure considerations into mining plans, early and regular engagement with regulators and other stakeholders (and vice versa), consideration of long term effects of climate and regional socio-economic dynamics, good water quality (through good waste management and also fewer geochemical issues in mine waste and pit void shell exposures) and relatively significant contributions of good water quality to the pit lake e.g., though rapid filling or ongoing flushing such as flow-through.

Different end uses require different water quality and habitat structures. While low productivity is favourite for recreational diving fishery will suffer from low productivity. Dense standings of macrophytes, favoured by large littoral zones and sallow depth may hinder swimming. Therefore, not all potential uses can be combined in every single lake, in particular regarding small lakes.

Since water depth is a decisive factor for the occurrence of seasonal thermal stratification and the amount of oxygen available in the hypolimnion during stratification, the shaping of final mine void and the defined final water level have considerable influence on the recycling of phosphorus (so-called internal loading; see Nürnberg (2009) and other chemicals from the sediment. In other terms: future water quality problems can be mitigated by appropriate design of the final mine void.

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Filling, Remediation and Management of Pit Lakes by Using Mine Water – an Update

M Schultze *UFZ Helmholtz-Centre for Environmental Research, Germany*

P Jolas *MIBRAG Mitteldeutsche Braunkohlengesellschaft mbH, Germany*

L Weber *LMBV Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH*

Abstract

The beneficial reuse of mine water is an important strategy for mining to save regional water recourses. The use of mine water for filling, remediation and management of pit lakes is one option for such beneficial reuse of mine water. In the eastern part of Germany, more than 100 pit lakes have to be filled since 1990. The reuse of mine water has considerably contributed to that filling. Since reporting on this issue last time at an IMWA congress in 2011, further experiences have been collected, particularly regarding the sustainability of the strategy.

In this paper, we focus on the southern part of the Central German lignite mining district. An overview on the pit lakes and their management including filling and remediation is given for this region. Lake Cospuden is presented in detail as a successful example for experiences from almost 20 years. Other lakes needed lime for neutralization in addition to the use of mine water, partly due to insufficient buffering capacity of the used mine water. In two cases, the mine water keeps the water level stabile although the lakes are located in the groundwater depression cone of a neighbouring, operating mine.

Based on those examples, we discuss the advantages and limitations of the strategy. The main advantages are that the mine water remains in the region and that the use of mine water provides an additional water resource for rapid filling of pit lakes resulting in a stabilization of the sidewalls of the pit and, thus, lowering the needed effort for safety. A further advantage is caused by the relatively high concentrations of iron acceptable for the filling water for pit lakes lowering the needed effort for mine water treatment. Neutral mine water also contributes considerably to the neutralization of the rising pit lakes. The main limitation is that pit lakes need to be located close to operating mines. Although that is the case not very often, mine water has been used for filling, remediation and management of pit lakes not only in Germany but also in Poland. A second limitation is the water quality of the mine water. Usually, only neutral mine water having limited metal concentration is suitable for filling, remediation and management of pit lakes.

Keywords: *pit lake, mine water, acidification, neutralization, beneficial end use*

1 Introduction

The beneficial use of mine water is an important aspect of modern mining. It saves local and regional water recourses, has the potential to save costs under optimal conditions and to increase acceptance for actual and future mining (Balfe 2006; Barrett et al. 2010; Schultze 2012; Simons et al. 2015). Beside use of mine water for satisfaction of water demands of the mining operation and related activities like ore refinery and smelting, several other kinds of beneficial mine water use have been reported, e.g. irrigation, water supply, heating, and cooling (Schultze 2012). Under favourable conditions, a further option for the use of mine water is the filling and management of pit lakes (Schultze et al. 2011a,b; Marszelewski et al. 2017).

Pit lakes are important features of the post-mining landscape released by many surface mining activities (Miller et al. 1996; Klapper & Geller 2001; Castendyk et al. 2015a,b). The goal of pit lake creation and development is usually to reach a water quality in the final pit lakes that does not pose threats to humans, wildlife and downstream water bodies (streams, rivers, other lakes, ground water; Miller et al. 1996;

Castendyk et al. 2015a,b) and allows for diverse beneficial end uses (e.g. recreation, angling, commercial fishery, flood protection, water storage; McCullough 2009; Swanson 2011; Geller et al. 2013a). Accordingly, legislation in most countries requires measures ensuring acceptable water quality, which have to be basically designed already during mine planning according to predicted quality of mine water and final pit lake water (Bolen 2002; Jones and McCullough 2011; Oldham 2014).

The most important water quality concern in pit lakes is acidification resulting from pyrite oxidation accompanied by high concentrations of sulphate, iron and other metals and limited diversity of aquatic life (Klapper & Schultze 1995; Miller et al. 1996; Geller et al. 2013a). There are diverse approaches for the avoidance and abatement of acidification in pit lakes (Klapper et al. 1996; Geller et al. 2013b): avoidance by special measures during mine operation and overburden dumping (addition of neutralizing materials to the overburden, dumping of materials with considerable potential of acidity formation in deepest part of the mine void, rapid water rebound in dumped overburden), rapid filling with river or mine water, in-lake water treatment, treatment of inflowing water, flushing with river water or mine water.

Rapid filling of pit lakes keeps the water level in the lake above that of the groundwater in the vicinity of the lake during the filling period. In this way, an inflow of groundwater into the lake is avoided or at least minimized and the transport of acidity by groundwater into the filling lake is minimized too. Furthermore, the side walls of the lake basin (i.e. the mine void) are stabilized (Jolas 1998; Schultze et al. 2011a). This allows for steeper slopes of the side walls minimizing the effort needed for shaping the side walls. Under the special conditions given in the eastern part of Germany in the 1990s this was an important aspect since many lignite mines were decommissioned not according to the initial planning but almost without any preparation for closure. The breakdown of the Berlin Wall and the German reunification caused a sudden reduction in demand for lignite resulting in the reduction of the lignite production by 66% in the Central German lignite mining district between 1989 and 1992 and the closure of 17 of the formerly 22 operating mines (Jolas 1995; Fritz & Benthaus 2000; Kaltenbach & Milojcic 2017; SKW 2017).

We report on results of the use of mine water for filling and management of pit lakes focussing on water quality issues and experiences in the southern part of the Central German lignite mining district. Lake Cospuden is presented in detail and general advantages and limitations of the approach are discussed.

2 Study area and data sources

The lignite mined in Germany is of Tertiary age. The geological conditions vary within the southern part of the Central German lignite mining district considerably. While the lignite seams are lying quite horizontal and have relatively uniform thickness in the north close to Leipzig, dissolution of Permian salt deposits in the deeper underground during and after the formation of the lignite caused much more complicated conditions in the south (Eissmann 2002). Mine Profen (Figure 1) is an example for the latter conditions. The lignite mining started in the study region already in the 19th century and included until the 1960s not only surface mining but also underground mining. Underground mining was mainly done in the south, close to the outcrop of the lignite.

Figure 1 shows a map of the southern part of the Central German lignite mining district. The lakes filled and managed using mine water are listed in Table 1. The table also provides the morphometric data of the lakes, the amount of mine water discharged into the pit lakes, the pH of the lake water at the beginning of the filling with mine water and in December 2017, and the end use of the pit lakes. For more details on the other lakes in the Central German lignite mining district see Schultze et al. (2010, 2013).

According to the motivations mentioned above, a pipeline was constructed in the years 1997-99 connecting the still operating mines Profen und Vereinigtes Schleenhain (VSH; comprising three formerly separate mines) with the mine voids which had to be filled and transformed to pit lakes (Figure 1; Jolas 1998). The mines Profen and VSH are operated by the Mitteldeutsche Braunkohlengesellschaft (MIBRAG, Zeitz, Germany) while the Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft (LMBV, Senftenberg, Germany) is responsible for the remediation of the pit lakes except Lake Großstolpen (no 8 in Figure 1) as a consequence of the development after German reunification (Kaltenbach & Milojcic 2017).

Table 1 Pit lakes filled and managed with mine water in the southern part of the Central German lignite mining district (state: December 2017; No – number of lake in Figure 1; VSH – Vereinigtes Schleenhain; nat. protec. – nature protection; data from LMBV, MIBRAG)

No	Lake	max. depth[1] [m]	Surface area[1] [ha]	Volume[1] [10^6 m^3]	Filling state[2] [%]	Mine water[3] [10^6 m^3]	Source mine water	pH at start of filling	pH in December 2017	End use	Remarks[4]
1	Cospuden[5]	54	439	109	100	89,8 44.8	Zwenkau, Profen	3.1-8.1	7.6	recreation, nat. protec.	inflow from Lake Zwenkau since 2015
2	Markkleeberg	58	252	60	100	0.1 83.7	VSH, Profen	7.2	7.4	recreation, nat. protec.	inflow from Lake Störmthal since 2013
3	Zwenkau[5]	49	963	176	95	85.9	Profen	2.3	6.8	flood protection, recreation, nat. protec.	addition of lime; inflow of river water; overflow to Lake Cospuden since 2015
4	Störmthal	52	733	157	100	62.2 74.7	VSH, Profen	3.0	5.2	recreation, nat. protec.	outflow to Lake Markkleeberg since 2013
5	Werben	32	80	9	65	2.5	Profen	7.8	7.8	recreation, nat. protec.	located in depression cone of mine Profen
6	Kahnsdorf	44	125	22	100	11.0	VSH	2.8	2.7	nat. protec.	nat. succession
7	Hain[5] Haubitz[5]	49 25	405 160	73 25	100	54.2 31.8	VSH, Profen	2.3 3.6	6.2 6.6	recreation, nat. protec.	addition of lime
8	Großstolpen[5]	5	28	0.25	100	3.4	VSH	6.9	7.8	recreation	located in depression cone of mine VSH
9	Haselbach[5]	33	335	24	100	94.8	VSH	7.5	7.2	recreation, nat. protec.	located in depression cone of mine VSH

[1] at final water level [2] based on volume [3] total volume of mine water discharged into the lakes
[4] flows mentioned in this column mean flows from lake to lake, not flow of mine water [5] for more details see Section 3

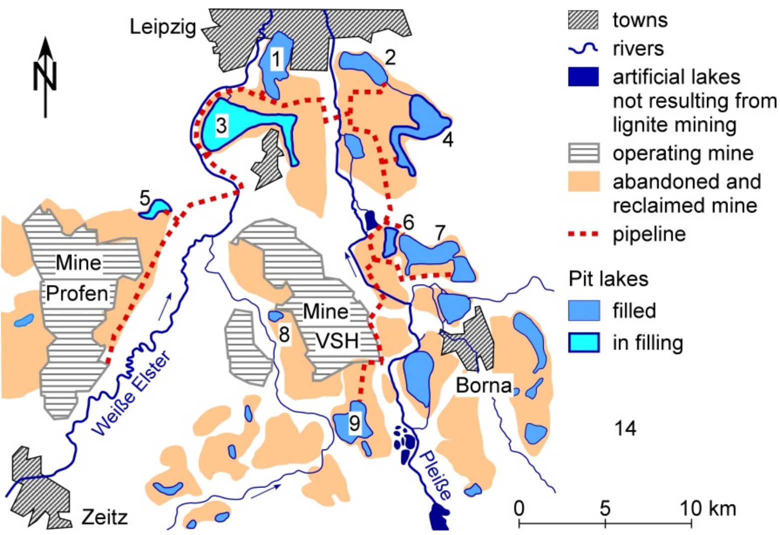

Figure 1 Map of the southern part of the Central German lignite mining district. Numbered lakes (Table 1) have been filled and managed using mine water (VSH – Vereinigtes Schleenhain).

The data on the used mine water and the pit lakes were mainly provided by LMBV and MIBRAG. Chemical data were produced in their own laboratories or by contractors of LMBV and MIBRAG according to German standard methods (DEV 2009). The only exceptions are the water quality data for Lake Cospuden before 2001. They originate from research activities of the department Lake Research of the Helmholtz-Centre for Environmental Research – UFZ (Magdeburg, Germany), also applying German standard methods (DEV 1995).

3 Results from the southern part of the Central German lignite mining district

3.1 Lake Cospuden

Like for the majority of pit lakes in the Central German lignite mining district, the filling of Lake Cospuden began with a limited rebound of groundwater which resulted in the formation of small separated water bodies at the bottom of the mine void already during the late phase of shaping the side walls in order to save costs for dewatering. The monitoring of the water quality of Lake Cospuden started in those small water bodies. The water quality was widely varying depending on location and local composition of surrounding soil and flow paths of local runoff (Figure 2B; Schreck et al. 1998; Woefl et al. 2000).

In 1994, the filling with mine water started with water from three different dewatering systems of the neighbouring mine Zwenkau (Figure 2A). Mine Zwenkau was operated until 1998 for lignite production. In the following years, the dewatering of mine Zwenkau was continued as far as necessary for remediation work in mine Zwenkau (e.g. shaping the side walls of the mine void). The main portion of this water had only limited alkalinity (i.e. acid neutralization capacity; Figure 3B) and was even temporarily acidic (Figure 3A). Consequently, the increase of pH of the lake water was initially slow (Figure 2B). The addition of mine water from mine Profen strongly promoted the neutralization and was the main driver for the establishment of considerable buffering capacity in the lake water. The bicarbonate content of the mine water was the major neutralizing agent while dilution did not play a relevant rule (Schultze et al. 2011a). When the final water level was reached in summer 2000, the lake water was already neutral and the main end use for recreation including swimming could be permitted. Due to the location of Lake Cospuden close to the city of Leipzig (ca. 550 000 inhabitants), the lake immediately became a favourite destination for recreational activities such as swimming, diving and sailing (Linke and Schiffer 2002).

Although the pH of the lake water remained in the neutral range after 2000 (Figure 2B), the temporal variation of the alkalinity clearly indicated different phases of the development of the water quality (beginning from completion of filling in 2000): decrease from 2000 to 2003, stabilization in 2004, further decrease until 2005, increase until 2014 and again slight decrease till now (Figure 2B). Although no detailed investigations have been made to identify all reasons for the described changes in detail, the probably most important processes behind shall be discussed briefly.

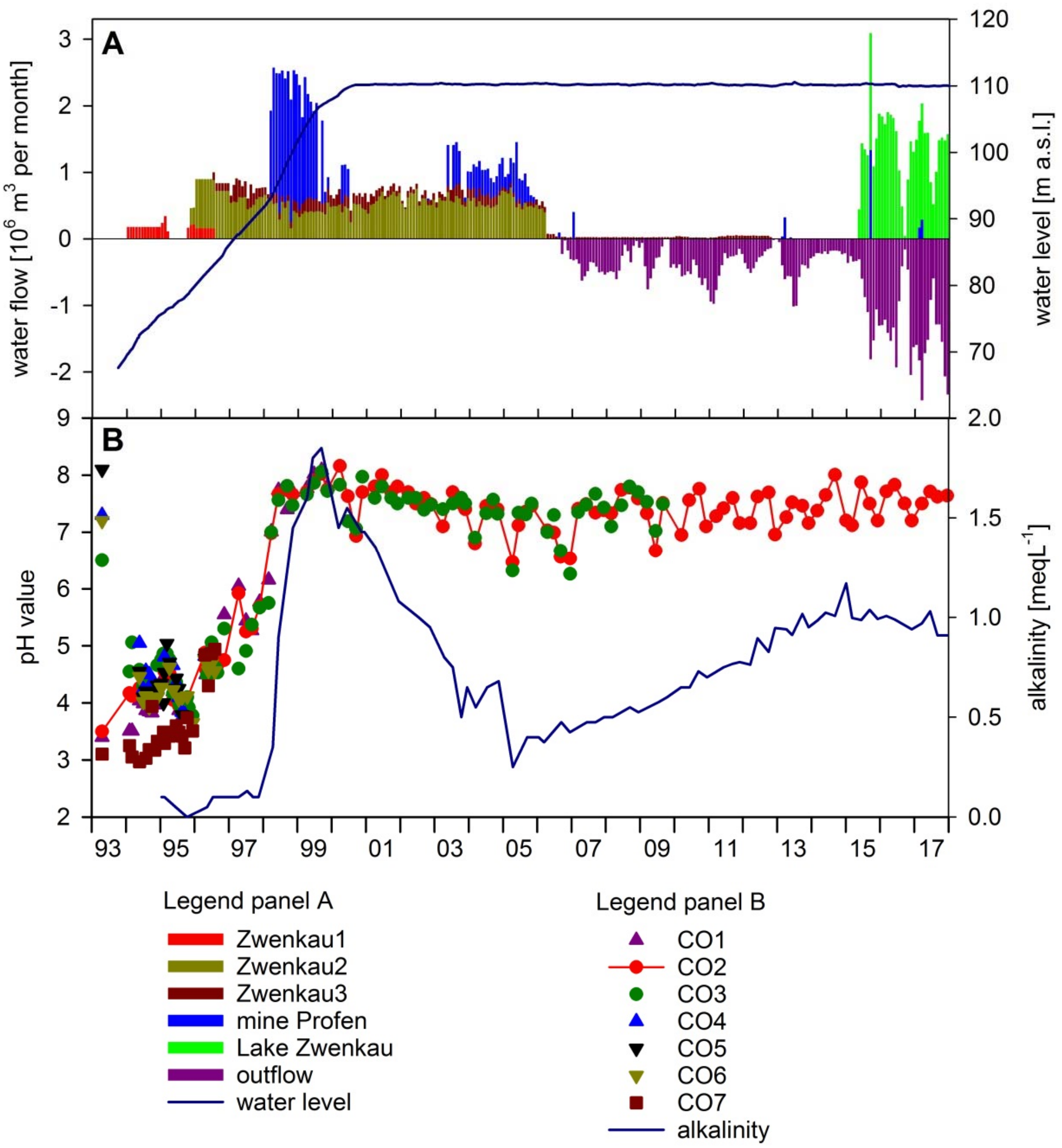

Figure 2 Temporal evolution of Lake Cospuden. A: Inflow of water from different sources (Zwenkau1-3: mine water from neighbouring mine Zwenkau; mine Profen: mine water from mine Profen; Lake Zwenkau: water from Lake Zwenkau; outflow: discharge into the downstream system of ditches and brooks in the north of Lake Cospuden). B: CO1-7: sampling sites, initially in separated local depressions at the bottom of the mine void; alkalinity was measured by titration with 0.1 HCl to pH 4.3. Details are shown only for pH for better clarity.

The side walls of mine voids of German lignite mines usually contain considerable potential for washout of acidity. Furthermore, dumped overburden usually has higher acidification potential due to more intensive aeration and, thus, more complete pyrite oxidation (Wisotzky 1998; Grützmacher et al 2001). Therefore, much acidity is mobilized during filling and in a certain period following filling, until the majority of easy to mobilize acidity is washed out or neutralized. This was the reason for the initial acidification, the occurrence of highly acidic waters as described by Woelfl et al. (2000) and probably for the decrease of the alkalinity after 2000. The mine water from mine Zwenkau also contributed to the decrease after 2000 because of low pH and alkalinity (Figures 2, 3).

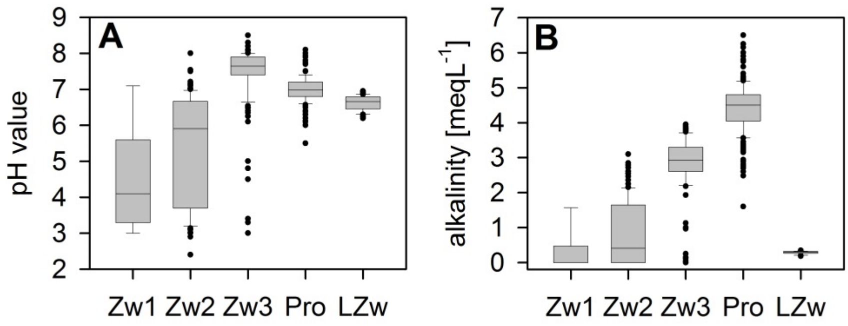

Figure 3 Water quality of the water used for filling Lake Cospuden. A: pH of the mine water from the different sources (Zw1-3 (identical to Zwenkau 1-3 in Figure 2): mine water from neighbouring mine Zwenkau; Pro: mine water from mine Profen; LZw: water from Lake Zwenkau). B: alkalinity of the mine water from the different sources (measured by titration with 0.1 HCl to pH 4.3). Lines within the boxes are median values, box limits are 25 and 75 percentiles, and whiskers show the 10- and 90-percentile values. Single dots indicate data below 10-percentile or above 90-percentile, respectively.

The stabilization in 2004 obviously was caused by the mine water from mine Profen. The increase of alkalinity after 2005 probably had mainly three reasons: (1) the inflow of mine water from mine Zwenkau ceased, (2) the inflow of groundwater from West and East, i.e. not mined underground, became more and more relevant due to natural groundwater rebound while the groundwater inflow from the south, i.e. dumped overburden remained small due to the still very low water level in the former mine Zwenkau and partly continued dewatering for remediation purposes there, and (3) alkalinity producing processes (iron and sulphate reduction in the lake sediment and in the surrounding underground) may have become more and more relevant as reported for other post-mining sites (e.g. Storch et al. 2007; Opitz et al. 2017). The final decrease of alkalinity since 2014 is obviously caused by the inflow of water from Lake Zwenkau which has low buffering capacity (Figure 3B). This inflow was started to stabilize the water level of Lake Zwenkau once the lake water of Lake Zwenkau exceeded stably pH 6.

In summary, Lake Cospuden is an example demonstrating the high potential of successful use of mine water for filling and sustainable management of pit lakes. However, it also demonstrates the sensitivity of Lake Cospuden to changes in the management and underlines the need of careful planning and monitoring for safe management.

3.2 The other lakes filled and managed using mine water

Neutral conditions were reached in all lakes except Lake Kahnsdorf making the use of mine water for filling and management of pit lakes a successful measure in the Central German lignite mining district. However, the use of mine water from mine VSH was not fully successful. The alkalinity of this mine water was relatively low (0-1.7 meqL^{-1}, median 0.18 meqL^{-1}) already at the beginning of its use (1999-2000) and it further decreased in the following years (0-0.21 meqL^{-1}, median 0 meqL^{-1} for the period 2009-2010). This decline of alkalinity was caused by increasing influence of dumped overburden on the water caught by the dewatering system of mine VSH. Therefore, the use of mine water from mine VSH for filling and management of pit lakes was stopped in 2010. The only exception is Lake Haselbach. The mine water used for this lake originates from aquifers below the mined lignite seams and from the margin of mine VSH and has an alkalinity ranging from 1.01 meqL^{-1} to 1.68 meqL^{-1} (for period 2016-2017; median 1.42 meqL^{-1}).

For Lakes Zwenkau (26,145 t CaO) and Hain-Haubitz (10,034 t CaO), lime was used to promote neutralization in addition to the inflow of mine water. The addition of 314 t of limestone to Lake Haselbach was not relevant on the long run but helped to overcome a temporary minimum in alkalinity.

Lake Zwenkau also received river water from Weiße Elster River. In 2013, 35x10^6 m^3 flew into Lake Zwenkau during a flood event since one of the end uses of Lake Zwenkau is flood protection. This river water also contributed considerably to the neutralization of the lake water as well known from other pit lake filled and managed using river water (Schultze et al. 2011a). Since mid-2016, river water is diverted regularly in addition to mine water to Lake Zwenkau, roughly in the same order of magnitude like mine water.

Lakes Haselbach and Großstolpen are located in the groundwater depression cone of mine VSH due to the ongoing dewatering operations of mine VSH. Therefore, they received amounts of mine water representing multiples of their volume (Table 1).

4 General aspects and conclusions

The use of mine water for filling and management of pit lakes has three main prerequisites: (1) operating mines have to be close to forming pit lakes, (2) there has to be an excess of mine water not urgently needed for other purposes, and (3) the quality of the mine water has to be acceptable. The latter requirement can be fulfilled by mine water treatment. The major advantages are stabilization of the side walls in case of rapid filling, limitation of acidification and keeping the mine water in the region.

Often, the content of iron is a limiting factor for the discharge of mine water. In case of discharge into pit lakes, in particular in initially acidic ones, this is of limited relevance. Firstly, the pit lakes have elevated iron concentrations anyway in case of low pH and usually also receive groundwater rich in iron for decades. Secondly, the iron of the mine water has the potential to fix phosphate and, thus, to avoid eutrophication in the pit lakes. Therefore, elevated concentrations (<10 mgL^{-1}) of iron (mainly ferric, particulate iron) are acceptable for the filling and management of pit lakes.

The use of mine water for filling and management of pit lakes has been applied also in the Lusatian lignite mining district (Germany; Schultze et al. 2011b) and in Poland (Marszelewski et al. 2017). Certainly, the above discussed limitations are the reason for the very few published reports about use of mine water for filling and management of pit lakes. In conclusion, the use of mine water for filling and management of pit lakes is a valuable approach in the toolbox of pit lake management, despite its limitations.

Acknowledgements

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Hydraulics of Underground Mine Flooding – Optimization of Prediction and Monitoring Procedures

S Westermann *University of Applied Sciences Georg Agricola, Germany*

B Reker *University of Applied Sciences Georg Agricola, Germany*

P Goerke-Mallet *University of Applied Sciences Georg Agricola, Germany*

C Wolkersdorfer *Tshwane* University of Technology, South Africa

C Melchers University of Applied Sciences Georg Agricola, Germany

Abstract

In 2018, the subsidized hard coal mining in Germany will end. Concurrently, this will terminate a shutdown process that lasted for decades and induced many tasks for the future. From 2019 onward, one of the foci in the Ruhr, Saarland and Ibbenbüren mining districts will be to establish a perpetual and eternal environmentally responsible mine drainage system. Controlled rebound of mine water is a complex process that can be linked to both risks and chances for the environment as well as the safety of the surface.

Many abandoned underground hard coal mines in Germany and Europe have already been flooded. During the flooding processes, important insights and experiences relating to the mine water rebound process per se and its environmental impacts have been gathered. Due to the site specific hydrogeological characteristics, some of these experiences are of local importance, while others can similarly be used at other mining areas.

Our study provides a systematic overview of selected European hard coal mine water rebound processes that already have or are about to be finished. The focus will be on the analysis of time and space-depended flooding processes. It will describe the flooding process from a hydrodynamical point of view and summarize the important parameters controlling and influencing the process.

Based on this analysis, the general properties and interdependencies of mine flooding are to be identified. In addition, the effects caused by the local conditions will be identified. Based on past mine flooding scenarios, and focusing on potential environmental effects, conclusions for optimising predictions and monitoring measures will be drawn. Finally, the project will provide a better understanding of the processes involved in mine water rebound which can be implemented in future mine closure plans. This will provide measures for transferring the experience-based knowledge to future mine water rebounds in other hard coal mining districts, thereunder the Ruhr, Saarland and Ibbenbüren mining districts.

Keywords: *underground mine floodin, hard coal mine, monitoring*

1 Introduction

Germany has a long tradition in ore and coal mining. Annually, nearly 180 Mt of lignite are being mined in open pits and more than 500 Mt of ore, earth and stone minerals are being extracted (VRB 2016). Especially hard coal, salt and different ores have been mined for centuries in underground mines. In 2018, the last two hard coal collieries in Germany will close, both situated in North-Rhine Westphalia. With the closure of the mine “Prosper-Haniel” in the Ruhr District and the Ibbenbüren colliery situated at the northern border to Lower Saxony, the era of underground hard coal mining will come to an end. The closure of these two collieries, however, does not correspond to an end of the mining operator’s responsibilities. It is the operator’s legal responsibility to take care for a sustainable and environmentally acceptable post mining management, especially regarding handling of mine water. In Germany, the term “perpetual tasks” underlines the timeframe of this responsibility, which includes the long-term regulation of the mine water table at an environmentally agreeable level, poldering measures for controlling the ground water table close to the surface and the treatment of ground water at old colliery sites, coking plants and spoil heaps. For many years, the mining companies developed monitoring concepts to tackle these tasks, and it is a fundamental aim to enhance these concepts continuously (RAG 2014). As a lot of ground water rebound processes are already at a mature stage or can be regarded as completed, a lot of scientific experience have been gathered in deciphering the patterns of these rebound phenomena. Nevertheless, many findings are just of local importance, as both the geological and hydrogeological backgrounds differ from one mining area to another (Baglikow 2010, Rosner 2011, Goerke-Mallet 2000, Goerke-Mallet et al. 2017).

2 Current study

Currently, no systematic collection and interpretation of mine water rebound experiences on a European scale exists. Therefore, the Research Institute of Post-Mining at TH Georg Agricola, Bochum, Germany, initiated a first-time project, systematically investigating mine water rebounds in European hard coal mining districts. Within this study, all European coalfields will be considered and examined in detail regarding the experience made with processes and patterns of mine water rebound. The main coal mining areas to be surveyed are as follows (Figure 1):

- Germany (Ruhr area, Saar area, Ibbenbüren, Aachen-Erkelenz, Saxony),
- United Kingdom (Yorkshire, Durham & Northumberland, East Fife),
- France (Lorraine),
- Netherlands (South Limburg),
- Poland (Upper Silesia),
- Czech Republic (Upper Silesia)
- Spain (Asturias).

The evaluation focuses on the analysis of the spatial and temporal development of the mine water rebound, the related influences and interdependencies which comprise both the quantitative and qualitative changes of the mine water to be drained; the ground movements caused by the processes and mine gas migrations close to the ground surface. This overall evaluation intends to identify generally applicable causal relations of mine water rebound, to separate the locally specific conditions and to transfer the insights to other hard coal mining areas where mine water table rises are imminent. This objective applies to the Ruhr area, the Saar hard coal mining and the Ibbenbüren colliery.

3 Life Cycle of a mine

The influence of mining activity to the environment does not end with the closure of the mine. As the original pre-mining hydrogeological conditions are often irreversibly altered, the potential environmental impacts should last for a very long time (Wolkersdorfer 2008).

The life cycle of a mine splits into three main phases (Figure 2). The first phase is usually the shortest one and deals with the exploration of a deposit to estimate the profitability and the extent of investment needed to exploit the resources. The second phase corresponds to the actual mining activity and lasts until all resources are being extracted or the profitability of the mine is no longer granted. The third and last phase of the life cycle, the post-mining phase, is usually the longest one. It deals with the consequences of the mining activity and can last up to eternal scales (RAG 2014).

One of the most important parts of the post-mining phase is handling the mine water rebound, which usually starts immediately after mine decommissioning. In an ideal case, the first considerations regarding the rebound process and the appropriate management should be already made in the first phase of the life cycle.

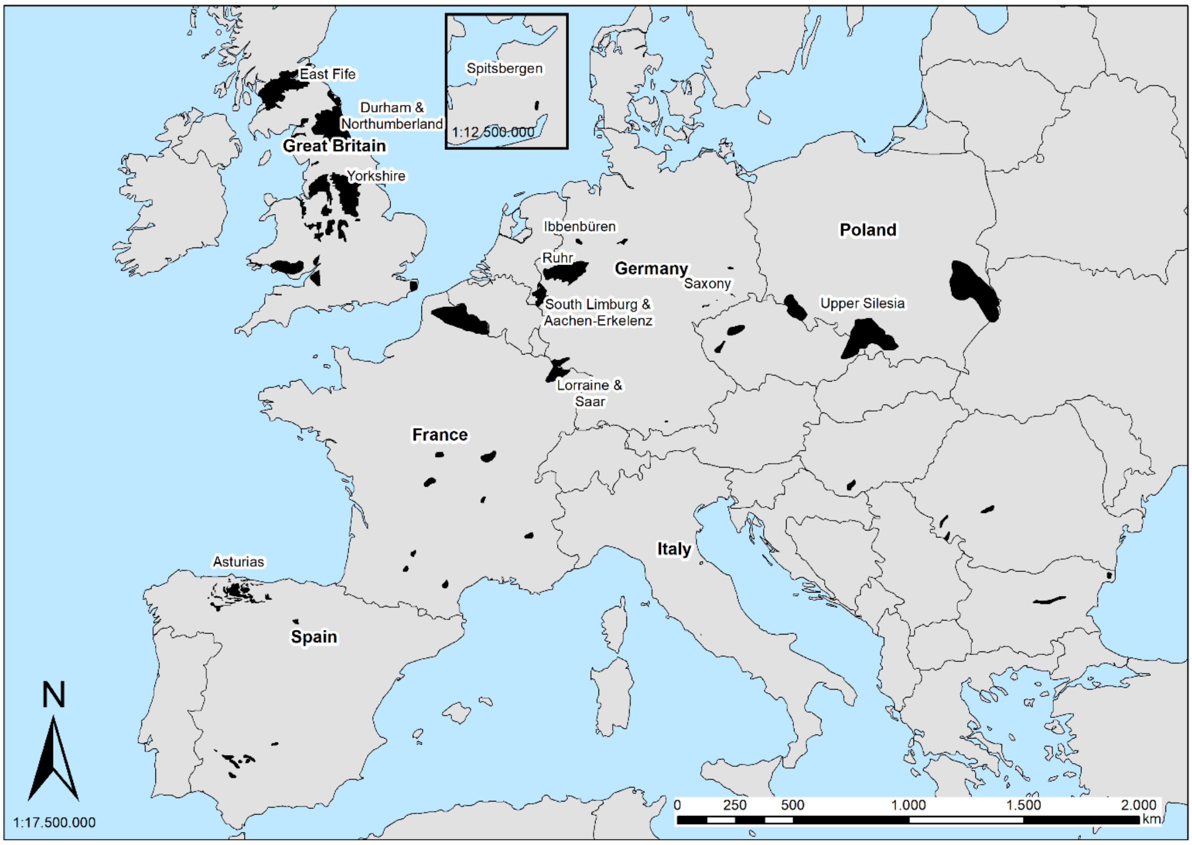

Figure 18 European Coal mining areas.

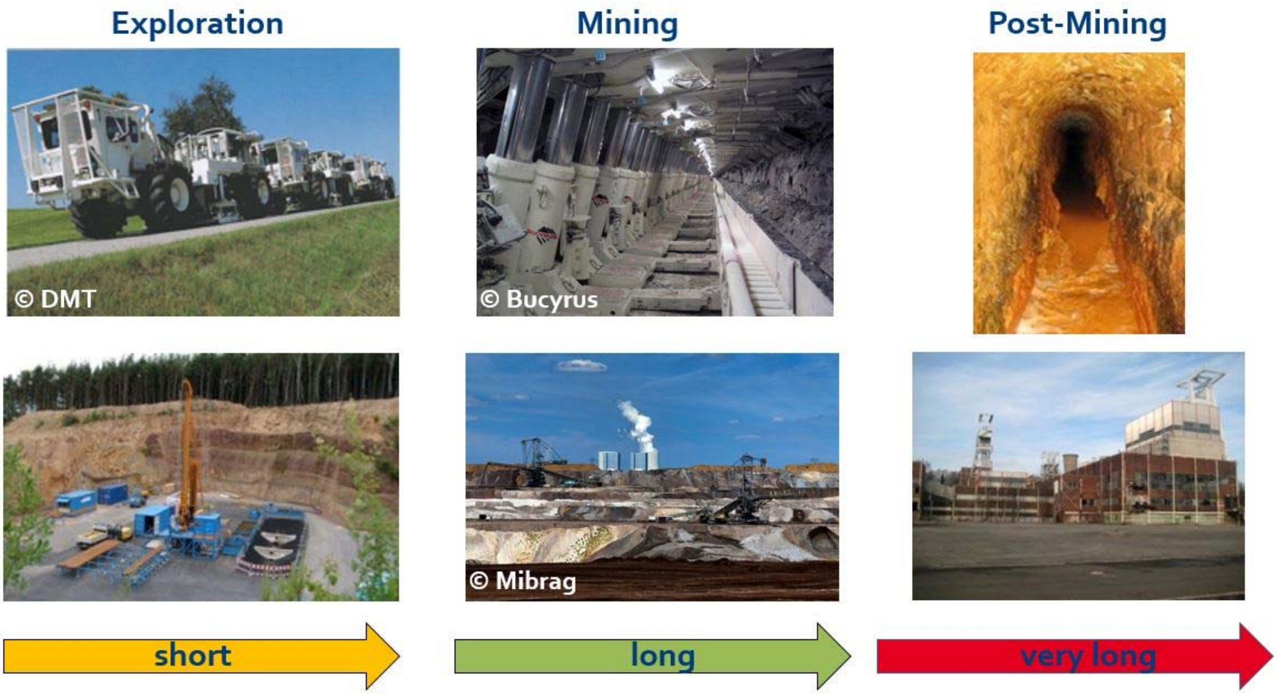

Figure 19 Life cycle of a mine.

4 Potential parameters influencing mine water rebound

The mine water table rise is often monitored in old shafts or boreholes and for a graphical visualization, the measured water level data is plotted against time. Usually that is done to estimate the time the entire rebound process lasts. Basically, this time is a result of the two parameters: floodable volume and water influx. The floodable volume of the underground workings as well as the influx of the water into these mine workings is not evenly distributed with depth. The floodable volume is largest in the worked main coal seams and decreases above and under these horizons. If mining plans are available, the floodable volume may be calculated in an accurate way excluding compaction and estimating mean porosities of goaf areas. This is not a trivial exercise. The estimation and/or calculation of the water influx in every depth of the mine is associated with higher uncertainty. Even if reliable data of the water abstraction of a single colliery is available, amongst other things, the source of the water as well as its corresponding decrease of the potential difference, and thus, the decrease of the influx must be regarded. For the latter, a model is presented and discussed in Banks (2001). A lot of effects influencing the spatial-temporal rebound process have been extensively studied and described in Wolkersdorfer (1996, 2006), and many parameters influence the rebound process (Table 1).

Table 1 Rating matrix of the essential parameters of mine water rebound (Goerke-Mallet et al 2017).

SECTOR 1	**GEOLOGICAL CONDITIONS**					
	Cap rock					
Features	**Lithology**	**Tectonics**	**Aquifer**	**Floodable Volume**	**Ground Water recharge**	**Environment**
Boundary conditions	*Variety of layer sequence*	*Hydraulic activity*		*Tectonic elements*	*Precipitation dependency*	*Hydraulic head*
				Ground water horizons		
	Deposit					
Boundary conditions	*Type of resource*	*Tectonic stress*	*Floodable volume*	*Water inflows*		
				Inflow of juvenile water		
				Seepage		
				Hydraulic balance		
SECTOR 2	**Mine**					
Features	**Mining depth**	**Underground workings**	**Rock mechanics**	**Hydraulic routeing**	**Infiltration rate**	**Mass of water body**
Boundary conditions	*Mining method*	*Residual volume mining horizons and workings*	*Rock pressure*	*Hydraulic effectiveness*	*Goaf*	*Deformation of floor / layers*
	Excavation ratio	*Floodable volume*	*Rock strength*		*Rock mass*	
		Damming	*Pressure ratios*			
		Water joinings				
		Water inflows and their locations				
		Hydrochemistry				
SECTOR 3	**Rock and ground movements**					
Features	**Stratigraphy**	**Mining depth**	**Uplift**			
Boundary conditions	*Lithology*					
	Rock strength		*Excavation radio*			
			Aquifer			
			Increase in floodable volume			

A lot of these parameters indicate a strong dependence with depth and have potential interdependencies. It is a goal of the present research to qualify, quantify and finally rank these parameters in terms of their effects on the rebound process. The links and dependencies of each of the parameters, hence their reinforcing or weakening effects needs to be considered as well. The evaluation of many complete or nearly complete rebound processes helps to better understand the governing effects, develop future strategies for sustainable water management approaches and predict the associated environmental impacts.

5 Monitoring

For the scientific analysis of the rebound process and its influencing parameters, as well as an adequate risk evaluation and appropriate management of the post-mining challenges, monitoring of relevant parameters is essential (Goerke-Mallet et al. 2017). The Research Institute of Post-Mining at the THGA in cooperation with RAG AG has developed a novel hydrogeochemical probe head, which allows continuous measurements of relevant in-situ parameters as well as data transmission using General Packet Radio Service (GPRS) (Kruse et al. 2017). These parameters include water pressure, temperature, electrical conductivity, flow rate and flow direction. This equipment allows to obtain insights into the temporal and spatial development of the rebound process.

6 Environmental effects and process understanding

Mine water table rise can cause several risks for people, ecology and infrastructure. These risks are even higher, i.e. unpredictable, if the rebound is not accompanied by a reliable monitoring system as well as potential corrective mechanisms, which can control the mine water rise and mitigate environmental effects. Mining operators, authorities and scientists have to deal with include increased gas emissions, impaired water quality or ground heavings (Westermann et al. 2017, Figure 3).

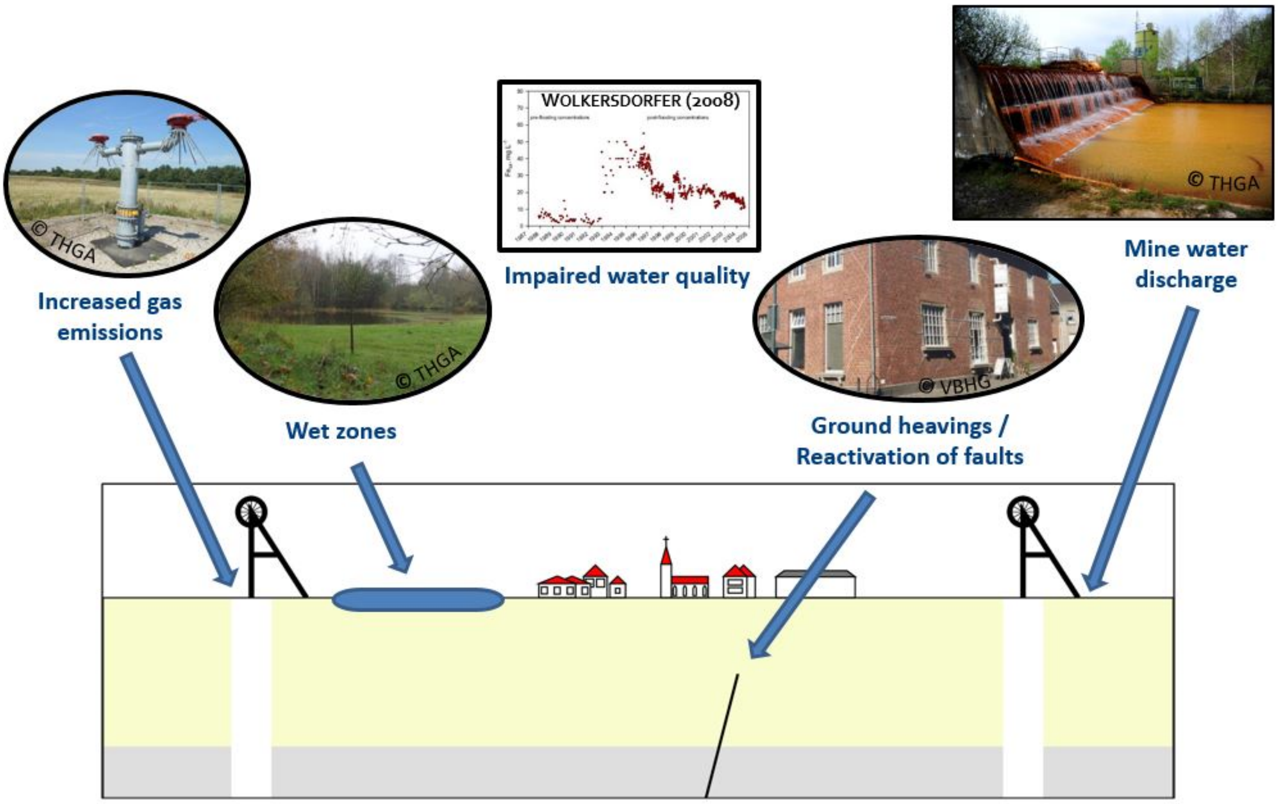

Figure 3 Possible environmental impacts of mine water rebound.

Understanding the processes that are associated with these environmental impacts is a key to predict the consequences. This includes a profound process-understanding of three essential parts:

- Hydraulics and hydrodynamics,
- hydrochemistry,
- geomechanics.

6.1 Hydraulics and hydrodynamics

As stated above, the speed of the mine water level rise is a function of the infiltrating water, the floodable volume and the available water conduits (Àlvarez et al 2018). These factors influence the course of the rebound. The origin of the infiltrating water is often a mixture of ground water and infiltrating water. However, these water intrusions are successively decreasing when they get gradually suppressed by the rising mine water table. Furthermore, the infiltration pathways influence the retention time of the infiltrating mine water and thus the hydrochemistry as outlined below. The precise quantification of the floodable volume is usually uncertain as it depends on the extent of the underground workings, the mined volume, the storage volume of the dewatered strata, the mining induced void volume (collapsing rock, goaf and fractures) and tectonic elements (void space of faults), amongst others (Table 1). Besides the absolute values of these volumes which do change with time due to general vertical compaction or collapse of mine workings, the distribution of them with depth further influences the rebound process. A good example for this issue can be seen at the Barredo and Figaredo Mines in Asturias, Spain. Ordonez et al (2012) calculated the void space and its distribution within the reservoir of both connected collieries and their water influx. Plotting the mined horizons against the rebound speed shows that the rebound speed decreases drastically when the rising water table reaches a mined horizon (Figure 4). Between these areas of elevated void volume the rebound speed increases, as the lower availability of void volume in the intact strata also suggests (Younger & Adams 1999).

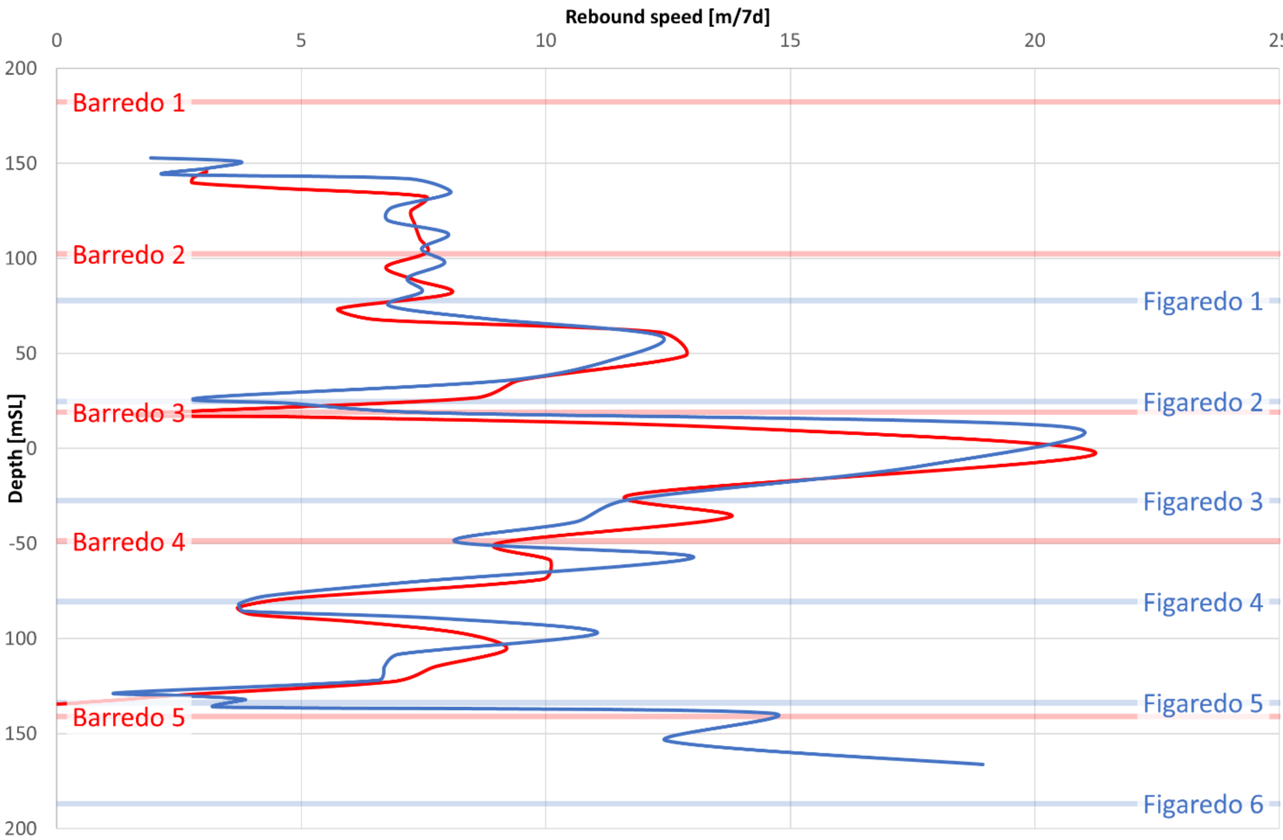

Figure 4 **Plot of the rebound velocity against the depth of the mined horizons (red lines for mined horizons at Barredo mine, blue lines for Figaredo mine (Asturias)). The rebound speeds for Barredo and Figaredo are shown as red and blue lines as well. Calculations based on reproduced rebound data from Ordonez et al (2012).**

Another good example of the influence of available void volume gives the Königsborn colliery in the Ruhr area. This rebound can be subdivided into three main phases (Figure 5) due to the availability of void space: In the first rise stage, in which underground mine workings and deepest horizons are flooded, high rise velocities occur, if converted accordingly, of in parts several hundreds of metres per year. On the one hand, this is due to the excavation ratio which is much lower at the deeper horizons and thus the cavity volumes are much smaller there; on the other hand, there is an increased influx of deep waters at this early stage which are pushed back with the rise of the mine water table. That stage is followed by a phase in which the main working levels are flooded. This stage is often marked by a more or less even rise. Changes of the hydrogeological properties, for example, the mine water table reaching the base of the overburden or of individual levels are reflected by the course. The continuing rise pushes the water influx from both the top and the bottom further down. Therefore, the rise velocity decreases and the curve levels off. The mine water rebound ceases to rise once it has reached an equilibrium between inflow and outflow of water or the level of a dewatering adit.

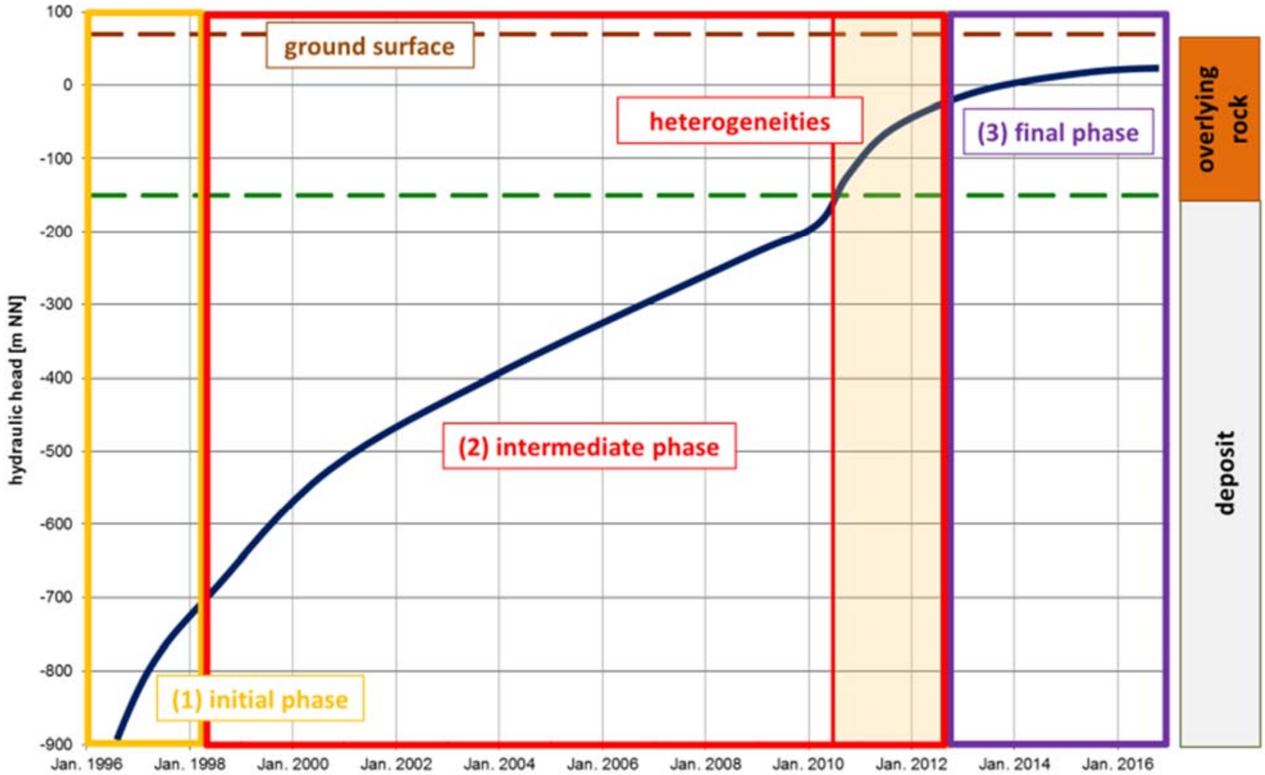

Figure 5 Graph of the mine water rebound at Königsborn colliery (Ruhr) and its separation into phases (modified after Rosner 2011).

Underground connections to adjacent collieries, as it is common in many coal mining areas, can lead to a temporal stagnation of the water level due to the increased void space of the connected workings. The difficulties to handle these uncertainties can be seen at the connected mine workings of Thurcroft, Silverwood, Treeton and Maltby in the Yorkshire Coalfield, Great Britain. Burke (2000) modelled the rebound of these collieries confronting the problem, that the capacity of the hydraulic connection between Silverwood and Maltby was uncertain. This was mainly due to the lack of monitoring data of the water table in any of these collieries. He handled this issue by considering three possible scenarios for this connection. In scenario one, the roadway failed so that there was no effective hydraulic connection. In scenario two, there was a connection with a medium capable connection, resulting in a "modest flow to Maltby" (Burke 2000). Scenario three emanates from a highly capable hydraulic connection, resulting in an "unrestricted flow to Maltby" (Burke 2000). The results of this modelling approach are shown in Figure 6. For a better overview, just the results of scenarios two and three are shown, as these were the most probable cases. The graph makes clear, that this single uncertainty leads to a difference of the rebound time of several tens of years for the scenarios two and three. It is obvious that such a difference in time is not an effective basis for a sustainable post-mining water management. Although Burke (2000) concluded, that the most probable case was a scenario between two and three, he could not prove this statement until the first monitoring data was available in

2001, confirming his assumption. All in all it should be noticed that even a single uncertainty may lead to big discrepancy between a prediction based on modelling and the actual water table rise. This underlines the importance of an adequate monitoring system.

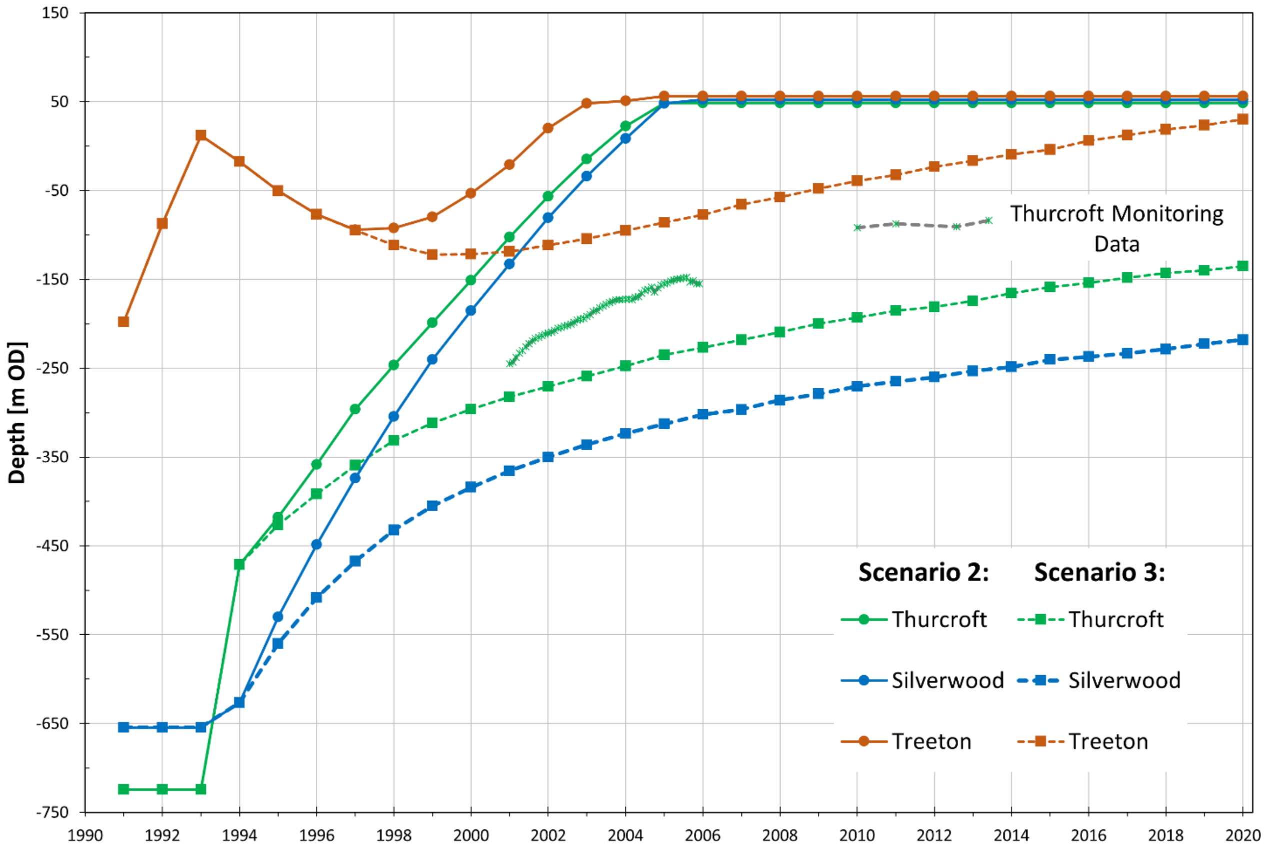

Figure 6 Modelled mine water rebound at Thurcroft, Silverwood and Treeton and measured mine water rebound at Thurcroft in Yorkshire (UK). Data reproduced from Burke et al (2000, 2004, 2005) and Gandy & Younger (2007).

In dependence of the spatial distribution and temporal development of the cumulative flows, density layering in the mine workings can result, which is stable over a long time (Wolkersdorfer 2016, Henkel & Melchers 2017). Within this context some interesting observations at collieries that lie close to the sea were made. Whitworth (2002) and Younger (2002) report on a clear tidal effect on the rebound process and the density layering. With respect to the rebound process the water table in the shaft of the colliery fluctuates with a magnitude of some decimetres as a reaction to the tides (Fig 4 right). Younger (2002) explains this observation with the additional load of the high sea level. This additional load of the higher water table results in a compaction of the underlying strata (Figure 7 A). This compaction leads to a lower void volume and thus presses the water out of the rocks (Figure 7 B). This can be recognized by a slight water table rise at the monitoring point. With the lower tide this compaction decreases again and the water table follows this trend (Figure 7 C). The observed time shift between the tides and the maximum effect on the water table is about 2 hours for the collieries in East Fife. A more drastic effect is observed with respect to the density layering in these monitoring points. Wyatt et al (2014) describes a change of the hydrochemistry of the pumped mine water according to the tides and a fluctuation of the density layering by the order of 10 m. The effect that causes this fluctuation is not understood in detail, but Wyatt et al (2014) attribute it to the different densities of the waters, the pumping regime as well as to the tidal forcing.

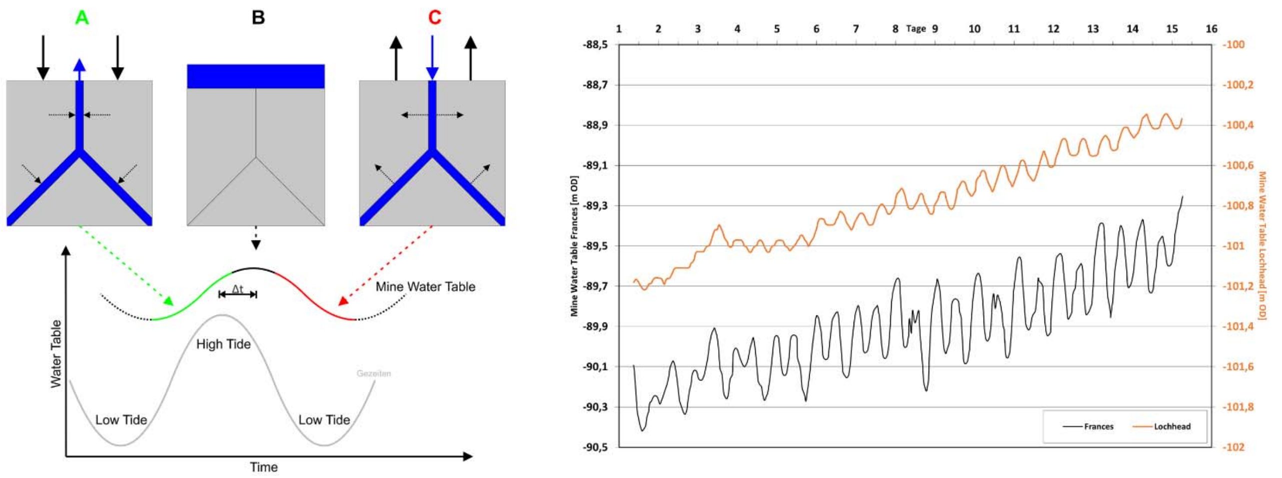

Figure 7 Tidal effects influencing the rebound process. Left (A-C): Basic mechanism discussed by Younger (2002). Right: Detail of a rebound showing tidal effects at Lochhead and Michael collieries in the East Fife coalfield, Scotland. Data reproduced after Whitworth (2002).

6.2 Hydrochemistry

The infiltrating water reacts with the rock matrix and with increasing retention times, the water will be continuously mineralised. Due to its genesis, the occurrence of hard coal is mostly associated with disulphide minerals (e.g. pyrite, marcasite or chalcopyrite). The dewatering of the strata when mining activity takes place and the ventilation of the underground workings favours the oxidation of these minerals (Barnes & Clarke 1964; Banks & Younger 1996). The intermediate oxidation products form a wide range of high soluble ferrous and ferric hydroxyl-sulphate phases (Younger 2000). This process is catalysed by acidophilic sulphide-oxidising bacteria, *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans* (Kelly 2000) (in literature often being referred to with their former names T*hiobacillus ferrooxidans* and *Thiobacillus thiooxidans, Banks & Younger 1997).* These evaporite mineral phases are highly soluble in water and are hence getting dissolved when the mine water table rises. If no buffer minerals (e.g. carbonates) are available, this results in Acid Mine Drainage (AMD). Once the mine water rebound has been completed and the water reaches the lowest surface point of discharge, this dissolution leads to a high content of iron and sulphate in the discharging mine water. Exposed to the atmosphere, the dissolved iron precipitates as yellow to red ochre, resulting in an explicit visual effect and a potential threat to the ground water and biosphere. Iron concentrations are usually highest in early phases ("first flush") and decrease exponentially with time (Younger 1997, 2000).

In areas where thick and impermeable rock layers act as a barrier between the rising mine water and the ground water, the risk of a contamination of the aquifer is substantially reduced (Heitfeld & Rosner 2015). Therefore, due to the (hydro-)geological properties of the deposit in the central and northern part of the Ruhr basin, where thick and impermeable claystone of the Upper Cretaceous Emscher Marl formation exists, a rise of the mine water table into the overlying strata of the Emscher Marl formation is unlikely (Hahne & Schmidt 1982, Baltes et al. 1998, Coldewey et al. 2014).

6.3 Geomechanics

The rising mine water table might result in a surface uplift in the centimetre to decimetre range. This can mainly be attributed to two reasons:

1) The rising water causes an increase in the buoyancy forces within the flooded strata.
2) The rising water may lead to a swelling of clayish rocks, resulting in a higher volume.

These ground heavings can be observed in many former mining areas and occur usually at large scale (Fenk & Tzscharschuh 2007). According to observations the heaving movements are less than 10 % of the subsidence volume (Preuße et al. 2017). In most cases, these ground heavings develop evenly and are not necessarily linked to damage-relevant events. Nevertheless, damage on structures caused by mine water rebound were observed in the Aachen-Erkelenz coalfield in Germany. The flooding of the coalfield caused the reactivation of a large fault, which led to heaving differences on both sides of the fault (Baglikow 2010). A second incident was reported by Oberste-Brink (1940) in the Wittener Mulde (Germany). Further reports of fault reactivations and damages to infrastructure because of mine water rebound were reported in the United Kingdom (Donnelly 2003, 2006; Yu et al. 2006). But in contrast to the discussions in Germany uneven uplift of the ground was not described, but a mine water rebound induced uneven subsidence.

7 Outlook

Out of the multiple completed or nearly completed rebound processes in European coal mining areas, many important conclusions regarding the prognosis of future mine water rebounds and their impacts to the environment can be done. The deeper and better understanding of the underlying processes are important steps to improve the long-term strategies and measures regarding the mine water management in accordance with sustainability, environment and profitability.

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Density Stratification of Mine Water Bodies in the Ruhr Coalfield – A Hydrogeochemical Approach

L Henkel *Technische Hochschule Georg Agricola, Germany*

H Jasnowski-Peters *Technische Hochschule Georg Agricola, Germany*

C Melchers *Technische Hochschule Georg Agricola, Germany*

Abstract

After cessation of mining activities in the Ruhr coalfield and adjustment of the existing dewatering measures the saline to brine type water, which has previously been retained by pumping activities, will rise dynamically up to its equilibrated level.

In flooded shafts of the Ruhr coalfield, distinct boundaries between differently mineralised water bodies have been observed at a variety of locations. The influx of more saline water from the porous network of the host rock and the void space of the mine workings on the one hand, and the penetrating less mineralised groundwater on the other hand, causes substantial density differences in the water column. These stratification patterns have been investigated at several sites in the Ruhr coalfield, including shafts, and wellbores. The temporal stability of the density stratification was proven by continuous, depth-based geophysical measurements in combination with hydrochemical and isotope-geochemical investigations on levelled samples.

Vertical thickness and stability of stratified water bodies vary according to site-specific lithology, shaft or wellbore lining and interconnected underground mine openings (i.e. levels and adits). Temporally stable conditions are driven by convection currents, which evolve from the influx of hotter and denser mine water. These currents may extend beyond the shaft or wellbore area into the adjacent underground void system. Hydrochemical data of levelled samples reveal variations in ionic concentration but no dependency of stratification concerning the gross water type.

According to these findings, the observed density stratification can be considered as the result of a complex flow pattern, which is controlled by the ionic strength and temperature of the water body independent of its detailed hydrochemical composition. In combination with stable isotope data, the results yield estimations of origin and residence time of stratified water bodies in the Ruhr coalfield and their connectivity to the hydrogeological system of the overburden. The phenomenon of density stratification is an important criterion in order to assess potential environmental impacts during the successive rebound of mine water in existing mine facilities after mine closure. In the future, density stratification can positively abate the breakthrough of saline to brine type mine waters to important ground and drinking water aquifers.

Keywords: *stable isotopes, stratification, hard coal mining, Ruhr coalfield*

1 Introduction

The last remaining active coal mine in Germany's largest hard coal mining area, the Ruhr District, will be closed by the end of 2018. The phase of post-mining will be taking over active mining operations with its major aim to manage the complex tasks around mine closures. Risk assessment and monitoring to avoid hazards is a key perspective of the research associated with post-mining and will be conducted in close collaboration with the mining authorities and companies. The Ruhr District is the largest urban agglomeration in Germany and one of the most densely populated coal mining areas worldwide. Early coal mining activities date back to the 12th century. Since then, a total of about 10 billion tonnes of coal has been produced (Melchers et al. 2015). As the coal-bearing Upper Carboniferous strata is gently dipping to the north the extensive underground mining process reached a maximum depth of 1,600 m below the surface in the northern part of the mined Ruhr coal deposit. Consequently, numerous shafts and exploration boreholes were drilled to enable mining of deep coal seams during the active production phase. Some of these shafts were used to install submersible pumps for mine water drainage in order to retain the groundwater at a certain level. Currently, there are eleven mine water management facilities, which are pumping more than 60 million cubic metres of water per year (GVST 2015). Moreover, the existing drainage system must be maintained for the future to prevent urban and rural areas from being flooded or impacted by mine water due to prolonged subsidence associated with the extensive mining operations. Therefore, adjusted water management measures will continue for an unlimited period after coal mining has ceased. Within the decommissioning area abandoned mine shafts are filled with water to varying degrees, and hence provide an excellent possibility to monitor the water quality trend with depth. Depending on the geology and tectonics of the surrounding strata and the shaft lining, mine cavities are pathways for heat and material flows between the ground-water reservoir, other geological strata and the atmosphere. Monitoring measures reveal stratification of mine water bodies at some of the investigated sites. Those are characterised by substantial changes in electrical conductivity (EC) as a measure of dissolved ionic constituents and/or temperature, both affecting density as a major controlling factor to separate homogenous bodies of water. Individual water bodies typically have constant levels of density throughout the water column and can be regarded as “fully mixed” or equilibrated. Geophysical measurements for determination of physico-chemical parameters together with depth-differentiated sampling in flooded abandoned mine shafts, monitoring wells and boreholes are carried out to evaluate stratification patterns in mine water bodies. Understanding the development of the chemical composition and possible density layering of rising mine water in disused collieries plays a key role in any risk assessment process associated with environmental impact.

2 Methodology

Downhole measurements are conducted with a multi-parameter probe, which is measuring pressure, temperature, EC, pH, reduction-oxidation (i.e. redox potential) and dissolved oxygen of the fluid. With a diameter of up to 45 mm, a length of 1.5 m and a system of measurement cables up to 1.000 m in length the probe records a continuous profile of the borehole fluid properties with depth. The probe’s specifications are presented in Table 1.

Table 1 Technical specifications of the used multi-parameter probe

Parameter	Range	Accuracy	Resolution
Pressure	0..1000 dbar	0.05 % F.S.	0.0015 % F.S.
Temperature	1..+50 °C	0.005 °C	0.001 °C
EC	0..70 mS/cm	0.007 mS/cm	1.1 mS/cm
Oxygen	0..50 ppm	1.1 ppm	1.1 ppm
pH	0..14 pH	0.01 pH	0.001 pH
Redox	+/- 1000 mV	1 mV	0.1 mV

According to the response times of the probe`s sensors the sampling rate is adjusted to one metre per minute. During the first measurement downhole, the water column is directly logged in order to reduce the possibility of self-induced water turbulences of the measuring device. Following a preliminary assessment of the results, water samples are collected with a 1,0 litre capacity water sampler at different depths of the water column. Directly after sample collection, on-site parameters such as pH and EC are measured with a multi-parameter portable meter (*WTW ProfiLine Multi 3320*). Total iron and volatile sulphide concentration were determined with the HACH powder pillow method in the field. The values are compared to those obtained later by lab measurements using spectroscopy or ICP-MS instruments. All water samples are transferred into containers and, if necessary, treated and preserved for major ion and stable isotope analysis according to DIN 38402-13. Stable isotope analysis includes measurements of isotope ratios of hydrogen, oxygen, dissolved inorganic carbon (DIC) and sulphur. All values for the isotopic composition are expressed in per mil relative to the international isotope standards: The hydrogen and oxygen isotopes of H_2O relate to Standard Mean Ocean Water (SMOW), the values for the carbon isotopes of dissolved inorganic carbon (DIC) relate to the standard of the Vienna Pee Dee Belemnite (V-PDB) and the isotope values of sulphur are reported relative to the Vienna-Canyon Diablo Troilite (V-CDT). As the electrical conductivity increases with temperature, all values refer to 25°C in order to standardize the temperature effect (Langguth & Voigt 2004). The redox potential is measured with an Ag/AgCl- electrode. All reported values are corrected to the standard hydrogen electrode and a temperature of 25 °C after Wolkersdorfer (2008).

3 Study site

The majority of the investigated sites are located in the Ruhr District, North-Rhine Westphalia (NRW), Germany. It is the largest hard coal mining region in Germany and has become the third largest urban agglomeration in the European Union. Thus, it is one of the most densely populated coal mining areas worldwide. The hard coal in the Ruhr District was formed during the Upper Carboniferous period (lat. carbo = coal). The coal-bearing strata was extensively folded during the Variscan orogeny, and later on dissected by syn- to post-Variscan fault tectonics. The whole strata is gently dipping to the north, so that the extraction of hard coal in the very beginning of mining activities was concentrated in the south of the Ruhr District, where the coal seams crop out directly at the surface (Pfläging 1999). North to the river Ruhr, the thickness of the overburden increases continuously, and the Carboniferous rocks are unconformably overlain by massive post-Variscan deposits of Late Cretaceous to Quaternary age (Fig. 1). According to its extensive distribution, the Upper Cretaceous strata with thicknesses of up to 900 m (Hilden 1995) comprise the most important overburden unit. In the stratigraphical sequence, massive, fissured and locally karstified limestones of Cenomanian and Turonian age are overlain by an, up to 800 m thick, unit called the Emscher Mergel - Coniacian to lower Santonian clay- to marlstones. Beneath the topmost water-impermeable upper one to two metres thick horizon, which has been weathered to a clayey silt- or silty claystone, the clayey marlstone can be fractured and water-bearing to a depth of some 30 to 50 m. Fracturing becomes less common towards the bottom of the zone and finally fade out completely, creating an aquiclude. The Emscher Mergel acts as a major regional seal / aquiclude and separates the deeper groundwater storey of the Cenomanian and Turonian from the upper groundwater storey of the Quaternary and the fractured zone (Melchers et al. 2014).

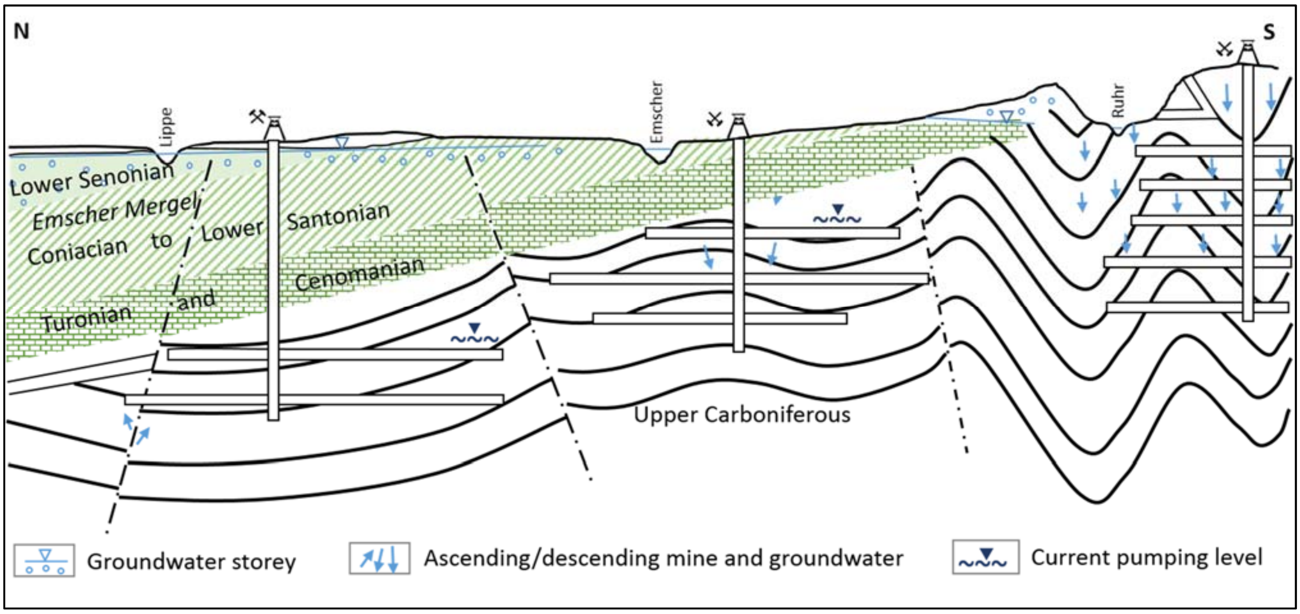

Figure 1 Schematic section through the Ruhr coalfield (greatly exaggerated), redrawn after Hahne and Schmidt (1982)

The extensive mining in the Ruhr coalfield formed a huge underground network of mine workings at several levels. Therefore, a network of pumping stations is still active in the former coal mining area. In 2016, 66.3 million cubic meters of mine water where pumped to the surface by a network of eleven dewatering stations and one active mine in the Ruhr coalfield (Drobniewski et al. 2017). In total, a number of four abandoned water filled mine shafts, which are not influenced by current mine water management activities have been identified as study sites. All of them are located in the northern part of the Ruhr District. The following chapter summarizes the measurement results for one of these sites.

4 Results

4.1 Physico-chemical Parameters

The investigated site is situated at the northern rim of the Ruhr District isolated from any water management measures. The abandoned mine shaft is around 1,000 m deep and has not been backfilled yet. Mine water rebound in the mine has already been terminated by the end of the 1920s, so that the water level has already reached equilibrium. The thickness of the overburden rock (Upper Cretaceous strata) accounts for roughly 800 m. The first 600 m of the drilled sequence consist of marls of the Emscher Mergel. The lower 200 m comprises the stratigraphically older Cenomanian and Turonian limestones which unconformably overly the bedrock of the coal seam-bearing Upper Carboniferous. Two horizontal working levels for coal mining were built in 850 m and 950 m depth respectively. The results of the geophysical measurements with the multi-parameter probe are plotted in Figure 2. Lithology and stratigraphy are illustrated on the left hand side of the figure. Depth is indicated in metres below ground surface. The black line specifies the calculated regional geothermal gradient after Leonhardt (1983).

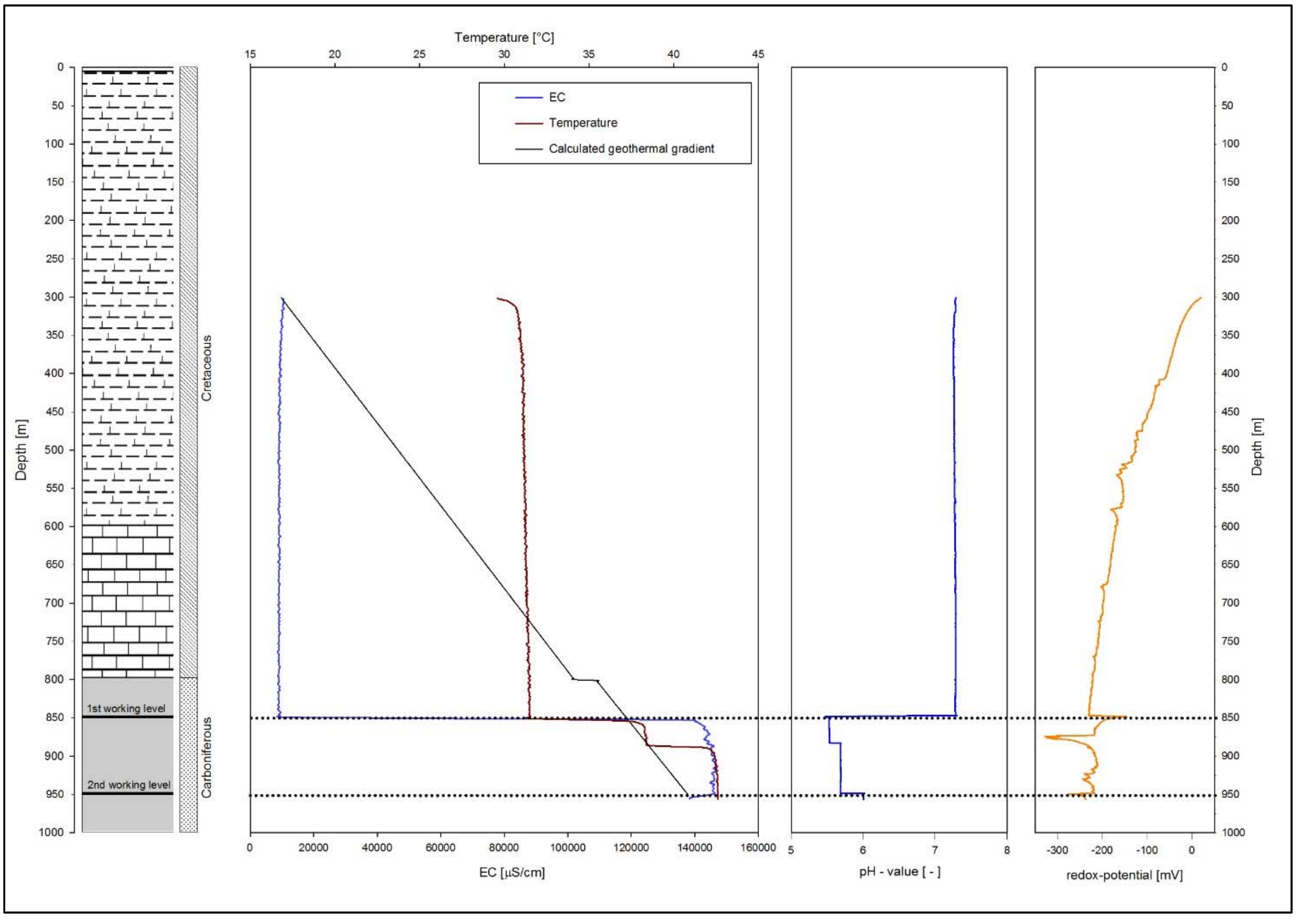

Figure 2 Physico-chemical parameters of the water column in an abandoned mine shaft of the Ruhr coalfield

With reference to the physico-chemical parameters determined, the water column of the shaft can be divided into two main sections. Up to a depth of 850 m, the specific electrical conductivity (EC) and the temperature show constant values averaging around 9,000 µS/cm and 30 °C. Below 850 m, a 1.3 m thick boundary layer follows in which the values increase sharply to an average of 146,000 µS/cm and 41 °C respectively. After Leonhardt (1983), the rock and groundwater temperature increases with approximately 3.7 °C per 100 m depth in the Ruhr District. A brief look at the log provides clear evidence that the geothermal gradient is largely eliminated within the two sections of the water column. The pH shows constant values around pH=7 for the upper section and decreases sharply in the area of the first working level to values averaging around pH=5.5. The course of the redox-potential points to increasing reducing conditions within the upper water body from Eh=+7 mV to Eh=-224 mV. Beneath the boundary to the lower water body, a short sharp increase is followed by a decrease until the values seem to vary widely over the rest of the section.

4.2 Hydrochemistry and Isotopic Composition

In total, four depth-differentiated samples were collected from the water column, two from the upper and two from the lower water body. Hydrochemically, all samples are sodium chloride water with Na^+-concentration being directly proportional to that of Cl^-.

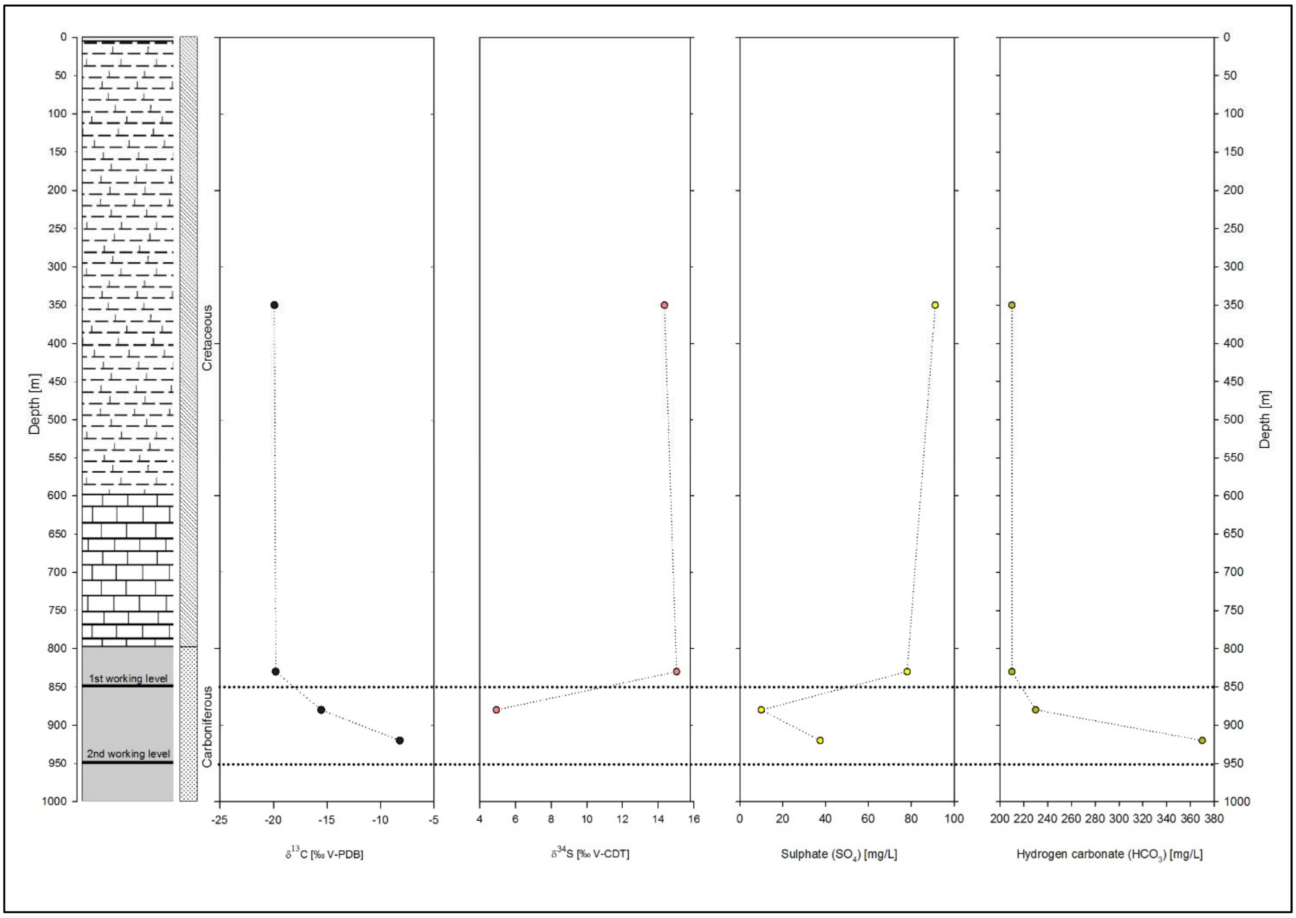

Figure 3 Hydrochemical and isotopic composition of the water column in an abandoned mine shaft of the Ruhr coalfield

First evaluations of stable sulphur isotope data within the investigated water column reflect the stratification pattern displayed in the geophysical log. All water samples taken from the upper water body indicate similar values accounting for the homogeneity of the water body between the water surface and 850 m. The determined $\delta^{34}S$ value for the deeper water body is 10.0 ‰ lower than in the upper water body in combination with a decrease in the total sulphate concentration around 70 mg/L. No $\delta^{34}S$ value could be determined for the deeper water body due to the low sulphate concentration. The $\delta^{13}C$ of the dissolved inorganic carbon in the lower water body is significantly more positive, than the $\delta^{13}C$ of the upper water body. The concentration of the bicarbonate shows a comparable trend, with a 160 mg/L higher concentration in the deepest part of the water column.

5 Discussion

Repeated geophysical measurements display the formation of a stable density stratification in the water column of the abandoned mine shaft. A sharp boundary layer is located at a depth of 850 m. It is apparent from the documents that the first working level (850 m-level) can be found in approximately this depth. The constant values of both the hydrochemical and isotopic data for the upper section of the water column are pointing to homogeneous conditions. Previous studies dealing with this subject considered a temperature-dependent density-driven flow as a reason for this phenomenon (e.g. Gebhart et al. 1988, Wolkersdorfer 1996). Triggering force for this movement can be deducted from the geothermal gradient. Theoretically, in an underground water column this gradient warms up the deeper mine water and induces currents that can develop into stable convection cells (Berthold 2009). These prevent the mixing of inflows of a different composition, which leads to the formation of a secondary convection cell. Flow velocity measurements in combination with numerical simulations conducted by Kories et al. (2004) revealed numerous circular current bales being responsible for the homogeneous conditions within the water body. Current velocities appear to be high in regions of homogeneity and low near the boundary layer. The authors further demonstrated that a continuous fresh water recharge is crucial for a stable stratification. In available records dealing with the investigated mine site, relatively high quantities of water flowing in from the side-walls during the active production phase are documented. In combination with high underground temperatures and sales problems at the coal market, the costs for the drainage forced the early closure of the mine. Latest camera inspections of the upper shaft lining above the water surface in course of on-going monitoring measures point to steady inflow of near-surface water through the brick walls. As a whole the observed conditions plead for a continuous water recharge.

All hydrochemical and isotope data, which have been evaluated so far, conclude to an active hydraulic communication over the mine workings and possibly the surrounding rock. In geochemical terms, the mine water generally equates to a mixture of ground water and soil leachate that has been geochemically altered by the various processes taking place in and around the mine workings. As a result, processes such as gas dissolution and release, evaporation and condensation can produce a difference in ionic concentration within the water column. According to the results of the hydrochemical analysis combined with the regional hydrogeology, the upper water body is subject to exchange reactions with water from the upper as well as with water from the lower groundwater aquifer. Pursuant to the assumption that hardly any water exchange between the two water bodies takes place across the boundary layer, the highly mineralised deep water points to a communication with the deep waters of the Carboniferous. The decreasing sulphate concentration is indicative for the limited inflow of sulphate-rich water from the overlying rock. In combination with the sulphur isotope signature and the lowered pH values of pH = 5-6 the residual sulphate can be identified as a product of the pyrite oxidation from the existing coal horizons / working area. In this case, sulfidic components in the coal were oxidized to sulphate. The development of the bicarbonate concentration in conjunction with the carbon isotope signature of the dissolved inorganic carbon indicates active carbonate solution from the Cenomanian / Turonian host rock.

6 Conclusion

The formation of density stratification has been identified in shafts that have already been flooded, as well as in shafts that are still undergoing this process. It is obviously not related to the chemical composition of the water, as stratifications are acquired between different water types, such as bicarbonate and sodium chloride water, and also between individual sodium water bodies of different concentration (like it is the case in the shaft discussed in this paper). The thickness of homogeneous water bodies can vary from just a few metres to as much as several hundred metres. However, the boundary layer is usually no more than a few decimetres in depth. According to present knowledge, the formation of boundary layers is largely dependent on water inflow from the surrounding rock and on rock-specific properties such as thermal conductivity and fracturing. However, the shaft lining can also play a significant role, as it provides water inflow at the individual horizon levels. The water in the mine workings consists of a mixture of deep formation water from the Carboniferous, deep groundwater from the Turonian and Cenomanian and near-surface water, which is influenced by infiltration of rainwater. The overarching goal of the study is to hydrogeochemically identify these three endmember water types. In order to specify origin and flow path of the water in the investigated sites, the obtained data will be interpreted in the context of the regional hydrogeological setting combined with available data from these three systems. Subsequently, the data has to be interpreted in the light of stable isotope distribution patterns under consideration of equilibrium and kinetic isotope effects.

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6. Hydrogeochemistry, AMD and treatments

A Stitch in Time Saves Nine: A Case Study of the Importance of Quality Water Models and Surface Rehabilitation to Optimize Closure Options

R Botha *Anglo American, South Africa*

R Muhlbauer *Anglo American, South Africa*

J Human *Anglo American, South Africa*

Abstract

Kromdraai is a coal operation in South Africa that is approaching closure with mining ceasing at the end of 2018. The most significant closure issues relate to the lack of progressive rehabilitation impacted by topsoil shortages, which in turn exacerbate the generation of acidic metal-rich mine water with the potential to discharge into adjacent streams. Significant Acid Rock Drainage (ARD) issues are complicated further by the complex interaction between surface water and groundwater associated with historic underground and adjacent open cast mining. The current strategy involves the operation of a liming plant, dosing with caustic soda, management of water levels in pits, extraction of water from dewatering wells and subsequent treatment.

This paper focuses on the development of a numerical and geochemical groundwater model which is underpinned by a detailed conceptualization of the groundwater system. A multi-disciplinary phased approach was used to collect data which included intrusive geophysics, water monitoring and data collection programs, to ensure a high confidence level model outcome. Good quality data input reduced the uncertainty associated with the initial decant prediction and resulted in a reduction from 8 mL /day ARD to less than 5 mL /day thereby reducing water related closure costing significantly.

The model output was used to undertake trade-off studies between improved surface rehabilitation and various water treatment options to address long-term closure liabilities and to determine the most cost-effective closure option that reduced closure risks to an acceptable level. Various water treatment technologies and rehabilitation methodologies were considered and trade-off studies with cost benefit analysis were undertaken as part of this project. The case study discusses the project learnings and demonstrates the business case for improved surface rehabilitation, and resultant long-term liability reduction associated with active water treatment (Reverse Osmosis). Critical to closure liability reduction is ingress management in the form of optimised surface rehabilitation and vegetation cover as this results in reduced polluted mine water generation and allows for the implementation of more cost-effective passive treatment systems as well as phytoremediation.

The project demonstrated the importance of high-quality hydrogeological models and surface rehabilitation to optimise closure options, which reduces the long-term liability estimate and provides an executable mine closure plan that will produce an acceptable post closure residual risk profile.

Keywords: *Progressive, rehabilitation, acid rock drainage, geochemical, cost-effective, phytoremediation, reverse osmosis, passive, hydrogeological, residual, risk*

1 Introduction

Kromdraai is a coal operation in South Africa that is approaching closure with mining ceasing at the end of 2018. It was determined in 2014 that water management options needed further study specifically to quantify water discharge volumes, quality of discharge and water decant locations post closure.

The mine has significant dispersed ARD across the footprint, which is complicated by the complex interaction between surface water and groundwater associated with historic underground and current open cast mining. The current water management strategy involves the operation of a liming plant, dosing of water with caustic soda, management of water levels in pits, and future extraction of water through bores for potential reverse osmosis (RO) treatment at the eMalahleni Water Reclamation Plant (EWRP). Previous hydrogeological estimates (Hodgson, FDI *et al*.) indicated a post closure requirement for active treatment of 8 ML/day in perpetuity at a cost of more than ZAR2.5billion (150 year period). There are hence significant business drivers to reduce or eliminate this requirement for in perpetuity treatment using RO.

Key to understanding the post-closure water management risk is an understanding of the mitigation measures that will reduce rainwater infiltration and the effect it will have on decant water volumes and quality. Hence, a robust hydrogeological conceptual model, qualifying the groundwater flow regime, recharge rates and areas as well as discharge mechanism and hydrogeological and geochemical controls influencing the groundwater flow and quality over time was developed.

The conceptual flow and transport models were translated into a calibrated numerical groundwater flow and transport model for the site and the model was used to inform possible water management scenarios at closure. The objective of this paper is to highlight how the project identified the most cost effective long-term scenarios that will ultimately be developed into an executable long-term post-closure water management solution for the site that is cost-effective and delivers an acceptable risk profile.

2 Project Execution

The project was executed in seven steps to deliver a long-term post closure water management solution. Each of these steps is outlined in more detail below.

2.1 Collation of all existing data into a single GIS database

All existing mine plans, including historic aerial photographs, historical mine plans and the latest aerial images, were obtained from various sources and collated, ensuring all data was in the correct mine coordinate system. Due to the nature of the project, the primary focus was on where mining had taken place, when this had occurred and what rehabilitation had been done. As the information was collated, care was taken to ensure that all data was in the correct mine coordinate system; specifically, LO29, and using the Cape Datum. Once all the readily available data had been collated, it was noted that the exact location of the old Blackstone Colliery and other historical shafts and declines was missing. The missing locality data and understanding the locality of decant points were a key component in formulating a closure strategy. The corporate office aerial photography archives were accessed and three iterations of photography were found over Kromdraai Colliery from 1971, 1972 and 1986.

2.2 Geophysical delineation of structures and intrusions

Airborne electromagnetic (AEM) and magnetic data were collected in October 2015 over the mine site to characterise the hydrogeology and map geological structures (dykes, faults and sills) believed to act as pathways and/or barriers to water flow and contaminant pathways. Interpretation of the data mapped several dykes and faults (Figure 1), while possible pollution plumes were mapped and digitised from the processed conductivity-maps (Spectrem Air Report).

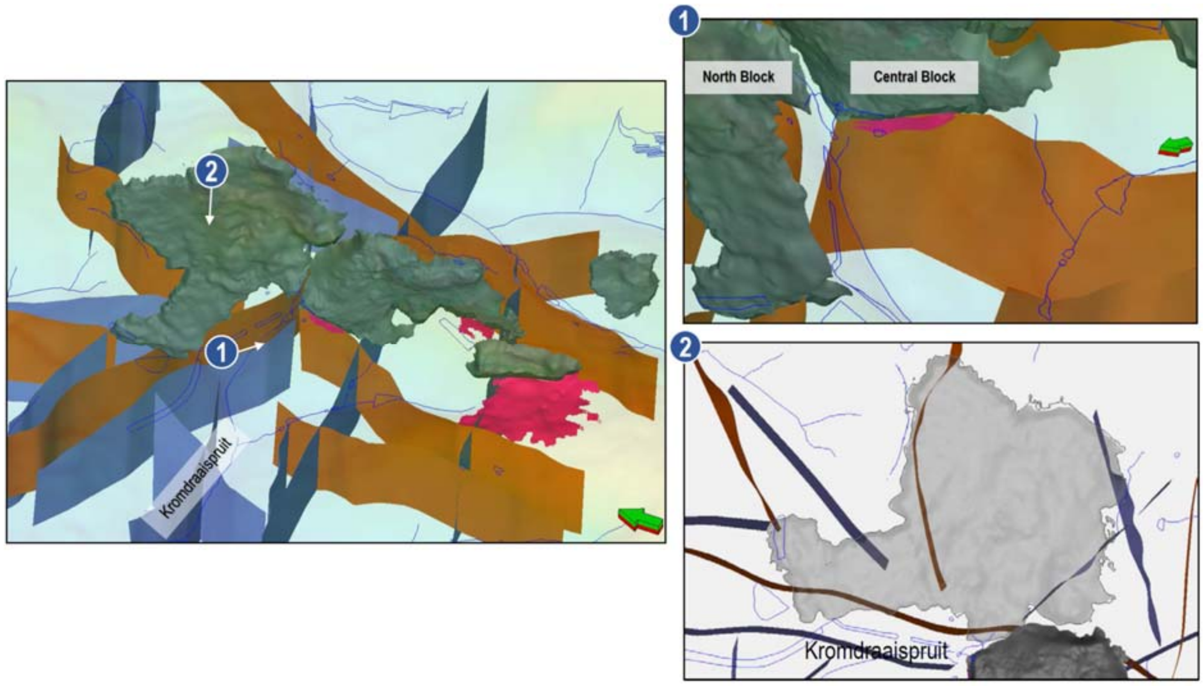

Figure 1 Location and layouts of dykes, faults/structures from geophysics

2.3 Drilling and sampling of additional monitoring boreholes

Based on the results and interpretation of the high-resolution AEM and magnetic data, 21 boreholes were drilled to test the water level and quality as well as to map the depth extent of possible pollution plumes. Additional geochemistry test work (Barr, J) undertaken included static Acid-base accounting (ABA) and Net Acid Generation (NAG) tests, as well as kinetic test work on the coal seam and inter-seam lithologies. A significant feature of the ABA dataset is the prevalence of negative neutralisation potential (NP) values. These characteristics are further reinforced by NAG test data which indicated an equilibrium pH following spontaneous oxidation of sulphide and consumption of reactive carbonate of the order of 2.4, with a residual acidity release of around 50 mg/L. Kinetic testing produced particularly poor-quality leachate, with a pH of less than 2 and extremely high concentrations of sulphate, iron, manganese and aluminium (WSP Parsons Brinkerhoff). It is hence unlikely that decant water will improve in quality to a point which would permit direct environmental release in the short term.

2.4 Building the numerical water transport model

All the additional fieldwork and data collation were used to compile a hydrogeological conceptual model, describing the dynamics of groundwater flow, infiltration, storage and contaminant movement underground. Aquifer parameters (Geo Pollution, September 2016) and infiltration rates as well as initial concentrations for sulphate were assigned to each source area. The conceptual model was translated into a numerical flow and transport model, using the polygons generated with the ArcView shape files, assigning aquifer parameters in the SPRING software (Delta-H June 2017), as reflected in Figure 2 below.

2.5 Rehabilitation scenario modelling

As the geochemical work and simulations in the groundwater model indicated that little can be done to change the quality of the water in the long term, the focus was to identify possible rehabilitation scenarios, which would result in the reduction of infiltration and hence the ultimate volume of water that would require post closure treatment. The four rehabilitation scenarios (as described in Table 2), consisted of different percentages of arable, grazing and wilderness land, based on different growth medium depths (650mm vs. 350mm vs. 250mm cover respectively), which resulted in different seepage rates and different levels of legal compliance, as demonstrated in Figure 3 and Table 1.

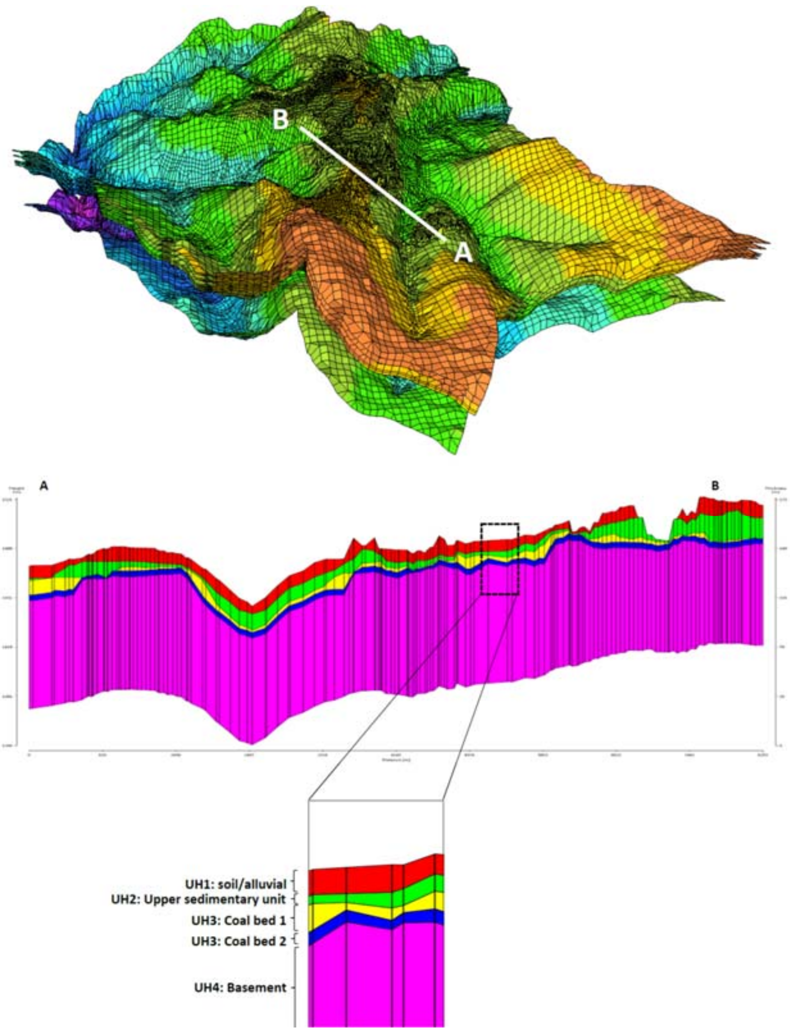

Figure 2 Vertical discretisation of the groundwater model

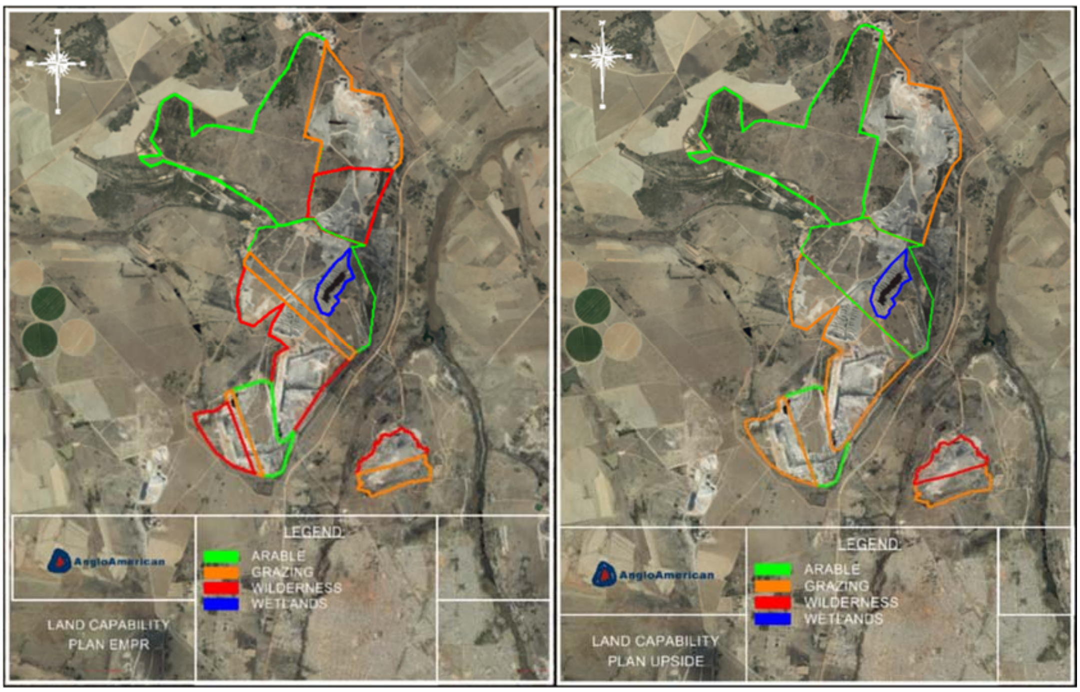

Figure 3 EMPR rehabilitation scenario (left) and Upside scenario (right)

Furthermore, closure calculations included rehabilitation requirements as reflected in Table 1, which were added to the capex component in the closure calculation and were spread over four to five years in line with the rehabilitation process. Each scenario was costed for import of topsoil as well as for scavenging of topsoil on site to address the shortfall of topsoil.

Table 1 Closure costs for rehabilitation scenarios

Scenarios	Legal compliance (Yes / No)	Growth medium volume required (m^3)	Rehabilitation cost (ZAR)
Scenario 3BS	No	-	84,776,553.63
EMPR Compliance	Yes	2,249,605.84	226,661,762.64
Upside	Yes	2,455,712.30	233,993,747.64
Scenario 4BS	Yes	5,265,044.02	419,469,506.16

2.6 Simulation of variable management scenarios

Two phases of scenario modelling were completed (Muhlbauer, R). The first phase included modelling of 22 different combinations whilst the second phase included modelling of only five scenarios based on the outcomes of the first phase. During phase 1, the 22 post-closure modelled scenario combinations considered the impact of various rehabilitation strategies on the predicted post-closure recharge, leakage from dams containing ferrihydrite ($FeOH^{3-}$ also known as Yellow Boy) and decant volumes. Model predictions provided decant locations and decant rates based on certain assumptions. Therefore, only approximate percentages of decant rates for the different decant areas were provided as reflected in Figure 4.

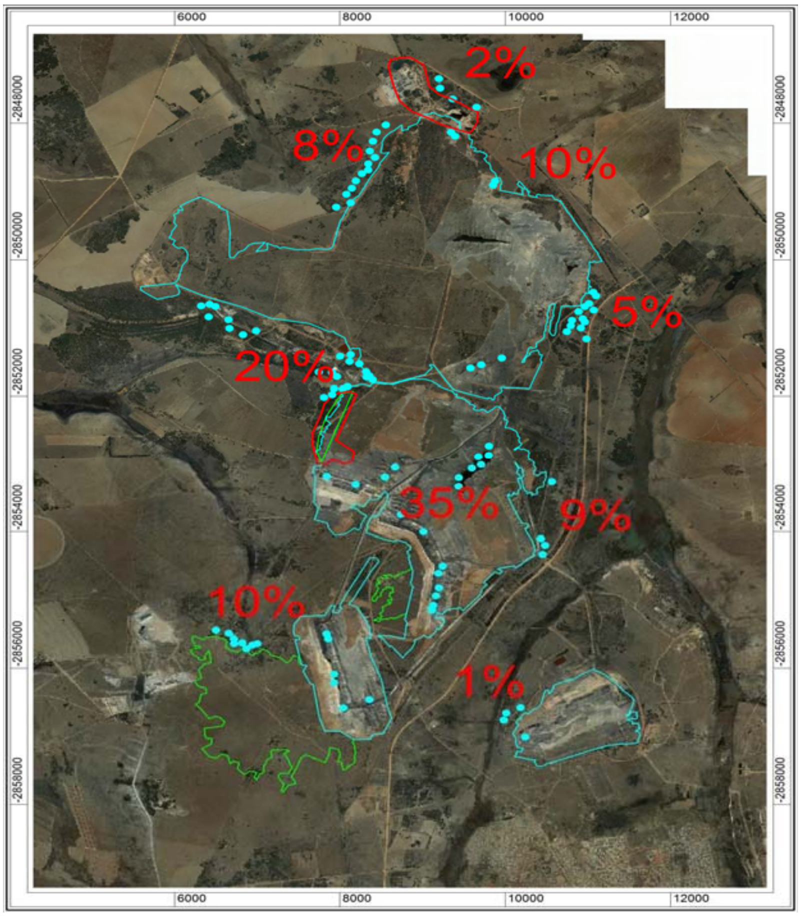

Figure 4 Apportionment of decant rates within the mining areas

Actual volumes were assigned to each discharge area to enable preliminary comparative water treatment cost calculations to be completed for the identification of scenarios which could then be further refined. In Phase 2, five scenarios (Table 2) were refined using the existing numerical hydrogeological water transport model (Delta-H, September 2017). To enable water treatment cost calculations, the estimated decant volume for each area as reflected in Table 2 was derived from the percentage apportionment of decant rates in each area using the total estimated closure decant volume for each scenario.

Table 2 Post-closure mine water balance for the rehabilitation scenarios

Scenario	Explanation	Recharge, backfilled and undermined areas (ML/d)	Predicted decant rate (ML/d)
Base case	The current closure plan for Kromdraai is to pump water 28 km to the EWRP and to treat through RO and sell a portion of the water to the municipality.	10.51	7.43
As Is	With no further interventions, large tracts of land will have limited land use and significant water ingress and higher post closure decant volumes can be expected.	7.01	4.61
3BS	Aims only to use all the available topsoil to cover the surface area at the best possible depth, but at least achieving a wilderness land capability.	6.35	4.04
EMPR	Post closure land use in compliance with existing legal commitments. Due to significant topsoil shortage, this scenario will require import of growth material.	5.68	3.48
Upside	Improves on the EMPR scenario by increasing topsoil depths with specific focus on upscaling post closure wilderness land use to grazing.	5.23	3.14
4BS	Aims to achieve the best possible outcome in terms of soil thickness. Soil thickness is believed to be the best preventative measure for water ingress in addition to vigorous vegetation cover. Import of large amounts of growth medium to achieve a minimum soil thickness of 650mm is required (all arable land).	4.39	2.51

2.7 Selection of the preferred post closure groundwater solution

The post-closure modelled volumes were used to assess the most appropriate treatment scenario. The following criteria for treatment of impacted water were made:

- Reactive barriers, phytoremediation and expanded wetlands would be used for flow rates of less than 0.2 ML/day. These flow rates are generally dispersed over an area resulting in diffuse seepage.
- Biological passive treatment systems would be applicable for flow rates between 0.2 and 1.4 ML/day. These flows can be collected in dedicated ponds and gravity-fed into passive biological systems.
- RO treatment at the EWRP for flows of 1.4 ML/day or above.

Capital estimates and operational costs were derived from the closure models used for water liability calculations for both the EWRP and passive treatment calculations. Phytoremediation information was based on planting trees at a certain density to achieve evapotranspiration based on water uptake rates for certain rainfall averages. This enabled the development of detailed cost benefit analysis for each of the various scenarios, comparing increased rehabilitation costs against the benefits of a reduction in long-term groundwater treatment. This ultimately resulted in the selection of the preferred long-term solution. The impact of improved rehabilitation on water liability costs is evident in Figure 5.

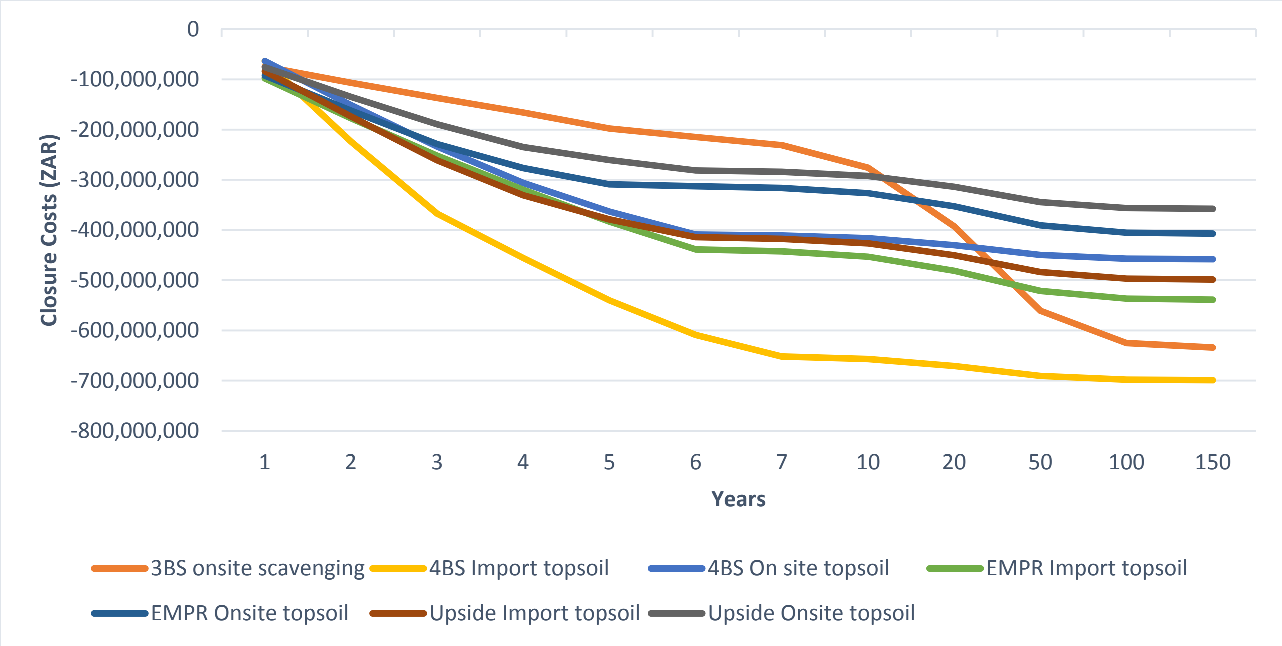

Figure 5 Closure costs for different rehabilitation scenarios (net present cost)

Based on the results from the financial modelling, the "Upside" scenario with on-site scavenging of topsoil aimed at upgrading the wilderness land use to grazing is the most beneficial solution in terms of long term liabilities, and hence the selected solution.

3 Conclusion

The development of a defensible calibrated numerical flow and transport model based on numerous studies to address significant hydrogeological gaps allowed for the simulation of the post closure water volumes and quality applying various rehabilitation scenarios. Improved rehabilitation practices are key to ingress management and as a result decant volumes that need to be managed. A reduction in decant volumes allows for the implementation of more cost-effective sustainable treatment options which ultimately reduce long term water liability costs, however this cannot be at the expense of importing topsoil.

Current closure practices tend to defer rehabilitation and mine closure to reduce costs in the short-term, however this increases our long-term financial liabilities, in particular water liabilities. These typically need to be managed in perpetuity which precludes sites from obtaining closure certificates. The project clearly demonstrates that the timeous implementing of appropriate surface rehabilitation will have a significant impact on the long-term groundwater and surface water liabilities, illustrating the concept of "A Stitch in Time Saves Nine".

The Upside scenario as the preferred long-term solution, will reduce the original estimated closure liability (pre-project) of more than ZAR 2.5 billion to less than ZAR 0.5 billion over a 150 year period. Even though the business case for improved and timeous surface rehabilitation has been demonstrated clearly through this project, the need for sustainable long-term use of the "post passive treatment" water is required to make the solution self-funding and truly sustainable. These requirements can be addressed by initiatives, such as the "The Green Engine" concept that is currently being developed for the Kromdraai area. The Green Engine will provide a self-funding agri-businesses opportunity that will contribute to the management of water ingress and ultimate reduction in decant of polluted water, by deploying solar PV farms that can capture water run-off, vertical greenhouses and other infrastructure where storm water is captured and used as part of the agri-businesses. The benefits are that water becomes an asset to the community and the agri-businesses and results in a reduction of closure liability costs related to import of top-soil and active water treatment. Changing a perpetuity liability into a sustainable post closure opportunity.

Acknowledgement

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A Case of River Recovery — a Brazilian Experience

M Weber *Brandt Meio Ambiente, Brazil*

W Brandt *Brandt Meio Ambiente, Brazil*

Abstract

River recovering after a mining process, as widely known, isn't quite a simple thing. This paper wants to sum up briefly a mining and reclamation case conducted over 20 years in one of the most inhospitable regions of Brazil. The river was dredged along 27 km for diamonds extraction and gold. Interdisciplinary follow-up work was done since the beginning of mining in 1989 until its definitive closure in 2007. Initially consistent licensing studies on hydrography, sedimentology, biotope mappings, regional flora and fauna, besides on embracing social issues were accomplished in that region of very low social development. Innovative techniques were driven on preventing and minimizing environmental impacts, taking into account the strong dynamics of the river as well as the altered ciliary vegetation and attached hydrological systems. The extremely low fertility of the final substrate, the utmost unfavorable climate, and coexistence of cattle deliberately placed by local residents, required the rupture of several management paradigms. Reclamation techniques were based on seedling-nucleation, backed by periodic monitoring of bioindicators like ant communities, spontaneous plants, as well as the temporary introduction of early soil-conditioning vegetation. Finally a process of floristic recovery began interacting with prior protected forest spots.

Some negative results, however, came on during the reclamation process as the constant intromission of cattle on the fresh reclaimed areas, despite the fences and constant surveillance in all recovered areas, requiring persistent rework and considerable losses on already consolidated efforts.

A Closure Plan was prepared, licensed and executed. The final monitoring over all area was accomplished and approved by the official authorities. Eventually the decommissioning attest was given to the miner, and the company leaved the area. Yet, a very small period of time later and much against all legislation, a massive invasion of small illegal miners came up, destroying a good loaf of the reclamation works carried out.

This loss of public control situation, after the decommissioning and farewell of the miner, can represent a trigger for environmental (and social) degradation, worse than before mining, despite of social and environmental investments done by the entrepreneur. Why is this article current in 2018? Fact is that the miner, having fulfilled all the legal obligations, is being submitted to a legal action these days moved by the Public Prosecutor for lack of reclamation, ten years after decommissioning. This may neither be a local occurrence nor a Brazilian exclusivity, but may achieve other countries due to a low institutional control and nowadays rapidly concept changing. As a result there may raise severe threats to the miner and also to important environmental systems in the post-mining period.

Keywords: *river recovering, environmental reclamation, long term monitoring, post closure issues*

1 Introduction

Recovery of rivers and their alluvial areas consists in a very complex process. In regions with adverse climatic and soil conditions, as rainfall extremes and sandy soils, it can become even worse. The present case was also inserted in a very low social indicators environment. According to official agencies it is one of the less developed regions of Brazil and historically strongly linked to purely extractive activities, although very traditional from an autochthonous cultural point of view (Minas Gerais 2015). The regional HDI (Human Development Index) was accounted to values of 0.404 in the 1990s, a number that increased to 0.659 in the surveys conducted by the Brazilian institutes to date (PNUD 2010).

Brazilian legislation limits the use of riverbanks in variable width according to the river's own width. In the case of mining the use is permitted, provided that all areas affected or degraded by the miner are 'duly reclaimed according to the accepted standards of the official environmental agencies' (Brasil 1988).

We are talking about a wet mining along 27 km of a river, covering all paleo-placed alluvium, with the purpose of a diamondiferous extraction having gold as byproduct. Among machinery there were used two suction dredges and a large bucket dredger.

This paper addresses tasks and opportunities as well as main restrictions given in a case of extreme complexity, accompanied from its initial licensing to its final closure in a period of approximately 20 years (1988 - 2007). The continuous technical follow-up of environmental reclamation work, during all that years of operation, allowed accumulate important knowledge and ongoing methodological increase in all steps. It's not the purpose here detail subjects concerning equipment, processes or method data, but rather share alternatives with other planners, not without inducing reflection.

2 Methodology

At the time mining was settled in the river, 1989, legislation and technological resources were much more precarious than those available today. For the elaboration of the diagnoses for instance no satellite images were used and all the surveys were carried out with many hours of field trekking by a multidisciplinary team. Today it's certainly easier.

The closure plan was written in 1999 and remaining tasks executed until 2006/2007 when the area eventually was decommissioned with official consent by government agencies. This plan was based on Mudder, T & Harvey, K 1998, being afterwards improved based on ANZMEC 2000. The starting idea was to ensure close data integration and modernization of methods whenever possible.

2.1 Starting situation - historical and environmental approach

Mineral exploration of diamonds, and secondarily gold, goes back to the historical roots of the region and the here considered river. Few of the alluvial areas had not been run over yet by human hands searching for wealth. These historical activities in general were carried out without the slightest technical care or any environmental reclamation endeavour. Even though, and considering the natural limitations, a part of the available areas to the given project regenerated to tall woodland again. Others were covered by mixed secondary shrubs or native 'Cerrado' (the Brazilian savanna, open wooded grasslands), as well as many pasture areas with some mixed ruderal vegetation and spontaneous production of livestock.

The mining occurred far from the next urban center. The demographic density in the surroundings was very low. Some low-income rural people inhabited the region sporadically.

Concerning climate issues, special emphasis should be given to weather factors. The rainfall collection on the projects site resulted in an annual average of 1,078.4 mm (between 1981 and 2006), with a very uneven distribution. In the dry season an average between May and August showed values below 10 mm throughout all these years. In the rainy months of November, December and January, the average collected on the site was always above 200 mm. This situation is hard to manage and can lead to great losses of time and money due to the drought or the floods in, say, one single year.

Prior to the beginning of field surveys more than 900 bibliographic titles on river dredging and their recovery were examined (there was no internet available at the time in Brazil).

2.2 Legal and regulatory issues

Only since 1988, in Brazil, mining has legal obligation of recovering its degradation. And this by the highest ranking of the law: the Federal Constitution. It mentions the obligation to reclaim the environment, '*according to the technical solution required by the competent public agency, according to the law*'. At the time there were no details of the technical requirements given by the organs, however the control performanced by these organs were and still are strict. In 1999 a standard was established that defines technical details for the Recovery of Degraded Areas, but without specific definitions for river environments.

In terms of mine closure a set of rules on the suspension and closure of mines was launched by the Brazilian National Department of Mineral Production, attached to the Federal Government. This norm is quite complete, although bureaucratic, and was published in 2001. Other standards, now well more detailed, have arisen afterwards. Brazilian laws are nowadays very rigid and ongoing complemented, especially with regard to mine closure issues.

2.3 Diagnostics and planning

Fieldworks were preceded by bibliographical survey and were classified into three groups of interest: professionals specialized on physical environmental aspects, on biotic environment and on the socio-economic environment.

Physical surveys such as on hydrography, fluviometry, bathymetry, sedimentology and others were performed. Furthermore, the biotic environment diagnostics were started on an integrated manner based on the principle of comprehensive biotopes mapping (Bede et al. 1997). This methodology, unknown in Brazil at the time, consists in finding out the ecological functions set up for the given landscape. It’s based on existing natural or artificial structures, their current anthropic uses and the natural function to flora and fauna of each mapped unit. During this mapping, typical ecologic indicators for each spot were identified.

Upon the biotope map, specific fauna and flora surveys on different classes and typologies were done on a geographically traceable way. Afterward drawings with an easy popular approach where done. The Figure 1 below shows a small part of one of these drawings showing the ecological landscape profile. The purpose was to represent flora and fauna in an integrated manner upon the morphological profile of the landscape:

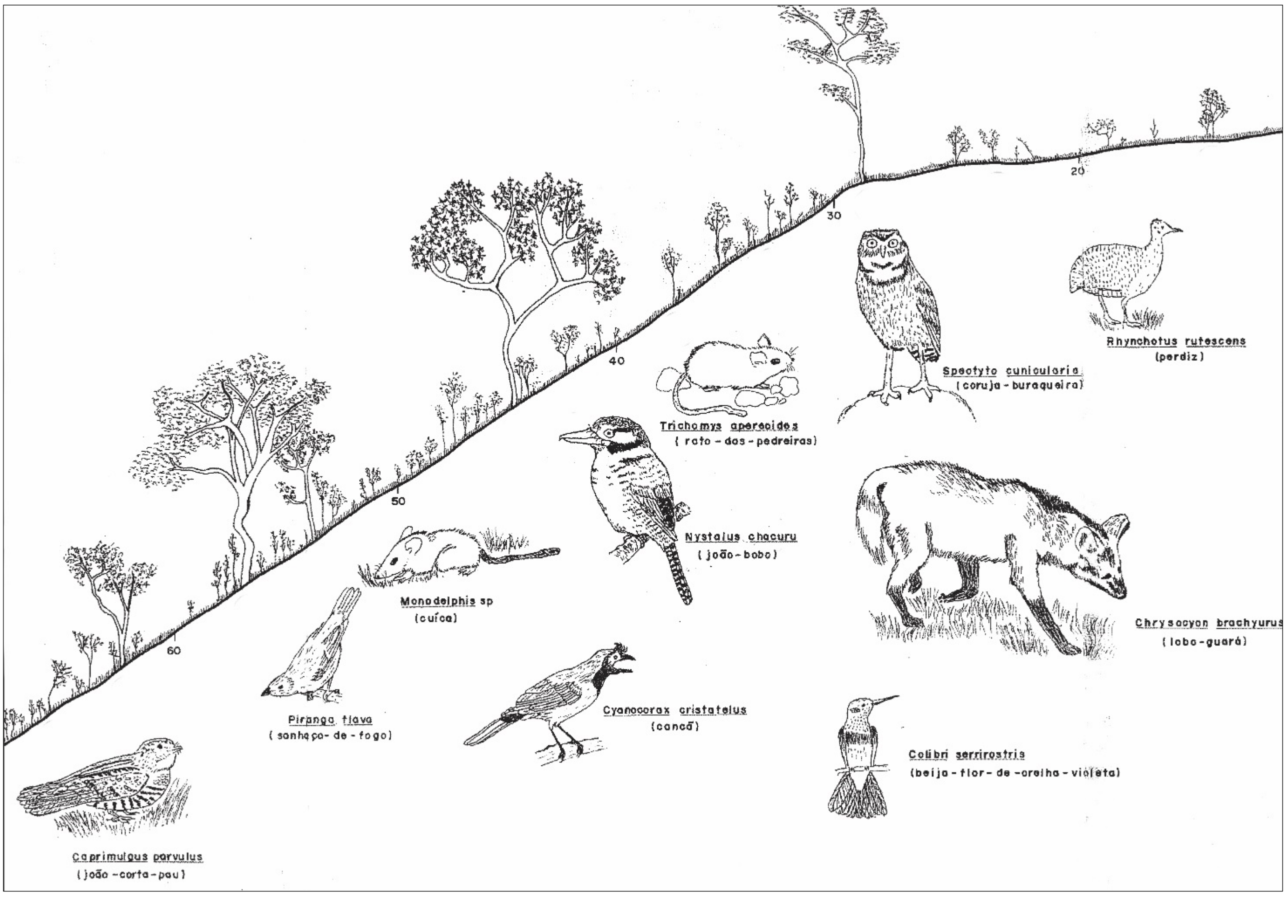

Figure 1 Schematic section of the local landscape with integrated representation of fauna and flora

For better uptake of the influential anthropic environment, despite the low demographic density in the surroundings of the mining, a zone of assumed influence was drawn including isolated houses, small urban places and the nearest cities / municipalities.

2.4 Comprehensive reclamation method

Based on the diagnoses a design was created with geographic location of all the measures designed for the river recovery after mining. In Figure 2, a cutting of the original handmade drawing is showed:

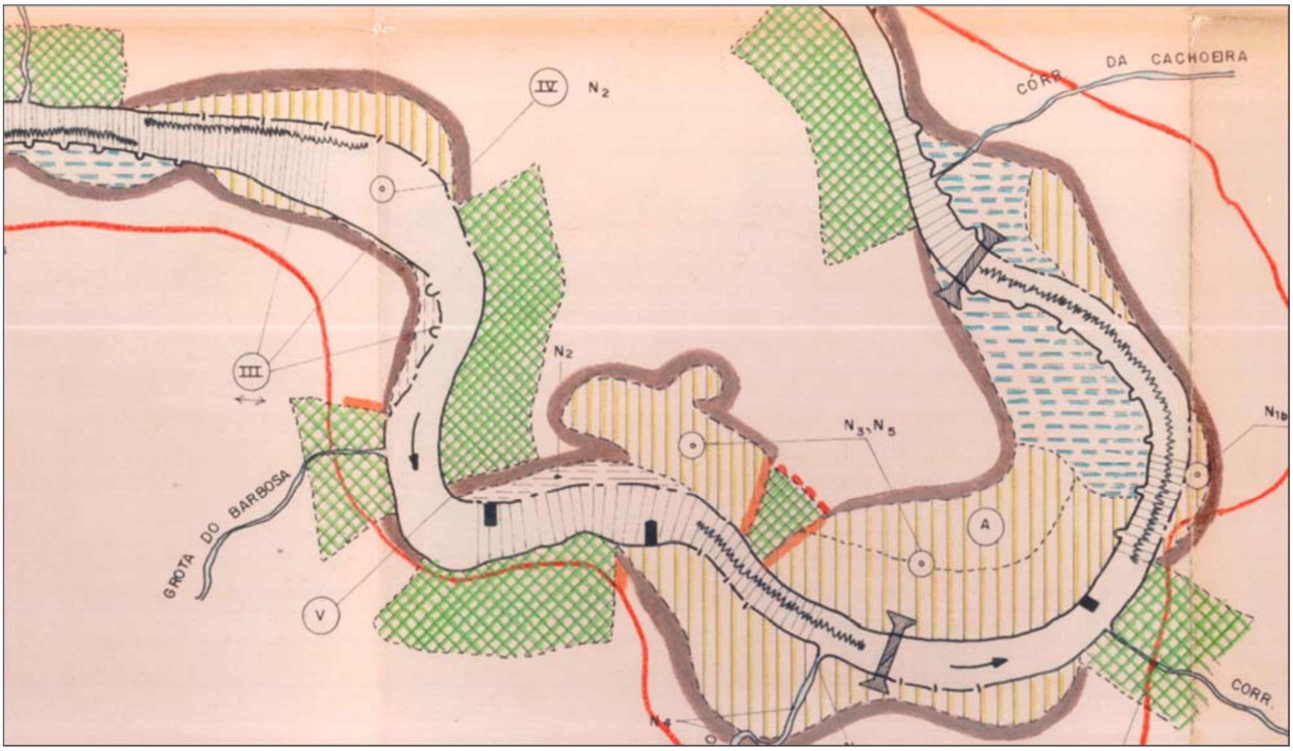

Figure 2 Cutting from the original drawing on interventions for environmental recovery of the river

Primarily minimization of deforestation impacts were done, note the green spots in the previous figure. For this, in conjunction with the miner, cost and benefit calculations were checked up considering leave some low content deposits behind in favor of preserving higher vegetation. After theses assessments which included subsequent environmental reclamation costs, new decisions on the eventual mining set up were possible. Thus, from 1,324.2 hectares of the concession area only 231.3 hectares were effectively used by the company (mining + support areas), i.e. 17% of the given surface. The actively preserved area included a significant portion of riparian forest already licensed for logging. The importance of this preservation mainly consists in the capacity of woodlands and native vegetation to disperse seeds and zoocorical fauna, in order to reach nearby degraded areas thus increasing their resilience (Chazdon 2016).

Concerning the final substratum quality, the sediment inversion during the mining process was prevented keeping the original stratigraphic order whenever possible. Otherwise right at the beginning of operations, a navigation route with lower impact, concerning sediment transport downstream, was designed for both suction dredges and mainly the bucket dredger. Additionally tests were carried out by means of polymers and decanters to soften that effect but with low success rates. The beneficiation of the gold (by-product) was done in a closed circuit process as not to generate uncontrolled waste.

Following measures were carried out before revegetation:

- Preservation of forest fragments dispersing seeds and fauna.
- Reconstruction of the riverbanks and channel according to the original design.

- Construction of drowned transversal dams to settle suspended solids.
- Riverbed recovering in a corrugated way to increase friction.
- Construction of marginal lagoons and marshes according to the original ecosystem.
- Piers construction on riverside to foment deposition of fine mineral and organic matter.

The goal of the recovery on the river banks was to allow a natural succession on the implanted vegetation leading to the prior scenario.

In order to start the revegetation of the affected areas, considering the replacement of the substratum in the natural stratification (underneath gravels, above alluvial sand), preliminary measures were implemented consisting of:

- Fencing the vegetated area.
- Runoff stabilization and terracing to control surface erosion.
- Replacement of the covering organic layer (previously stored for this purpose).
- Fertility analysis of the substratum.
- Correction of soil with limestone, agricultural gypsum and natural phosphate.
- Green fertilization with species of native grasses and non-permanent legumes.
- Maintenance of fences and possible rework in revegetation processes.

Fences were systematically broken by local residents in search of fresh pastures for extensive cattle ranching. The vegetation destroyed by means of the arbitrary and undue invasion of livestock were part of the routine redoes, such as the ever positive relationship with surrounding residents.

In sequence, a second attempt of revegetation was implemented consisting in native tree and shrub plantings among the spontaneous vegetation remaining from the first efforts. At this rate nucleation techniques were used by association of plant species compatible with each other in order to promote a new forest succession, with great fauna attractiveness. New land soil fertility corrections were done, as well as irrigation by motor-pumps when so determined by the technical assistance of executive follow-up. Briefly the second stage of revegetation was carried forward by following steps:

- Planting a mix of native shrub and tree seedlings.
- Application of water retention polymers with nutritional content to the planting pits.
- Construction of niches (structures) attractive to the fauna among plantation.
- Care and cultural treatment after planting.
- Identification based on bioindicators of potential new nucleation spots.
- Promote nucleation development by means of enlarge them with new surrounding plantations.
- Interconnection of successful vegetation spots by means of new plantings.

To promote plant propagation, seeds were locally collected from previous selected mother trees. The seeds of local varieties were procreated in a forest nursery built for this, with the capacity to produce up to 100,000 native seedlings per year. Given the great distances, the nursery had to migrate along with the main areas of rehabilitation.

The choice of planted species has been refined over the years in favor of species that have done better in the former mined areas despite local soil and climate. The plantings were carried out manually, with an average effort of 58,000 seedlings planted per rain season.

From this second phase on the revegetated areas entered into a maintenance and follow-up phase. In this phase firefighting, complementary fertilization, replanting, fixing ruptured fences, removing weeds, irrigation with motor-pump sets, among other activities were on the agenda.

For the purpose of surrounding communities and residents, several social and environmental development programs were implemented jointly with the local Municipality aiming Environmental Education, fostered in town schools and the surrounding countryside. The relationship between the company and the residents was always very harmonious and the closest community came to consider the project as part of its cultural context, given the social activities carried out.

2.5 Monitoring

In order to understand the ecological outcome on the areas under reclamation, besides the monitoring of conventional flora and fauna, some basic tools were implemented:

- Effort-zoning on all surfaces under treatment (Figure 3).
- Monitoring on invertebrate indicators for environmental recovery quality (ants).
- Register and understanding of spontaneous invasive plants.
- Monitoring of water quality.
- Fauna diversity increase checking (birds and small mammals).
- Evaluation of the ecological efficiency of the implanted niches for fauna attraction.
- Reprogramming of reclamation plans or methods.
- Technical inspection of all areas forwarding regularly reports to the official state and federal government agencies.

Figure 3, below, shows a section from the effort-zoning undertaken during the monitoring. This zoning was delimited on field by means of ecological indicators (ants and spontaneous vegetation). The zones were defined according to the results given by the indicators and compared to the endeavored efforts. Outcomes drove to sites that demonstrated a greater demand of efforts to achieve the same success compared to others. Findings mostly led to different soil conditions or unfavorable climate account. Thus, it was possible to improve the appointed methodology, remodeling it in order to achieve the targeted goal.

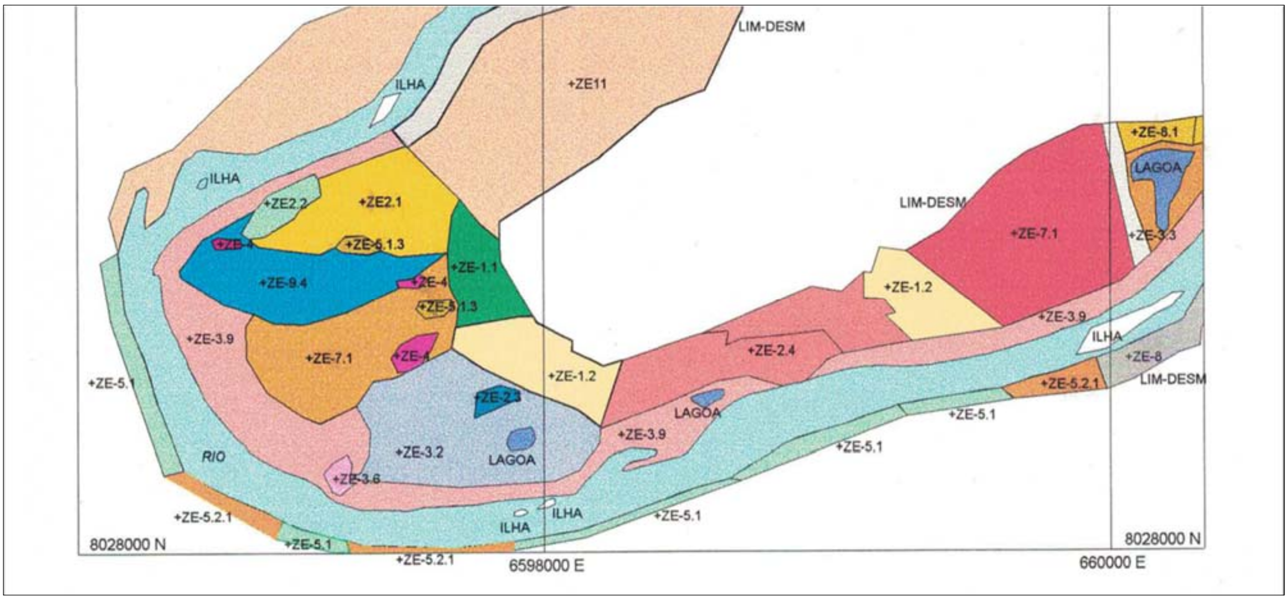

Figure 3 Sample of the applied effort-zoning

The use of ant species as bioindicators of the natural succession improvement has been referenced as an excellent tool to identify failures as well as correct used reclamation methods (Brown 2016). Ant samples taken twice a year, in the dry season and in the rainy season, showed a clear delineation between communities of riparian forests, of riparian beaches, a savanna community and tension bands between both. Some of the effort-zones of this intermediate range have, for example, the dominance of *Conomyrma* sp4, a typical beach ant, or some species of *Camponotus*, coming from the savanna, due to the general characteristics of the superficial layers of the soil and vegetation. Thus it was possible to anticipate the maturity and degree of correctness of the implemented environmental reclamation.

3 Decommissioning

In May 2007, the official decommissioning setting of the river recovery and its banks reclamation was sent to the official government body. Among the papers there was given a consolidation of all the reports issued on reclamation and monitoring. The final report was approved after official assessment and joint field inspection with Government and experts over all the rehabilitated areas. After this, the closure request was eventually granted.

These days, 2018, i.e., about ten years after closure and decommissioning, there is a legal action against the former miner going on, held by the Public Prosecutor, claiming lack of reclamation on the riverbanks invaded by small illegal miners after farewell of the company. This threat wasn't prevented by the former miner and became part of the uncertainties to be included in closure plans nowadays, considering the concept change regarding environmental responsibilities in a weak public atmosphere and raising social inequalities.

4 Results

Among the results there are the most diverse, positive and negative ones.

For the regional scientific and technical community, important (until then unknown) data about some regional features were established. Certainly the information contributed to increase the knowledge pool, as well as revegetation and environmental reclamation techniques.

The average cost of environmental reclamation, practiced in these areas, was approximately US $ 16,000 per hectare.

The long-term monitoring over all reclaimed areas has contributed positively with the evolution of the native vegetation implanted, despite of the restrictive environmental conditions from an ecological point of view.

More than one million native seedlings were planted and monitored regionally, with technical support, resulting in a 70% success rate.

Soon after the project was closed and decommissioned, some reclaimed areas were heavily invaded by small illegal miners ('garimpeiros'), who destroyed partially the recovering work done. The local police have been triggered oftentimes, but the strength of the Public Power was not enough to contain this type of degradation in the post-mining period.

5 Conclusions

Complex natural systems require accurate planning and extremely diversified efforts throughout the environmental recovery processes.

The knowledge gained through experience was the greatest legacy of this project.

The dynamics of the whole management process, and the given freedom of action by the miner throughout the project, led to a creative atmosphere and therefore better results.

Integration between environmental and mining staff is fundamental to improve execution quality.

Ongoing corrections and refinement of the environmental reclamation methods provide more reliability, diminishing uncertainties.

Environmental diagnoses based on an integrated approach, such as environmental function assessment (biotope mapping) and ecological indicators, are more effective to design reclamation methods than previous conventional diagnosis of flora and fauna.

Considering monitoring of environmental reclamation sites, invertebrates (ants) and invasive plants showed an excellent response to the executers.

Individual interests (small illegal miners), coupled with a lack of public control, can reverse important environmental recovery processes. It requires integrated solutions between entrepreneur and Government, not always prepared or willing to.

In some countries, such as Brazil, where public territory control is confined to local authorities and a weak institutional system rules, it is not possible to foresee all events after closure. Hence, there is an imminent risk in the post mining period leading potentially to large losses on important ecosystems, affecting biomes where mining and sensitive environment coexist, such as the Amazon, Atlantic Forest, Cerrado and others. But this unfortunately isn't a Brazilian freak, but multiplies worldwide.

The notion of guarantee given by the decommissioning to the entrepreneur may become increasingly fragile considering the modern dynamics of social and environmental concepts.

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Water Budget of Field Experimental Cells with Vegetated and Non-Vegetated Soil Layers Placed on Waste Rock

N Chevé *Université du Québec en Abitibi-Témiscamingue, Canada*

M Guittonny *Université du Québec en Abitibi-Témiscamingue, Canada*

B Bussière *Université du Québec en Abitibi-Témiscamingue, Canada*

Abstract

Field investigations were conducted in Abitibi region (Northwestern Quebec, Canada) from the end of July until the end of October 2017 and allowed to study the influence of the vegetation and the compaction of the supporting soil layers on the water balance of a waste rock pile. To do so, 5 lysimeters were constructed in a dike made of waste rocks and 4 of them were covered of 40 cm of overburden and 10 cm of topsoil. Overburden of Lys-1 and Lys-3 were compacted while fast-growing willows were planted on Lys-1 and Lys-2. Soil water content was monitored with sensors in the topsoil and the overburden as well as percolation through the waste rock. Results show that evapotranspiration is the main component of the water balance for all lysimeters with soil covers (58-87%). Soils layers decreased the cumulative percolation through waste rock by at least 30% and lysimeters with compacted soils showed a reduction of 57-58%. Plants increased the evapotranspiration rate during and slightly after rainfall by up to 8 mm/6 hours. Thus, vegetation and compaction of the supporting soil layers can significantly influence the relative contribution of the water balance components and the system dynamic.

Keywords: *Water balance, lysimeter, evapotranspiration, percolation, compaction*

1 Introduction

Mining operations produces a large amount of waste rock and tailings, and the laws and Canadian provinces regulations demand that the storage facilities containing these mine wastes be reclaimed at the end of the mine life. When mine wastes contain sulfide minerals and have the potential to generate acid mine drainage, reclamation methods aiming to limit water infiltration or oxygen migration are usually suggested (Albright et al. 2004; Aubertin et al. 2002; MEND 2001; Stormont & Morris 1998). In the province of Quebec, Mining acts also require to return the site back to a satisfactory state, which implies site revegetation.

Vegetation and its supporting soil layers can affect the water balance of the site. Presence of plants can increase evapotranspiration (Apiwantragoon 2014; Madalinski et al. 2003; Wels et al. 2002) and modify the hydrogeological properties of underlying material because of root penetration and changes in porosity (Angers & Caron 1998). The compaction of the soil layers supporting vegetation can limit water infiltration (Fourie & Tibbett 2007; Gregory 2006) and the root development of the vegetation, which can influence the amount of water lost by evapotranspiration (Hamza & Anderson 2005; Taylor & Brar 1991). Some studies presented the water balance of engineered covers and the parameters that affects each components of the water balance, but those were mainly conducted in arid, semi-arid and temperate climate or analysed evaporation or potential evapotranspiration (Apiwantragoon & al. 2014; Albright et al. 2004; Wilson et al. 1997, Woyshner & Yanful 1995, Yanful et al. 2003). Only few information is available on influence of vegetation or installation of the soil layers supporting the vegetation on actual evapotranspiration and measured percolation, especially in continental northern climate and in a mining context.

The research described in this paper addresses these latter points by quantifying the effect of vegetation on the water balance of waste rock materials and more specifically, by discriminating the effects of vegetation and supporting soil layers, compacted or not. To do so, five lysimeters with or without soil layers, vegetation or compacted soil, were constructed and instrumented in a dike made of waste rocks. The lysimeters are instrumented with probes allowing to follow the soil volumetric water content at three different depths in the soil layers and with systems measuring the amount of water percolating in the waste rocks. A water balance was developed for each lysimeter to assess the relative importance of the water balance components (evapotranspiration, percolation and soil water storage) and to evaluate the influence of vegetation and soil layers compaction.

2 Materials and Methods

2.1 Site and climate description

The five lysimeters were constructed close to an open pit gold mine site exploiting a low-grade and high-volume deposit; production rate at the mill is approximately 55 000tm/day. The mine site is located in the Abitibi region, Quebec, Canada (48°07'45" N – 78@07'20" W), in a cold continental climate region (Peel & al. 2007). The average cumulative annual precipitation is about 914 mm, with rainfall of 635 mm/year and 300 cm/year of snowfall. The average annual temperature is estimated to 1.2°C, with an average of 12.3°C for the months of June to October inclusively (EC 2018). Lake evaporation is estimated to approximately 515 mm/year (EC, 2018c) while potential evapotranspiration is estimated to 400-500 mm (Liu et al. 2003). The natural vegetation surrounding the site is a mixed boreal forest and woody species could colonize the site after mine closure and reclamation.

2.2 Design and construction of lysimeters

Five lysimeters (Lys-1 to Lys-5) were constructed in a dike made of waste rocks at the mine site, at the elevation 344 m (± 14 m above natural ground level). Construction took place in November 2016 (part of Lys-1) and in June-July 2017 (soil layers of Lys 1 and all Lys-2 to Lys-5). Lys-1 to Lys-4 include soil layers while Lys-5 is a control lysimeter, without any soil layer or plants.

The lysimeters have an area varying from 64 to 71 m² and a depth of 1 m. The bottom and sides of each lysimeter is made of a 1 mm thick PVC geomembrane protected on each side by approximately 0.2 m of sand. A drain, consisting of a 2-inches pipe protected by sand, was installed at the bottom of each lysimeter, with a slope of 1%, to carry percolating water to a reservoir. A single tank of a capacity of 2000 l was installed at Lys-1 to Lys-4, while 3 tanks in series cumulating 4000 l of capacity were installed at Lys-5. A leak test was performed at the bottom of the cell (water on the geomembrane) for 24 h before filling the excavation with waste rocks to the initial elevation of the dike (Figure 1).

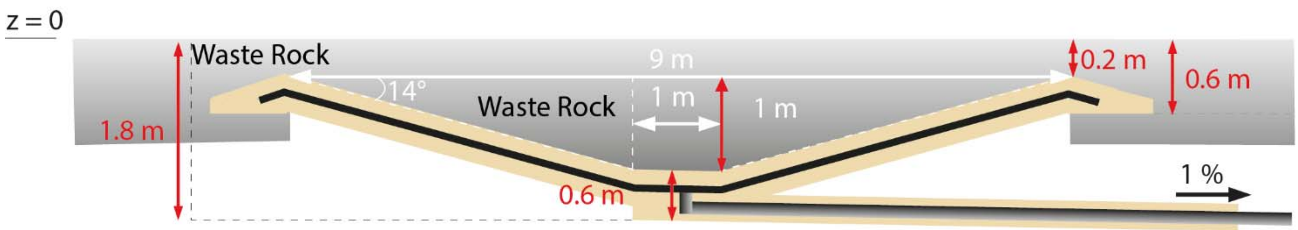

Figure 1 Schematic representation of the 5 lysimeters constructed into the dike

Lys-1 to 4 were covered with 40 cm of overburden stripped from the open pit. After placement with a mechanical shovel, the top of the overburden of Lys-1 and Lys-3 were compacted with a plate compactor while the overburden of Lys-2 and Lys-4 were not compacted (low static compaction by the mechanical shovel). A layer of topsoil coming from the excavation of a nearby ditch was installed over the overburden. This layer is 10 cm thick on average on Lys-1 and approximately 15 cm thick on Lys-2 to Lys-4.

Eighty-one cuttings of 1 m length of fast growing willows (*Salix miyabeana*, clone Sx64) were planted in the soil layers (30 cm deep) of Lys-1 and Lys-2 with a spacing of 1 m between each plant. Extreme care was taken to limit topsoil compaction during construction and plantation to favour regrowth of the cuttings. Cuttings came from a local plantation on the mine site. The choice of the soil thicknesses was based on previous plantation studies on the same mine site (Larchevêque et al. 2014), while fast-growing willows were chosen because it can quickly maximize plant effects on the water balance. The plantation was made before mid-June 2017 to allow a long-enough growing season for trees to acquire energy reserves before dormancy. A schematic representation of the whole lysimeters' design is presented in Figure 2.

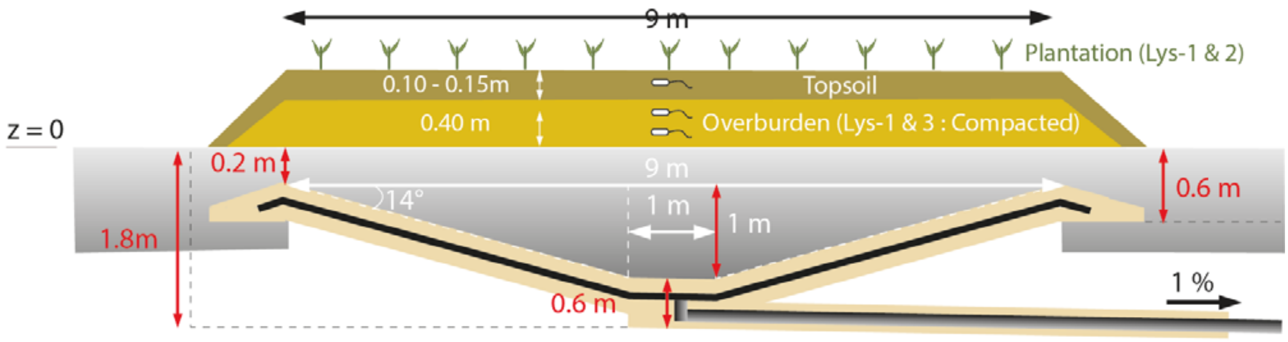

Figure 2 Schematic representation of soil layers and plants (for Lys-1 and 2) and location of volumetric water content probes

2.3 Materials characterization

Bulk overburden samples (20 l) were taken during construction of each lysimeter for grain size distribution analysis. They were performed using sieves (ASTM, 2007), with different opening size and laser diffraction particle size analyser for the 3 mm – 0.003 mm fraction (S3500 from Microtrac Inc., USA). No analysis was conducted on smaller grain-size fractions. Figure 3 shows the obtained results. All overburden samples are classified as a silty sand with gravel based on Unified Soil Classification System (ASTM 2017a). Overburden in Lys-1 is however slightly coarser than those used in the other lysimeters.

Characteristics of overburden were evaluated during the construction for quality control. Maximum, minimum and average water content (ω), volumetric water content (θ), in situ dry density (ρ_d) and porosity (n) are shown in Table 1. For Lys-1 and Lys-2, undisturbed samples were taken at the surface of the upper sublayer and brought back to the laboratory. Gravimetric method using a cylinder of known volume and oven drying was used for ρ_d and ω analysis. For Lys-3 and Lys-4, ρ_d and ω were evaluated in situ, with a nuclear density gauge (Model 3440, Troxler, USA; method ASTM 2017b). The results represented an average of the top 30 cm. In all cases, porosity was estimated from ρ_d and an average specific gravity (G_s) of 2.72 measured with a helium pycnometer (AccuPyc 1330, Micromeritics, USA; ASTM 2012). Higher ρ_d and lower porosity in Lys-1 and Lys-3 are expected since overburden was more compacted.

Bulk topsoil samples (20 l) were taken from each lysimeter during construction to evaluate the agronomic quality and innocuousness of the soil. Analysis were conducted on the topsoil of each lysimeter, on a composite soil samples made of 3 subsamples. Soil pH was evaluated with the pH water test (CEAEQ 2014a) at a solid : liquid ratio of 1:1 and led to values between 4.5 to 4.7 for all lysimeters. These slightly acid values are representatives of soils in the region (Larcheveque et al. 2011, 2013). Total organic carbon (TOC) was analysed using a titration method with potassium dichromate and ferrous sulfate (CEAEQ 2014b). TOC concentration of 16% were obtained for Lys-2 and Lys-4, 20% for Lys-3 and 23% for Lys-1. Chemical composition of the topsoil samples was obtained by digestion and ICP-MS analysis (CEAEQ 2014c). Metal concentrations in all topsoil samples respected the provincial regulation for use on a residential land (Land Protection and Rehabilitation Regulation, Quebec 2011).

One sample of topsoil was taken at the surface of each lysimeter on November 7, 2017, using a cylinder of known volume. Samples recovered on Lys-1, Lys-3 and Lys-4 were moderately disturbed; sample on Lys-2 was too disturbed to be analysed. Dry density and water content were evaluated by gravimetric method with oven drying. Topsoil is heterogeneous and specific gravity of the component of the material varies from 1.2 (wood chips) to 1.9 (black earth) and 2.72 (cobbles). Estimated porosity was calculated with an average estimated Gs value of 1.9. Obtained values are presented in Table 2, as well as porosity for a range of Gs from 1.6 to 2.1.

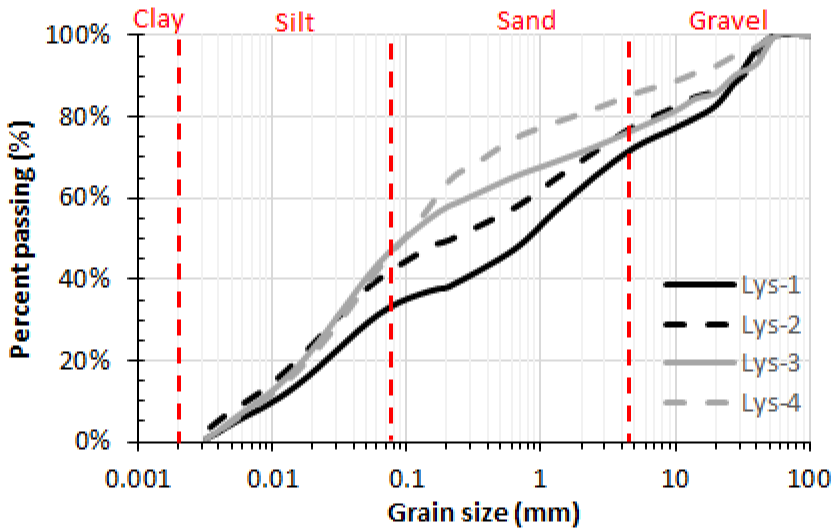

Figure 3 Grain size distribution of the overburden layer on Lys-1 to Lys-4

Table 1 Physical characteristics of the overburden installed on Lys-1 to Lys-4

Source	Number of samples	Gravimetric water content[1] (ω) %	In situ dry density[1] (ρ_d) g/cm³	Porosity[1] (n)
Lys-1[2]	5	16 (15-17)	1.94 (1.85-2.06)	0.28 (0.24-0.31)
Lys-2[2]	5	15 (14-17)	1.65 (1.46-1.82)	0.39 (0.32-0.46)
Lys-3[3]	4	11 (10-13)	1.86 (1.80-1.94)	0.31 (0.28-0.33)
Lys-4[3]	4	12 (9-14)	1.66 (1.60-1.70)	0.39 (0.37-0.41)

[1] Average values indicated. The range of values used for calculation of the average value are indicated between brackets (minimum-maximum).
[2] Evaluation of the characteristics by gravimetric method, at the surface of the upper sublayer.
[3] Evaluation of the characteristics with a nuclear density gauge, with a 30-cm rod inserted into the overburden.

Table 2 Physical characteristics of the topsoil installed on Lys-1, Lys-3 and Lys-4.

Source	Gravimetric water content (ω) %	In situ dry density (ρ_d) g/cm³	Porosity (n)[1]
Lys-1	231	0.21	0.89 (0.87-0.90)
Lys-3	177	0.25	0.87 (0.85-0.88)
Lys-4	101	0.50	0.74 (0.69-0.76)

[1] Range of porosity calculated with a Gs of 1.6 to 2.1 are indicated between brackets.

2.4 Instrumentation and monitoring

Components of the water balance monitored in this study were precipitations (P), percolation (Pr) and water storage variations (ΔS). Runoff and lateral drainage are supposed to be minimal considering the flat area where the lysimeters were installed and the flat soil layers. Evapotranspiration (ET) was calculated as the difference between the precipitation and the sum of the other components. It should be noted that in this paper, water storage (S) refers to the total amount of water in the soil, while storage capacity (ΔS_{max}) refers to the part of the water storage that can be stored or released in field conditions.

Meteorological parameters, including rainfall, air temperature, relative humidity, wind speed, speed of wind gusts and wind direction, were measured using an automated weather station (HOBO® U30, Onset Computer Corporation, USA). Data were collected every 15 minutes in June and July 2017 and every hour from August to November. Volumetric water content was monitored near the central axis of each soil layer of Lys-1 to Lys-4, at a depth of 5 cm, 20 cm and 40 cm from the soil surface (see Figure 2). These depths corresponded to the middle of the topsoil layer and the middle of upper and lower half of the overburden layer. Changes in volumetric water content were measured using frequency domain reflectometry (FDR) sensors (ECH$_2$O EC-5, METER Group Inc., USA). Accuracy of the measurements are of ± 0.03 m^3/m^3 (Decagon 2015). Data were recorded every 6h from June 8 for Lys-1 and Lys-2 and from July 8 for Lys-3 and Lys-4. No data were registered in the topsoil of Lys-1 from August 2nd to August 29 due to reading problems. Volumetric water content was converted to soil water storage in equivalent millimeter of rainfall from the area of the lysimeter and the corresponding thickness of soil (10-15 cm for topsoil, 20 cm for overburden). Relative water storage was calculated by integrating the increase and decrease of the volumetric water content compared to an initial value (value at the beginning of the period of interest). Waste rock volumetric water content should be similar for all lysimeters and was not monitored because of their low storage variation usually smaller than 5% (MEND, 1994).

Water percolating into each lysimeter was conveyed through PVC pipe to an accumulation tank. In June and July, water levels were monitored manually once a week. On July 27, water level dataloggers with an accuracy of ±1.0 cm (Micro-Diver, Van Essen Instruments, Netherlands) were installed in each tank. Water levels were automatically logged every hour. Accumulation capacity of the tank connected to Lys-5 was increased on September 7, by adding two 1000 l tanks connected in series. Each additional tank was equipped with a water level datalogger. Recorded water levels were corrected with the barometric pressure monitored every hour with a Baro-Diver (Van Essen Instrument, Netherlands) installed near Lys-1. Corrected water levels were converted into water volume taking into account the dimensions of the tank, and to equivalent millimetres of percolation from the area of the lysimeter.

3 Results

3.1 Meteorological data

The main meteorological parameter of interest for the site water balance was rainfall. It is presented per interval of 6 hour on Figures 4 and 5, while cumulative rainfall is illustrated in Figure 6. A total of 414 mm of rainfall was measured over the studied period, which is 10% more than the climate average of 377 mm at the Val d'Or weather station (30 km away). The more intense rainfall events were of 27 mm over a 6h period, and of 37 mm over a 24 h period. Rainfall greater than 0.2 mm occurred in average every 3 days. The longest sequence of rainy days was of 6 consecutive days with more than 0.2 mm/d, from August 10 to 15, while the longest sequence of dry days was of 10 consecutive days without rainfall, from September 8 to 17. These results indicates that even if the average climate was wetter than the average, no extreme rainfall event occurred over the reference period.

3.2 Volumetric water content (θ) and water storage (S)

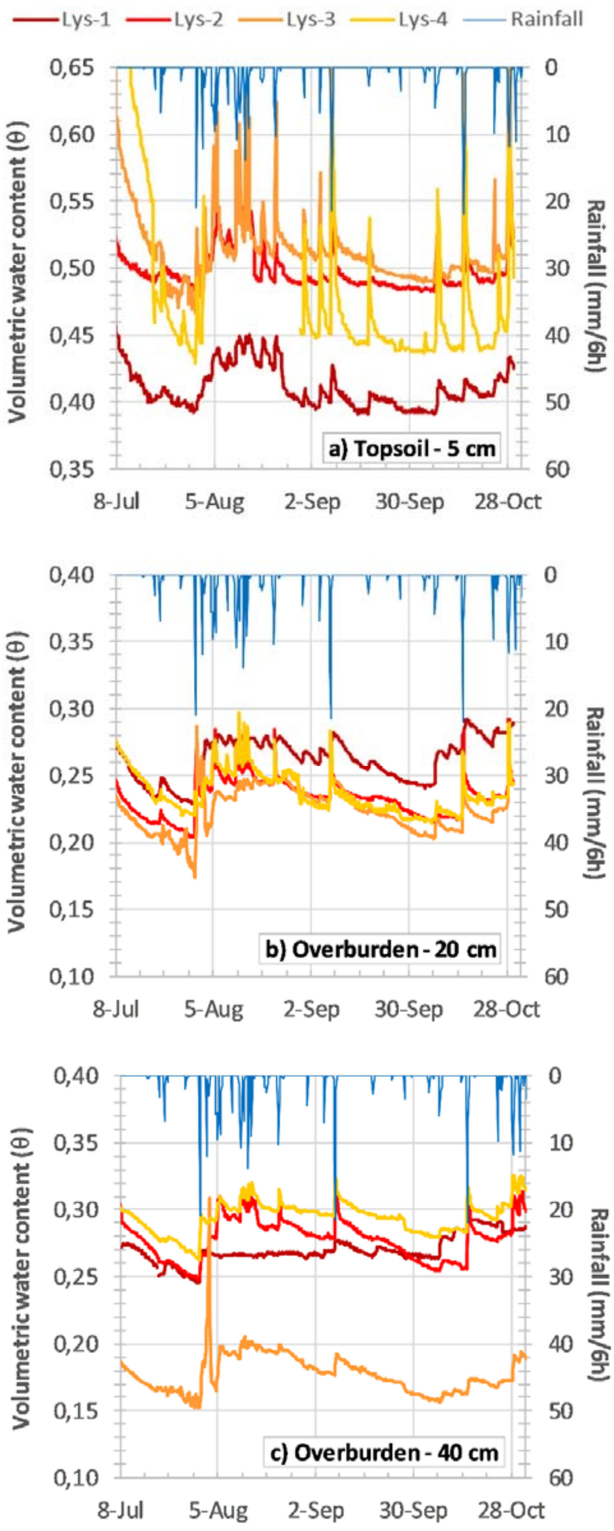

Figure 4 **Variation of volumetric water content in all lysimeters from July 7 to October 30 at a depth of (a) 5 cm (b) 20 cm and (c) 40 cm.**

Comparison of θ at a same depth of all lysimeters (Figure 4) allows to highlight the difference in term of reaction to rainfall for each lysimeter. In the topsoil (depth of 5 cm), θ values are different depending on the lysimeter (see Figure 4a). The lowest θ values were recorded at Lys-1 (from 0.39 to 0.46). During and after precipitation, θ increased quickly. For a same rainfall event, amplitude of increase of non-vegetated lysimeters was usually two times greater than those vegetated. Amplitude of increase did not exceed 0.08 for Lys-1 and Lys-2, while it reached 0.17 for Lys-3 and Lys-4. For all lysimeters, most of the water stored in topsoil was released 36 hours after a rainfall event, then topsoil reached a nearly constant θ value. Values of θ in the overburden, at a depth of 20 cm (see Figure 4b), were similar for all lysimeters with values ranging from 0.17 to 0.30. Amplitude of variations after rainfall was larger for non-vegetated lysimeters, but approximately half of what was observed in topsoil, with amplitude of 0.09 for Lys-3 and Lys-4 compared to 0.06 for Lys-1 and Lys-2. In the overburden, at a depth of 40 cm (Figure 4c), Lys-2, Lys-3 and Lys-4 showed similar trends during and after rainfall, with significant increases of θ during rainfall events greater than 5 mm followed by decreases on dry days. Lys-1 often showed almost no change in water content at this depth regardless of rainfall duration, intensity and frequency. Range of θ values in Lys-1, Lys-2 and Lys-4 were similar and ranged from 0.25 to 0.32, but the θ in Lys-3 was lower with values varying from 0.15 to 0.31. Moreover, while θ of Lys-2 and Lys-4 were slightly higher in the lower sublayer than in upper sublayer of overburden, the opposite was observed for Lys-3.

Table 4 presents water storage (S) after placement and the maximum S of the topsoil and the overburden sublayers according to their porosity (assumption of a full saturation for the total height of the layer). Figure 5 shows the ΔS for each soil layer for Lys-1 to Lys-4. The question marks on Figure 5a indicate that the maximum S of the lower overburden sublayer of Lys-1 could not be estimated because the porosity of this sublayer is unknown at a depth greater than 10 cm and a difference between the upper and the lower layer is expected because of compaction.

Table 3 Water storage after soil placement and maximal water storage of topsoil and both overburden sublayers of Lys-1 to Lys-4.

Source	Topsoil			Overburden		
	Layer thickness (m)	Water storage after placement (mm)	Max. storage (mm)	Sublayer thickness[1] (m)	Sublayer water storage after placement (mm)	Sublayer max. storage (mm)
Lys-1	0.10	61	80	0.20	32	56 (60)[2]
Lys-2	0.16	96	128	0.20	30	78
Lys-3	0.15[1]	108	120	0.20	22	62
Lys-4	0.15[1]	108	120	0.20	24	78

[1] Estimated layer or sublayer thickness, based on construction reports and site observations

[2] No sample were collected and analysed in the lower sublayer to estimate porosity. The number between parenthesis correspond to the maximum water storage calculated from the θ probe installed in the lower sublayer.

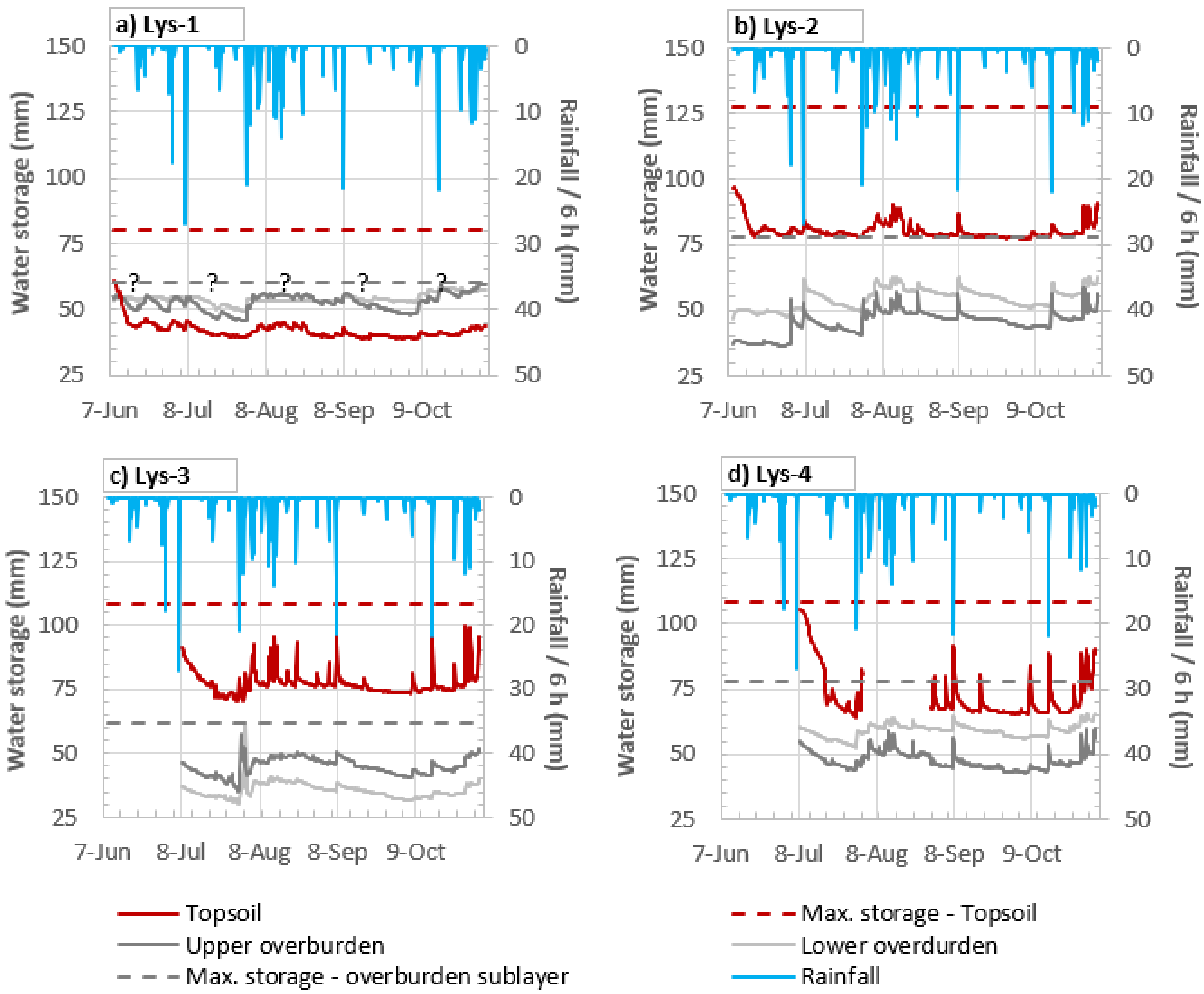

Figure 5 Variation of water storage (mm) with time in topsoil, and both overburden sublayers, from June 7 to October 30 for (a) Lys-1 and (b) Lys-2; From July 8 to October 30 for (c) Lys-3 and (d) Lys-4.

Apart from Lys-1 whose topsoil layer is thinner, S in topsoil was higher than in each separated sublayer of overburden. Water stored in topsoil during rainfall reached values closer to maximum S (i.e. full saturation) in Lys-3 and Lys-4 compared to Lys-1 and Lys-2. Difference between maximum water storage and actual water storage reached values of approximately 10-15 mm for Lys-3 and Lys-4, which corresponds to S_r of 85-93%, compared with differences of 30-40 mm for Lys-1 and Lys-2, which correspond to S_r of 63%-71%. Lysimeters 2 and 4 (Figure 5b and 5d) with uncompacted overburden stored approximately 10 mm more water in the lower sublayer of overburden than in the upper one. The opposite was observed for Lys-3 (Figure 5c), where S was usually 9 mm greater in the upper sublayer than in the lower one. S was similar in both sublayers of Lys-1. Water stored in overburden during rainfall reached values closer to maximum water storage in Lys-1 and Lys-3 than in Lys-2 and Lys-4. Difference between ΔS_{max} and S reached values of approximately 0-5 mm for Lys-1 and Lys-3, compared with differences of 10-15 mm for Lys-2 and Lys-4. For all lysimeters, water stored in the overburden continuously decreased after a rainfall event, even after a period of 10 days without precipitations.

3.3 Percolation measurements

Figure 6 shows the percolation registered in the reservoirs since the installation of the water level data logger on 2017, July 27. Frequent rainfall events in August lead to overtopping of the tank for Lys-2 to Lys-5. Missing percolations values, represented with a red dashed line on the figure, were estimated based on the time of reaction and Pr rate of the other rainfall events. Missing data at Lys-5 from September 14 to September 21 correspond to the installation of two additional 1000-l tanks and water level dataloggers.

Over the period of July 27 to October 30, 270 mm of the 346 mm of rainfall percolated through the control lysimeter Lys-5. The presence of soil layers reduced by at least 129 mm (48%) the cumulative amount of water percolating in the waste rocks. Lysimeters with compacted overburden layers showed an estimated reduction of Pr of 221 mm to 245 mm (82 to 93% of cumulative precipitation), compared to 129 mm to 151 mm (48 to 56%) for uncompacted layers. During this period, vegetated soil layers had 8% less percolation than their non-vegetated equivalent.

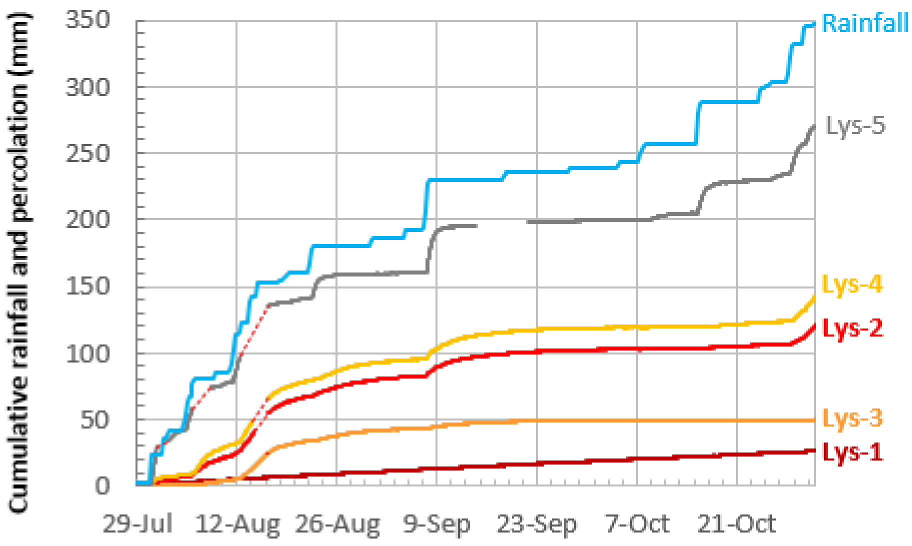

Figure 6 Cumulative rainfall and estimated cumulative percolation from July 27 to October 30, 2017, for Lys-1 to Lys-5.

3.4 Evapotranspiration

ET was calculated from the other components of the water balance at 6-hours time interval (Figure 7). Calculation was only possible when all percolation data were available, i.e. from August 18 to October 30. Missing part on Figure 7d corresponds to the period when topsoil water content was not recorded.

Cumulative ET is close to cumulative rainfall (178 mm) for lysimeters with compacted overburden layer, with values of 150 mm for Lys-1 and 155 mm for Lys-3. Uncompacted lysimeters reached values at least 25%

smaller than their compacted equivalent with 114 mm for Lys-2 and 103 mm for Lys-4. Cumulative ET is greater for Lys-2 with vegetation compared to Lys-4 non-vegetated, while compacted lysimeters with and without vegetation reached similar cumulative values. Rates of ET during and slightly after rainfall were however usually greater for both Lys-1 and Lys-2, compared to their non-vegetated equivalent. Maximal ET rates per 6 hours were of 16 mm for Lys-1, 11 mm for Lys-2, 13 mm for Lys-3 and 8 mm for Lys-4.

3.5 Water balance

Water balance combined all the previous parameters and showed the dynamic relation between them. Each lysimeter's water balance at 6-hours time interval from August 18 to October 30 is illustrated in Figure 7. ΔS was used to reflect variations of water stored in soils. S-values at the beginning of the analysis period were used as reference and corresponds to a ΔS value of 0 in relative water storage. For all lysimeters with soil layers, ET was the main component of the water balance, with contributions of 64% to 87%, followed by Pr_r with contributions of 12% to 40%. ET is 7 times greater than Pr for Lys-1 and Lys-3 with compacted overburden (difference of 130 mm between ET and Pr) compared to 1.5 to 2 times greater for uncompacted ones (difference of 42 mm for Lys-2 and 24 mm for Lys-4). Percolation was however a bit more than 2 times greater than evapotranspiration in the case of the control lysimeter (Figure 7e), with a cumulative ET of 54 mm and a Pr of 124 mm. *S* represented a small fraction of the water balance. Combined ΔS in topsoil and overburden did not represent more than 4% in all cases. Opposed trends between ΔS and cumulative ET are observed in all covered lysimeters and particularly in Lys-2 to Lys-4, with large and fast decreases in ΔS concomitant with large and fast increases in ET.

4 Discussion

4.1 Comparison with prior studies

ET was the main component of the water balance in the present study, ranging from 58-87 % (103 to 157 mm) of the cumulative rainfall when soil layers, vegetated or not, were placed above waste rocks. The main component of the water budget of waste rocks alone was rather percolation with 70% (124 mm) of the cumulative rainfall. Some prior studies had presented field water balance of engineered cover estimated through the use of lysimeters in climate regions similar to the one of the studied site. A first one was conducted over 5 years on a 1,5m thick landfill monolayer cover installed in Iowa, in a warm continental climate (Albright, 2004; Apiwantragoon, 2014). The covers were vegetated, had a slope of 5% and aimed at limiting water infiltration. A second study was conducted for one year in 1992-1993, on experimental cells where two multilayer covers of 1.3 m of thickness were installed over mine tailings in the Abitibi region. The covers were flat and without vegetation cover. The objective of the cover was to control water infiltration and gas migration (Woyshner & Yanful 1995). In both cases, ET was the main component of the water balance, as observed in the present study. ET corresponding to 74% of annual precipitations was measured in Iowa, and to 71% of the rainfall from June to September for the experiment located in the Abitibi region. Values between 58% and 87% obtained in the present study for soil layers of 50 cm supporting vegetation are in the same range of values obtained for thicker engineered covers.

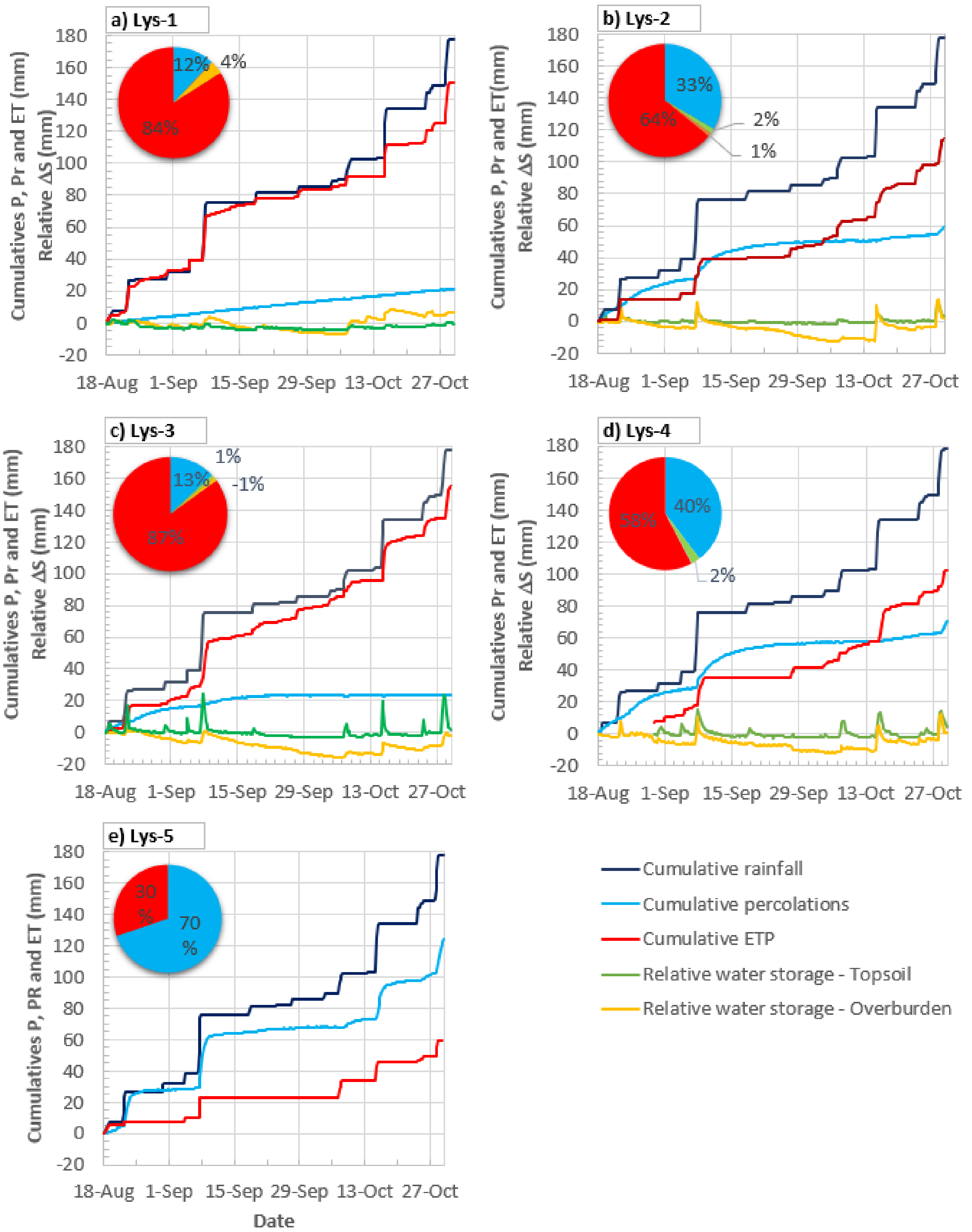

Figure 7 **Water balance components between August 17 and October 30, 2018 of (a) Lys-1; (b) Lys-2; (c) Lys-3; (d) Lys-4 and (e) Lys-5**

The second most important component of the water balance in the previously mentioned studies was percolation, with a value of 23% of the annual rainfall in Iowa and 10% of the cumulative rainfall of August and September for the Abitibi experiment. Preferential flow path was however observed in Iowa, which increased cumulative percolation. Once more, the percentage of percolation measured in the context of the actual study (12% to 40%) matches values from these studies, even if there were differences in soil thickness and in the vocation of the soil covers. Finally, change is soil water storage was always a small component of the water balance, with annual values varying from -5% to 6% in Iowa, of more or less 1% for the experiment performed in Abitibi, and ranging from -1% to 4% in the present study. It is interesting to note that runoff was estimated to 5% of the annual precipitation at the Iowa landfill site.

4.2 Influence of compaction and vegetation

4.2.1 Influence of compaction

As shown in Figure 6 and 7, compaction of overburden (Lys-1 and Lys-3) decreased significantly the cumulative percolation in waste rocks compared to uncompacted lysimeters (Lys-2 and Lys-4). This can be explained by the lower porosity induced by compaction on the upper overburden layer and the consequent decrease in hydraulic conductivity (Fredlund et al. 1994). Water percolated more slowly into the compacted overburden and more water stayed available near the surface for ET. During summer months, ETP is high and actual ET rates are at their highest after rainfall because more water is available (Apiwantragoon 2014; Wilson 1997). As a result, more water was evapotranspirated and less water reached the waste rocks. These mechanisms could be observed too in Figure 5a, and particularly in Figure 5c, where more water remained stored in the compacted upper sublayer of overburden than in the lower one.

Overburden in-situ porosity of Lys-1 and Lys-2 was evaluated only at surface of the upper layer, while Lys-3 and Lys-4 porosity represented an average value for the upper 30 cm of overburden. The porosity profile, associated water storage and hydraulic conductivity in the lower overburden layer is then unknown. This data will be obtained throughout the lysimeters dismantling at the end of the study.

4.2.2 Influence of vegetation

In the first growing season, willow cuttings mainly developed roots and small total leaf area (results not shown). Change in topsoil albedo and interception of rainfall by aerial biomass was limited, which made transpiration of plants the main contribution to water budget difference between vegetated and unvegetated lysimeters. This difference can be observed through the amplitude of volumetric water content change in the topsoil during and after rainfall (Figure 4a), that was two times greater for lysimeters without plantation (Lys-3 and Lys-4) compared to the planted ones (Lys-1 and Lys-2). , Moreover, for all lysimeters, the rate of evapotranspiration during and 6-12h after a rainfall was greater for lysimeters with willows compared to their equivalent without vegetation. This difference, that reached up to 8 mm/6 hrs for Lys-1 versus Lys-3 and 3 mm/6 hrs for Lys-2 versus Lys-4, can be associated to vegetation transpiration. These transpiration rate seem to be consistent with values measured by Hall et. al (1998), which correspond to a daily average transpiration of 6mm/day and a maximum of nearly 11 mm/day for 4 years old willows established in south-west England (hot and dry summer, 39 mm of rainfall from June to August).

Evapotranspiration varies with temperature, relative humidity, wind speed, and net radiation (Allen et al. 1998). In Val d'Or area, the average values of these parameters are higher from May to August than during the rest of the year. However, the contribution of evapotranspiration as part of total water balance was presented in this study from mid-August to the end of October. An even higher percentage of evapotranspiration could therefore be expected for a period covering the beginning of willow growing season (mid-May) until snow accumulation (November), if sufficient water is available.

The lowest cumulative percolation of 12% of the cumulative rainfall over the mid-August to end of October period, was recorded in Lys-1, where compaction and vegetation were combined. This result can be explained by the important accumulation of water near the surface after rainfall, due to the low hydraulic conductivity of the overburden induced by compaction, combined with high evaporation and transpiration rates made respectively possible by the presence of water near surface and the transpiration of the willow plantation.

4.3 Water storage (*S*) and storage capacity (∆S)

As presented earlier, ∆S is the smallest component of influence in the water balance. It represented a few percent of the cumulative precipitation, but still had an impact on the system dynamic during each individual rainfall event. Large water storage near the surface in the topsoil very likely favoured the evapotranspiration, but a lack of storage capacity is usually accompanied by an increase in percolation (Apiwantragoon 2014; Benson 2000).

For all lysimeters with soil layers, most of the water stored in the topsoil during a rainfall was released approximately 36 h after the end of the rainfall event. *S* then reached a value that barely varied (Figure 4a). The latter could be defined as an equilibrium S value in the topsoil ($S_{e\text{-topsoil}}$), for the field conditions encountered during the summer. It corresponded to 40%-50% of the maximum *S* estimated for each topsoil layer. The real water storage capacity could then be estimated as the difference between maximum *S* and S_e. This corresponded, to 40 mm for topsoil in Lys-1, and to around 50 mm for topsoil in Lys-2 to Lys-4. These values are larger than the biggest 24-h rainfall that occurred during the studied period (37 mm), but it should be noted that the maximum ∆S recorded during this biggest rainfall was of 25 mm in Lys-3. Because of the fast release of water after rainfall, a large ∆S was rapidly available after a rainfall event. However, some mechanisms limited the possibility to use all the storage capacity of the topsoil, like during the 37 mm rainfall event that occurred. Large and deep desiccation cracks were observed in the topsoil layer of all lysimeters during the summer. Precipitation reached directly the overburden and infiltrated in this layer, instead of being stored in the topsoil. This could explain why *S* in topsoil and overburden varied almost simultaneously rather than successively in Figure 7. Compaction of the upper overburden sublayer, because of its effect on the saturated hydraulic conductivity, influenced also the storage of water in topsoil. A layer of low saturated hydraulic conductivity placed directly under the topsoil layer favoured water accumulation at the interface of the soil layers and at the bottom of the topsoil layer, while higher saturated hydraulic conductivity dragged water deeper in the overburden. This can be observed by comparing Figures 7c and 7d, where Lys-4 (Figure 7d) had a smaller ∆S in topsoil and larger ∆S in overburden compared to Lys-3 for the same rainfall.

Water storage in all the overburden increased rapidly during a rainfall event and usually, at least 50% of the water stored during the rainfall was evacuated from the overburden layer within 36 h after the end of the event (Figure 5). However, S kept decreasing and no S_e in the overburden were reached, even after 10 days without rain. $S_{e\text{-overburden}}$ should therefore be lower than the minimum values shown on Figure 5, higher than the residual value of 0.08 found in literature for silty sands (Stormont & Morris, 1998), but could not be estimated. It could only be described as greater than 15 mm for Lys-1, of at least 70 mm for Lys-2 and more than 60 mm for Lys-3 and Lys-4. Storage capacity of all 40 cm of overburden of Lys-2 to Lys-4 was then greater than 10-15 cm of topsoil, but this capacity took more time to be available.

4.4 Long-term issues and scale effect

This paper presents data and water balance for 3 months, during the year of construction of the lysimeters. Several changes may occur in the upcoming years that could affect the water balance and modify its components' relative contribution. Fast growing willows were at their first growing season. The total root length and total leaf area should keep developing, which may affect the rate of transpiration and influence saturated hydraulic conductivity if preferential flow paths are created (Albright 2004; Apiwantragoon 2014). Increase in total leaf area should also increase precipitation interception and change the radiation that reaches the soil and influence evaporation (Liu 2003). Moreover, overburden was not yet exposed to freeze-thaw cycles. Depending on the plasticity of the soil, tension cracks may develop and create preferential flow paths (Othman et al 1993). This would result in a double-porosity soil, increase percolation rate and lower the capacity of the overburden to retain water near the surface for evapotranspiration.

Lysimeters constructed for this study represent an intermediate scale of investigation, which gave a lot of information on water balance dynamics in a specific context. Caution must be used for extrapolation to larger scale based on the data presented in this paper. Lysimeters were built on a flat area, in a tailings storage facility dike. Runoff was neglected but for inclined or larger areas, runoff and lateral drainage could be significant.

5 Conclusion

The reclamation of mine waste storage facilities requires the use of methods to limit environmental contamination and the return of the site to satisfactory conditions, which include revegetation . Installation of vegetation and soil layers to support the vegetation can affect the water balance and the efficiency of the restoration methods used. In order to evaluate the impact of vegetation and compaction of supporting soil layers on the water balance of a waste rock pile, five lysimeters were constructed and instrumented on a mine site in the Abitibi region, in Northwestern Quebec, Canada. Results of this study showed, for a first period of 3 months, that evapotranspiration was the main component of every water balance of covered lysimeters and represented between 58% and 87% of the cumulative rainfall. Compaction had a great influence on percolation and evapotranspiration by decreasing saturated hydraulic conductivity of the soil layers, which favoured accumulation of water near the surface of the cover and made more water available for evapotranspiration. Effects of vegetation remained small the first year after planting but are already observed after a first period of 3 months. Vegetation increased evapotranspiration rates by 3-6 mm/6 hours, especially during and immediately after rainfall. Water storage was a small component of the water balance but a thin topsoil layer had greater water storage capacity compared to overburden for the same thickness. This storage capacity of topsoil was rapidly available after a rainfall event and could contribute to limit water percolation in mine wastes.

The results presented in this study highlight that vegetated soil layers are important to consider with respect to the design of mine waste engineered covers, whether aiming at keeping water saturation of underlying soil layers to limit oxygen diffusion or decreasing water infiltration through materials with low saturated hydraulic conductivity. For mine sites where the control of percolation is wanted, early implementation of compacted soils combined to revegetated topsoils could be advantageous. However, performance may vary at larger scale and with slopes, because of runoff and lateral drainage, and with time, because of the evolution of soil properties with freeze-thaw cycles, root colonization and of the evapotranspiration because of vegetation growth. Further investigation will be conducted on these topics in upcoming years.

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Short Term In Situ Performance of a CCBE Made Entirely of Mining Materials to Control Acid Mine Drainage

A Kalonji-Kabambi *Université du Québec en Abitibi-Témiscamingue (UQAT),* Canada

B Bussière *Université du Québec en Abitibi-Témiscamingue (UQAT), Canada*

I Demers *Université du Québec en Abitibi-Témiscamingue (UQAT), Canada*

Abstract

Mining companies are increasingly interested to valorise mine waste by using them in geoengineering applications. Reuse of mine wastes can provide economic, environmental and technical advantages by limiting the need for natural materials and by reducing volumes of mine wastes to manage. In this study, an experimental cell was built at the LaRonde mine site, Québec, Canada, to evaluate the in situ performance of a cover with capillary barrier effects (CCBE) made entirely of mining materials. The CCBE technique used to control oxygen migration and reduce water infiltration is one of the scenarios suggested to reclaim the acid generating LaRonde tailings impoundment. To assess the hydrogeological and geochemical behavior of the CCBE made entirely of mining materials, an experimental cell having the shape of an inverted truncated pyramid was built, instrumented and is now monitored to follow the volumetric water content and suction in the three different layers of the CCBE. The leachate at the bottom of the cell is also collected for physico-chemical analyses. A meteorological station located on site allows, along with the other hydrogeological measurements, to estimate the water budget of the cover system. The preliminary results confirmed the effectiveness of the CCBE made with mine waste rock (as capillary break and drainage layers) and clean tailings (as moisture-retaining layer) to control acid mine drainage (AMD) generation. The effectiveness was evaluated by *calculating the oxygen flux on the surface and through the cover. The chemical quality of the leachate recovered at the bottom also allows assessing the capacity of the cover system to control AMD. Additionally, calculation of the efficiency of the system to control water contamination was done through comparison of the chemical parameters obtained in the covered cell with those from a control cell (that contains only reactive tailings).*

Keywords: *acid mine drainage, cover with capillary barrier effects, experimental cell, mining materials, hydrogeochemical behavior.*

1 Introduction

In the presence of sulphidic acid-generating minerals, it is essential to take appropriate measures to control the generation of contaminants in water courses. When the effluent from the mine is acid, this phenomenon is called Acid Mine Drainage (AMD) while it is called Contaminated Neutral Drainage (CND) at for effluents at pH near neutrality (e.g., Nicholson 2004; MEND 2004). The adoption of more restrictive regulations by the majority of industrialized countries favored initiatives to protect the environment during and after mining operations. Atmospheric oxygen, sulphide minerals and water availability are the main factors in the process of AMD or CND generation (e.g., Aubertin et al., 2002; Bussière et al., 2005; Johnson and Hallberg 2005). An oxygen barrier is usually considered the most efficient approach to control AMD generation (e.g., SRK 1989; MEND 2001; EIPPCB 2003), particularly in wet temperate climates. Oxygen migration control can be carried out using water covers, soil or other geological materials covers to reduce the availability of oxygen to the underlying acid-generating mine wastes. One of those cover techniques called cover with capillary barrier effects (CCBE) uses capillary barrier effects (e.g., Nicholson et al., 1989; 1991; Collin et Rasmuson 1990; Rasmuson et Erikson 1986; Morel-Seytoux 1992; Aubertin et al., 1995, 1996a; Aachib 1997; Bussière 1999;

Yang et al., 2004) to keep one of the multiple layers of the cover at a degree of saturation (S_r) of 85% or more in order to prevent oxygen migration (e.g., Rasmuson and Erickson 1986; Akindunni et al., 1991; Aubertin et al., 1995, 1996; Bussière et al., 2003). This technique must contain several layers of materials with different grain sizes and hydrogeological properties to be efficient to control water infiltration and oxygen migration to the underlying acid-generating tailings. Each layer is made of a distinct material that plays one (or more) particular role(s) in the overall behavior of the system. A typical configuration of this type of barrier consists of five layers (Aubertin and Chapuis 1991; Aubertin et al., 1995, 2002) but more complex cases exist, up to ten layers (Hutchison et Ellison 1992). The essential components that allow the CCBE to act as an oxygen barrier are the following three layers: (1) the bottom layer is called the capillary break layer (CBL) and typically consists of a fairly coarse-grained material used both for mechanical support and as capillary break; (2) the moisture-retaining layer (MRL) is made of fine-grained material and is placed over the CBL; (3) a second coarse-grained layer is placed over the MRL to prevent evaporation and to control water lateral drainage.

The implementation of a CCBE on the LaRonde tailings impoundment (with an area of approximately 1.3 Mm^2) would require an important volume of natural materials. The availability and the use of suitable, naturally-occurring materials can be a concern, particularly in terms of stripping, costs and required volume. Indeed, construction costs can greatly increase when these materials are not located within close proximity to the site to be reclaimed (e.g., Bussière et al., 1999; Gee et al*.,* 2006). Moreover, concerns related to the social acceptability and the environmental impact of stripping sites of natural materials put pressure on the mining industry to use alternative materials in CCBE. Consequently, mining companies are increasingly interested to valorise mine wastes by using them in geoengineering applications. Some previous studies, conducted in the laboratory (e.g., Aubertin et al., 1995; Aachib 1997; Bussière et al., 2004), at the Manitou site (e.g., Bussière et al., 1997; 2007) and Les Terrains Aurifères (LTA) site demonstrated that CCBE consisting of low sulphur or desulphurized tailings in the MRL and other natural materials (e.g., sand, gravel, etc.) in the CBL, are effective in controlling oxygen migration and thus limiting the production of AMD (e.g., Aubertin et al., 1999; Bussière et al., 2004).The possibility of using waste rock as a top and bottom CBL was evaluated as part of preliminary numerical modeling study (e.g., Pabst 2011). Under arid conditions, waste rocks were used to construct the CBL in a store-and-release cover (e.g., Zhan et al., 2001; 2006). Waste rocks were also evaluated as granular materials for CCBE in the laboratory and by numerical modeling (Kalonji-Kabambi, 2014; Kalonji-Kabambi et al., 2016, 2017).

This paper presents a preliminary assessment of the performance of a CCBE made entirely of mining materials which is one of the scenarios suggested to reclaim the acid-generating LaRonde tailings impoundment. The objective is to study the hydrogeological and geochemical behavior of the CCBE made entirely of mining materials in limiting the oxygen flux through the cover system. To achieve this, an experimental cell was built, instrumented and monitored to follow the performance of the system. This paper presents the design, construction and instrumentation of the experimental cell and the results from the first monitoring season.

2 Methodology

2.1 Origin and Materials Preparation

All materials used in the construction of a CCBE originated from the LaRonde gold mine, property of Agnico Eagle mines Ltd (AEM). The particle size of waste rock was truncated to 50 mm. This fraction was selected after considering, together with AEM, the possibility of producing this grain size in the field by crushing or sieving. Preliminary tests showed that the hydrogeological behavior of waste rock sieved at 50 mm can act as capillary break layer (Kalonji-Kabambi, 2014; Kalonji-Kabambi et al., 2016, 2017). Although materials exclusively from the LaRonde mine were used in this study, the purpose of the present study was not only to develop a specific reclamation scenario to the LaRonde tailings impoundment, but also to assess the effectiveness of the CCBE built exclusively with mining materials.

2.2 Materials Characterization

Concomitantly to the construction of the field experimental cell, characterization of the main physical, mineralogical, and hydrogeological properties of the cover materials was performed. The grain size distribution of reactive and clean tailings was determined using a Malvern Mastersizer laser particle size analyser (Lee Black et al., 1996). The grain size distribution of waste rocks was performed by mechanical sieving according to ASTM standard D422 (ASTM 2007) for the particle larger than 425 µm, and Malvern Mastersizer laser particle size analyser for finer grain sizes. The specific gravity (G_S) of each material was determined by a helium pycnometer (Micromeritics AccuPyc 1330) according to ASTM standard D854-10 (ASTM 2012). The mineralogy of all materials was obtained with X-Ray diffraction (XRD) using the quantitative Rietveld method with TOPAS software (Rietveld 1993). The tailings saturated hydraulic conductivity (k_{sat}) was evaluated using a standard permeameter according to ASTM standard D5856 (ASTM 2007). The k_{sat} of waste rock was determined using the constant head permeability test in large high-density polyethylene (HDPE) columns (80 cm in height and 30 cm in diameter) using the method proposed by Peregoedova et al. (2013). The water retention curves (WRC) of tailings were determined using a pressure cell (Tempe Cell) following the procedure by ASTM D3152-72 (ASTM 2000). The waste rock WRC was obtained through column drainage tests similar to the one used for the permeability test also conducted following the procedure proposed by Peregoedova et al. (2014).

2.3 Construction-Description and Monitoring of the Field Experimental Cell

An experimental cell was built in early autumn 2016 at the LaRonde mine site. An excavation was carried out with a hydraulic excavator until reaching the bedrock at 0.80 m in the center of the cell (Figure 1a). This was followed by the excavation of the trench for the exit of the drain with a slope of 1% over a distance of 16 m (Figure 1c). Construction continued with setting up 30 cm of fine sand at the bottom of the trench, their compaction with the vibrating plate and the installation of the 2-inch diameter PVC pipe for water exfiltration (Figure 1d). The constructed experimental cell had the shape of an inverted truncated pyramid (Figure 1b). A sand layer was emplaced along the bottom and the side of the cell, which were then lined with a geomembrane to control exfiltration and to avoid eventual external water contamination (Figure 2ab). The configuration of the field experimental cell was, from bottom to top: the reactive tailings (1.00 m thick), a waste rock (P) CBL (0.30 m thick), the clean tailings MRL (0.6 m thick), and a waste rock (L) drainage layer (0.30 m thick) (Figure 2cde). The surface of the cell is horizontal and of approximately 144 m^2 (12 m × 12 m). Finally, the sides of the cell were sloped with a hydraulic excavator to obtain the desired size and geometry (Figure 3b).

Figure 1 Excavation with a hydraulic excavator (a), inverted truncated pyramid form of the experimental cell (b), excavation of the trench (c) and installation of the PVC pipe for water exfiltration (d)

Figure 2 Sand and geomembrane setting up (a and b), sensor placement and setting up the different layers of the field experimental cell (c and d) and location of the instruments in the cover (e)

The experimental field cell was equipped in the center with a monitoring station (Em50 data logger, Decagon Devices, Inc) which recorded volumetric water contents (θ) at various depths (see Figure 3b). 5TM and GS3 sensors (Decagon Devices, Inc.) were used to monitor volumetric water contents in tailings and waste rock, respectively (see Figure 2e). The 5TM and GS3 probes were calibrated before for each material to improve measurement accuracy. When calibrated with a specific material, both probes have an accuracy of ± 0.03 m^3/m^3 for a range of 0 to 100 % humidity. Knowing the porosity (n) of the material, the degree of saturation (S_r) was calculated by dividing θ by n. Matric suction (ψ) measurements were performed using the Watermark blocks from IRROMETER Company with a measure range of 0 to 200 kPa and an accuracy of 1 kPa (IRROMETER Compagny, Inc.). The measurement frequency was fixed at one measurement per four hours for θ. The ψ values were taken every two weeks using a Watermark Electronic Meter. Exfiltration waters from experimental cells were collected at regular intervals once every two weeks (see Figure 3c), between May and November 2017 for physico-chemical analyses.

Figure 3 Final profile of the control cell (a), CCBE experimental cell (b) and exfiltration waters (c)

The experimental cell was also equipped with an oxygen-consumption test (OCT) device installed in the MRL (Dagenais et al., 2012) and interstitial gas sampling (IGS) tubes installed at the same depths as the θ and ψ probes. The OCT consists in measuring the oxygen concentration decrease in an air-sealed chamber during a short time period (three to five hours) using the method proposed by Elberling et al. (1994) and Elberling and Nicholson (1996). The IGS, inspired by Mbonimpa and Mantoy (2011), consists in measuring the interstitial oxygen concentration at different depths of the cover. The decrease in the oxygen concentration and the interstitial oxygen concentration were converted into an oxygen flux by using analytical methods (Elberling and Nicholson 1996) and Fick's first law (Elberling et al., 1994; Mbonimpa et al., 2002, 2003, 2011) respectively. Oxygen consumption tests were also conducted on uncovered LaRonde reactive tailings in order to obtain reference values.

3 Preliminary Results

3.1 Main Physical, Mineralogical and Hydrogeological Properties of Cover Materials

The main materials characterization data are presented in Table 1. These data show that the clean tailings are somewhat finer than the reactive tailings and both types of waste rock have almost the same grain size. The order of magnitude of the k_{sat} value is 10^{-2} cm/s for the waste rock, 10^{-4} cm/s for the reactive tailings, and 10^{-5} cm/s for the clean tailings. Air entry values (AEV), obtained from measured WRCs, are 2 and 2.5 m of water for the reactive and clean tailings respectively. The AEV for the waste rock varies between 0.002 and 0.003 m of water. Mineralogical analyses identified different types of sulphide and carbonate minerals, including pyrite (27%) in the reactive tailings, traces of pyrite (< 1%) and calcite (9%) in the clean tailings, pyrite (<2%) in the waste rocks (P) and pyrite (< 1%) and calcite (4%) in the waste rocks (L). Given the high density of sulphide minerals, their respective proportions explain the higher G_S of the solid grains of the reactive tailings (3.2), compared with that of clean tailings and waste rock, which is between 2.7 and 2.8.

Table 1 Main physical, hydrogeological and mineralogical properties of cover materials

Parameters	Reactive tailings	Clean tailings	Waste rock (P)	Waste rock (L)
Physical and hydrogeological properties				
D_{10} (µm)	9	2.6	160	165
D_{50} (µm)	68	16	10000	10000

D_{60} (µm)	88	22	17000	15000
Specific gravity (-)	3.2	2.7	2.7	2.8
Porosity in the cell (-)	0.37	0.35	0.26	0.26
Saturated hydraulic conductivity (cm/s)	2×10^{-4}	5×10^{-5}	3×10^{-2}	2×10^{-2}
Air entry value (m)	2	2.5	0.002	0.003
Mineralogy (by order of importance)	Quartz 61%	Albite 52%	Quartz 68%	Albite 38%
	Pyrite 27%	Quartz 22%	Albite 27%	Quartz 34%
	Albite 9.5%	Chlorite 13%	Muscovite 3.4%	Chlorite 14%
	Gypsum 1.4%	Calcite 8.7%	Pyrite 1.4%	Actinolite 5%
	Muscovite 0.5%	Muscovite 2.8%		Calcite 4%
		Dolomite 1.2%		Pyrite 0.5%
		Gypsum 0.7%		
		Pyrite 0.3%		
		Anhydrite 0.2%		

3.2 Hydrogeological and Geochemical Experimental Cell Results

3.2.1 Degree of saturation and matric suction profiles

Figure 4 shows S_r and ψ values measured in the different layers of the CCBE in the experimental cell during the first year of monitoring. Instruments were installed respectively at 0.20, 0.40, 0.80, 1.00 m and 1.30 m depth in the experimental cell. The capillary barrier effects associated with a low S_r in both CBL and a high S_r in the MRL are observed (e.g., Aubertin et al., 1996). The S_r values in bottom of the MRL, excluding the winter period, are always > 85%, and the values in the top of that layer have gone down to 65% in summer. ψ values are usually < AEV (25 kPa) of the clean tailings, but one measurement is higher than this value at the top of the MRL in the summer. In the CBL, S_r values were not measured because of the probe defect. However, the ψ values in the CBL remained below 20 kPa. In the drainage layer, S_r and ψ values are between 40 and 50%, and 5 and 25 kPa, respectively.

3.2.2 Water quality

Figure 5 presents pH values and sulfate concentrations of exfiltration waters in the control and experimental cells. The pH values in the control cell are usually around 3 and those in the experimental cell lie between 6 and 9 (Figure 5a). Sulfate concentrations in the control cell increase over time to 24,000 mg/L at the end of the year (Figure 5b). The values in the control cell are higher than in experimental cell where concentrations tend to stabilize over time to 2000 mg/L.

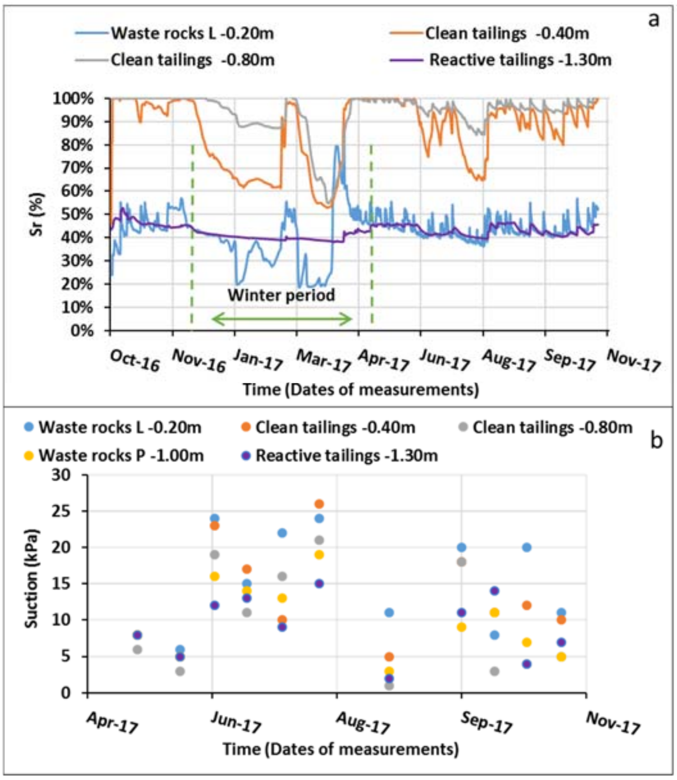

Figure 4 Degree of saturation (a) and suction (b) distribution in the experimental cell

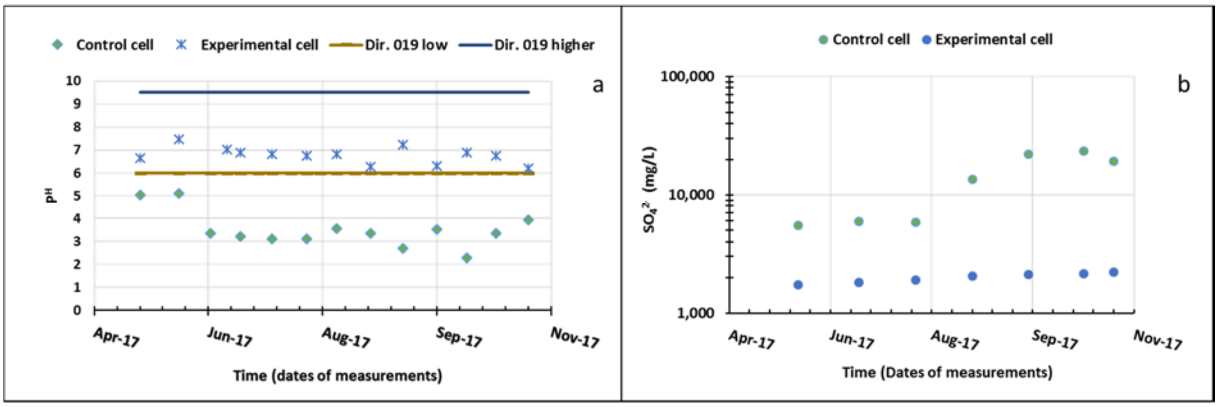

Figure 5 pH values (a) and sulfate concentration (b) in exfiltration waters

Figure 6 presents values of different concentrations of metals in exfiltration waters in the control and experimental cells during the first year of monitoring (Figure 6a-f). In Figure 6, the concentration values of the metals are compared to the values required by the environmental regulations in Québec ("Directive 019") in the final effluent. The concentrations of arsenic [As] in two cells are less than the detection limit of the method used (0.06 mg/L) (Figure 6a). The [Cu] in the control cell are higher than those of the experimental cell which remained constant over time (0.003 mg/L) (Figure 6b). The concentration values in the control cell increase over time with values from 0.3 mg/L in May to 11.5 mg/L in November 2017 (Figure 6b). The [Fe] in the control cell are higher than those of the experimental cell. In the control cell, the values increase over time with values from 2000 mg/L at the beginning of the first year of monitoring to around 9000 mg/L at the end of the year (Figure 6c). In the experimental cell, the average value of [Fe] is 47 mg/L (Figure 6c). The values of [Pb] are around 1 mg/L in the control cell and below 0.01 mg/L in the experimental cell (Figure 6d). The values of [Ni] range from 0.6 to 2 mg/L in the control cell and 0 to 0.1 mg/L in the experimental cell (Figure 6e). Finally, the values of [Zn] are between 100 and 400 mg/L and 3 and 15 mg/L in the control and experimental cells respectively (Figure 6f).

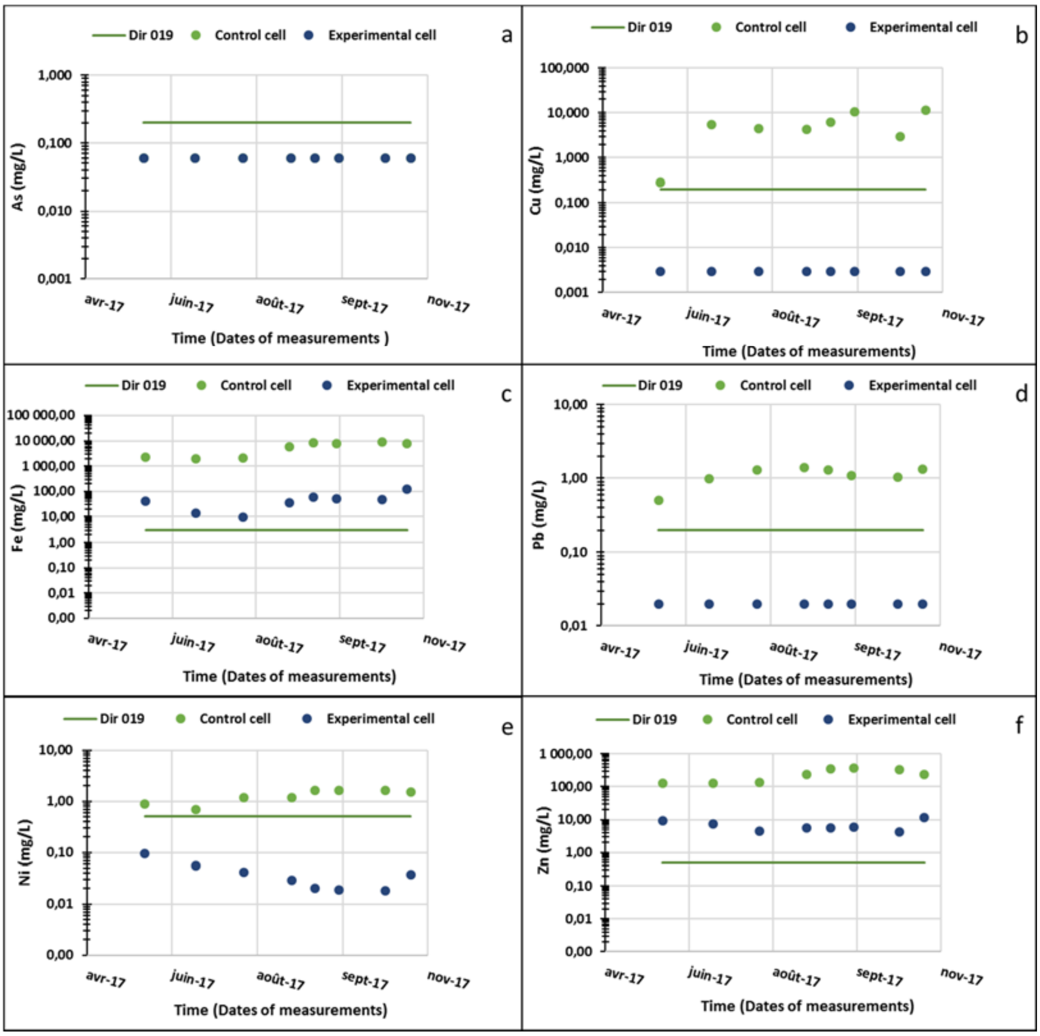

Figure 6 Concentrations of different metals in the exfiltration water

3.3 Oxygen Fluxes Values

In the control cell, the surface oxygen flux is typically around 700 mol/m^2/year. However, in the experimental cell, the effective diffusion coefficient evaluated using volumetric water content measurements in the MRL is 2.60 10^{-10} m^2/s and the oxygen flux in the MRL is 0.10 mol/m^2/year, which represents an efficiency of 99%. These results show that the CCBE made of clean tailings in the MRL and waste rocks in the CBLs reduce availability of oxygen to the underlying reactive tailings.

4 Preliminary Conclusion

This study seeks to assess the performance of a cover with capillary barrier effects made exclusively of mining materials as reclamation measures for tailings storage facilities. An experimental CCBE cell was built at LaRonde mine site to test this technique under field climatic conditions. Continuous monitoring of volumetric water content, suction, exfiltration water quality was used to evaluate the cover performance. The effectiveness was also evaluated by calculating the oxygen flux on the surface and through the cover. The data presented in this paper represent only the first year of monitoring. Thus, a steady state in hydrogeological and geochemical behavior was not necessarily reached, and a longer monitoring period is required to draw general conclusions on the hydro-geochemical behavior of this reclamation scenario. However, the hydrogeological profiles that were obtained demonstrated that high S_r in the MRL should limit the oxygen fluxes reaching the reactive tailings.

The preliminary geochemical results indicate that AMD generation should be limited by the CCBE made exclusively of mining materials. However, the concentrations of Fe and Zn exceed the environmental regulations. The monitoring of the CCBE experimental cell will be continued for a minimum of three years before drawing final conclusions. In parallel to the field experimental cell monitoring program, detailed laboratory characterizations are being conducted and hydrogeological and hydrogeochemical modeling will be realized. The laboratory testing program includes the determination of clean and reactive tailings reactivity and the detailed mineralogical characterization for both materials.

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Reduction of Iron and Sulphate in the Groundwater by Stimulated Microbial Sulphate Reduction

C Hildmann *Research Institute for Post-Mining Landscapes (FIB), Germany*

M Walko *Research Institute for Post-Mining Landscapes (FIB), Germany*

R Schöpke *Brandenburg University of Technology (BTU), Germany*

Abstract

Several surface water bodies of the Lusatian mining district are heavily loaded with high iron and sulphate concentrations. Both iron and sulphate are sourced from iron sulphides like pyrite and marcasite, which decompose under oxic conditions. These conditions dominate large subsurface areas after artificial lowering of the groundwater table for opencast lignite mining. After mining cessation, groundwater regained pre-mining levels in these areas. Consequentially, iron and sulphate got washed into surface water subsequently. This is problematic because especially iron tends to adversely affect freshwater fauna (fish, insect larvae) and aquatic plants by lowering aquatic pH or promoting high turbidity.

To develop a counter-treatment technology, we developed and successfully operated a pilot plant near "Ruhlmühle" (north Saxony) from December 2014 to June 2017, where an iron hot spot (between 400 and 550 mg/L Fe) in groundwater was detected. Using wells, we extracted a part of the groundwater from that hot spot. We then mixed that water with glycerol to finally re-infiltrate it to the groundwater body. Our infiltration line consisted of 30 lances with a total width of ~100 m.

Thus infiltrated glycerol served as a carbon source for sulphate-reducing bacteria (SRB). The microbes operated under the difficult starting conditions (pH-value of about four), why it took a longer time than expected to rise the pH above five by bacterial metabolism. Under these conditions, iron could be precipitated as iron sulphide, generating additional alkalinity. Finally, we could reduce the iron concentration of our test site by one order of magnitude, to less than 30 mg/L. In the same time, sulphate and electrical conductivity decreased (SO4 from about 1100 mg/L to less than 100 mg/L) too, whilst neutralization potential switched from between -15 to -20 mmol/L to positive values. In post-experiment drilling cores we measured increased ferrous disulphide concentrations, and we did not detect evidence for interstice blocking. We conclude that stimulation of microbial sulphate reduction has the potential to serve as effective countermeasure for both high environmental iron and sulphate concentrations.

Keywords: *Iron, Sulphate, Groundwater, AMD, Microbial Sulphate Reduction*

1 Introduction

In the course of lignite mining in the Lusatian mining district (eastern Germany), groundwater level was lowered in an area of more than 2100 km². Not only dumps, but also the adjacent, not directly by mining affected sediments were aerated. Consequentially, environmentally effective amounts of locally existing iron disulphides such as pyrite and marcasite were oxidized in a process that is microbially catalysed (Bloomfield 1972). After the decommissioning of many lignite opencast mines, groundwater level re-increased on a large scale and freshly formed iron and sulphate got mobilized and washed out by the groundwater flow into local surface waters, becoming subject to aeration as a result.

During the oxidation of Fe (II) to Fe (III) and finally iron hydroxide, protons are released and the pH value of the surface waters drops. Oxidised iron is already visible in small concentrations (> 3 mg / l) as a red-brown coloration. Iron hydroxide not only dyes the water brownish, but also hinders the photosynthesis of submerged macrophytes and the gas exchange through gills of fish and insect larvae as a result of turbidity.

High sulphate concentrations in turn have a corrosive effect on concrete and impede the production of drinking water. They also have an influence on the composition of the aquatic fauna (Halle & Müller 2015).

For water protection reasons, adverse effects on water quality must be minimized. Areas of particular public interest, such as the nearby Spreewald biosphere reserve, which is criss-crossed by many streams, therefore are subject to special protection interest. In this regard, numerous much effort has been put into solving the iron problem by mining companies and by rehabilitation miners. This included the further development of microbially induced iron retention in the subsurface as set out here. The method makes it possible to treat the groundwater near the source of increased matter loads.

The use of sulphate reduction for acid mine drainage (AMD) treatment has been discussed for years, and its general suitability has been proven by various experiments (Elliot et al. 1998, Katzur et al. 2001, Preuss 2004, Gast et al. 2010). The aim of sulphate reduction is to reverse pyrite weathering, namely the formation of iron sulphides. Permanently reducing conditions, typical for many aquifers, are required to sustainably immobilize the reaction products. The addition of a carbon source stimulates the activity of SRB, which use the sulphate-bound oxygen for their metabolism. The resulting sulphide, together with the iron, can then be precipitated to iron monosulphide. Finally, the iron monosulphide can transform to iron disulphide. Hereby, additional alkalinity occurs.

In our study, microbial induced sulphate reduction was employed using a pilot plant under real conditions. Thus, we wish to elucidate whether the method is suitable as a water rehabilitation technology.

2 Methodology

Our pilot plant was located in Ruhlmühle near Neustadt (Spree) in the Lusatian mining district. The site itself was not directly affected by mining. However, mining companies lowered the local groundwater table for decades for their nearby lignite mines (Lohsa, Burghammer, Nochten). From a geological perspective, the location is part of the Spreewitzer groove, a relic Pleistocene landscape feature. Sediments, characterized by a heterogeneous mixture of finer and coarser sands, in which small deposits of xylites occur, dominate the local lithologies. Through these sedimentary layers groundwater flow below our pilot plant into the Altarm (fig. 1), a river Spree tributary, that shows dramatically increased iron and sulphate concentrations (5 - 190 mg / l Fe, 240 - 765 mg / l SO4).

In our study, we used glycerol as a carbon source. Glycerol's suitability in this regard has been shown in previous experiments (Gast et al. 2010, Schöpke et al. 2013). As part of the pilot plant operation, the use of glycerol – a substance classified as slightly hazardous to water – was approved by the authorities. Generally speaking, various other substances are suitable as glycerol substitutes, however, with each of these having their advantages and disadvantages (e.g. Elliot et al. 1998, Hüttmann 2016).

Figure 1 The 'Altarm', a tributary to river Spree, with high iron and sulphate loads (left) and the pilot plant with the dosage unit, located in the container.

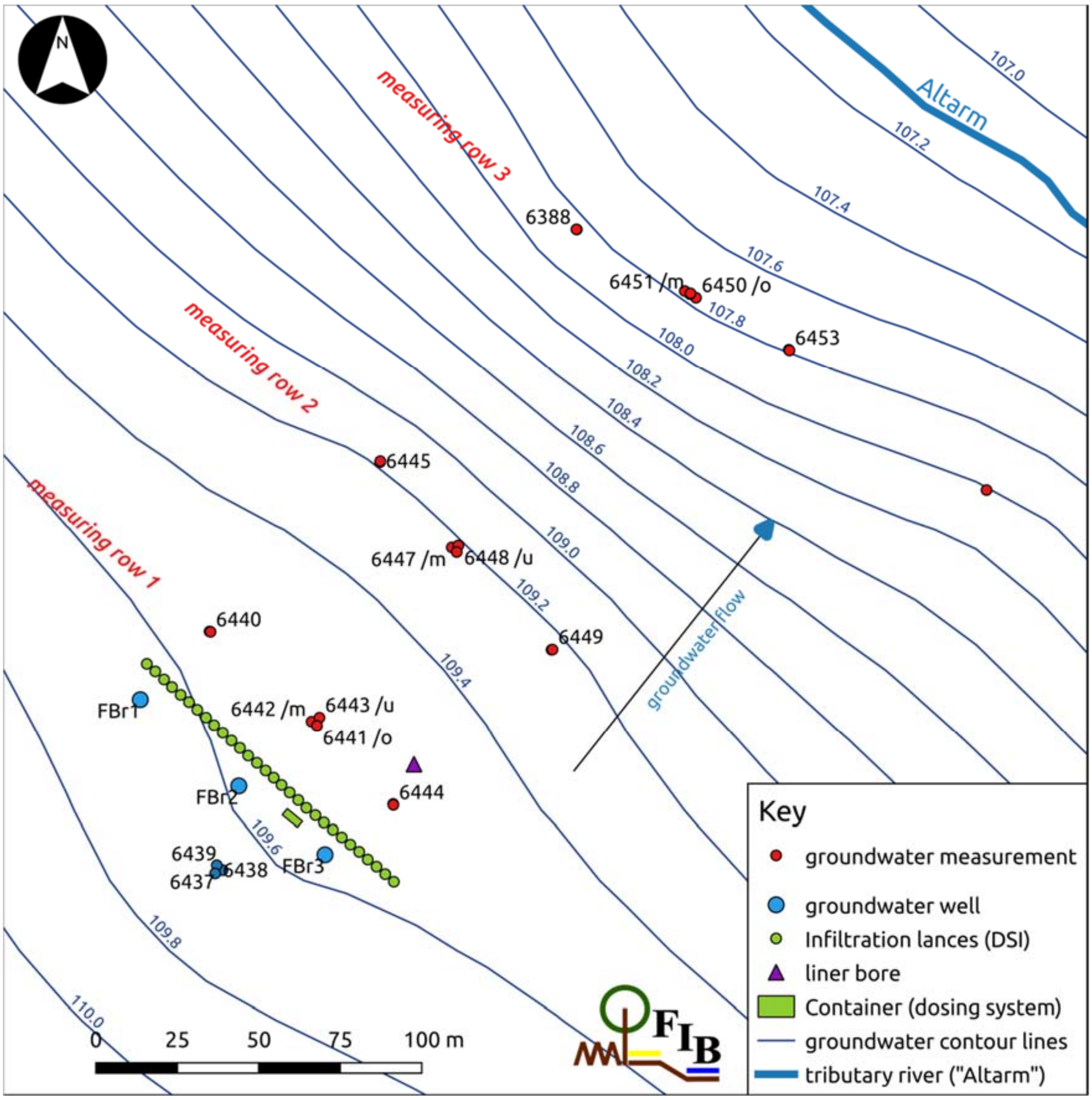

Figure 2 **Overview of the pilot plant Ruhlmühle.**

For our experiment, the glycerol had to be injected into underground. Since glycerol is very viscous, pre-injection mixing with the groundwater was required. For this purpose, part of the groundwater flow was extracted via three wells (fig. 2). The glycerol was mixed with the groundwater with a dosing system (fig. 1) and infiltrated into the underground via DSI lances. For this purpose, 30 lances at three different depths (9.5-11.5, 13-15 and 16.5-18.5 m below surface) were installed at a width of about 100 m across the groundwater flow. Each lance was individually regulated in order to achieve the best possible mixing of the glycerine with the groundwater. An infiltration phase of about 9 days was followed by a break of about 14 days during which the glycerol-enriched groundwater could flow down, according to the local gradient. We additionally infiltrated phosphate and nitrogen to promote optimum conditions for the growth of sulphate reducers.

To control and steer the processes a comprehensive monitoring was carried out. For this purpose, we installed nine groundwater measuring points (in three rows perpendicular to the groundwater flow direction), of which three measuring points were filtered at three different depths. After completion of the pilot operation, we drilled a liner bore to check for possible blockage of the pore space.

We commenced operation of the pilot plant in December 2014, and continued for 31 months until June 2017. During this time, a total of 38 m³ of glycerol was infiltrated in 42 infiltration cycles. The infiltrated amount of glycerol was stoichiometrically proportioned to the local iron and sulfate concentrations. In the starting phase, significantly less glycerol was added to initially stimulate the growth of SRB. This was to avoid that non-metabolised glycerol enters the surface waters. For the infiltration of glycerol 87 500 m³ of groundwater were extracted. In addition, 8.3 kg of phosphorus and from August 2016 also 24.4 kg of nitrogen were infiltrated to keep the supply of the sulphate reducers at a constant level.

3 Results

Prior to the start of our experiment, groundwater at Ruhlmühle had comparatively low pH values of ~4.1. Additionally, the water was highly mineralized with an electrical conductivity between 1500 and 1950 µS/cm, and total iron contents ranged between 455 and 490 mg/l whilst sulphate contents were between 1005 and 1465 mg/l.

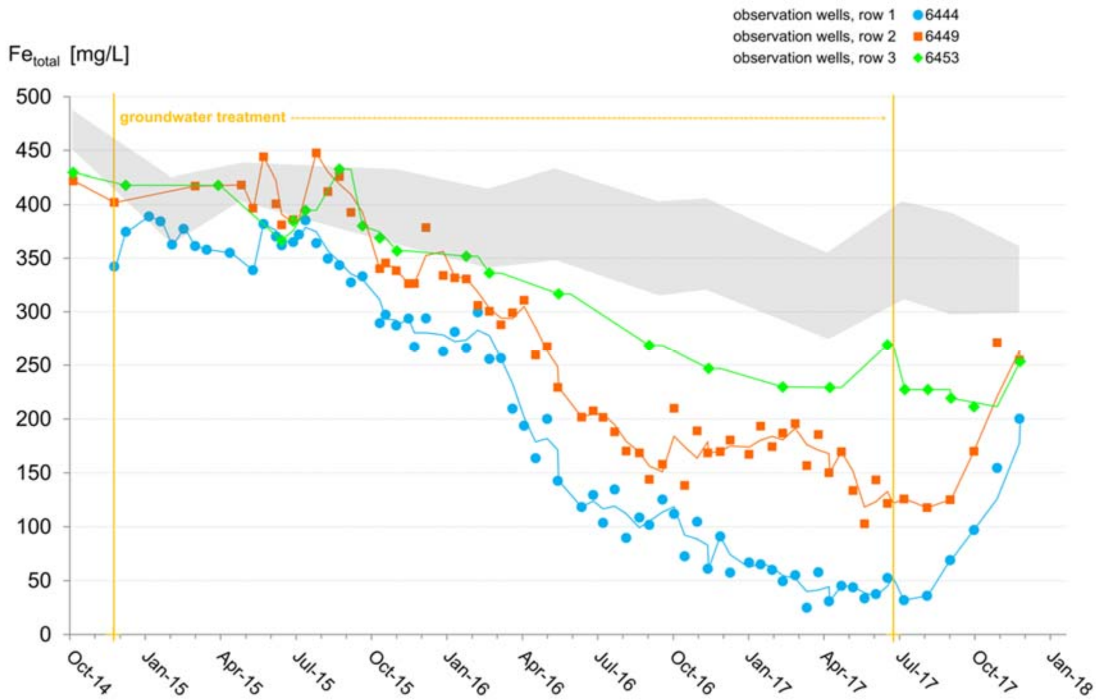

Figure 3 Development of iron concentrations at selected groundwater observation wells.

After the first three months of our experiment, and despite still low pH levels, sulphide levels showed increasing microbial activity. At the same time, pH values commenced to increase measurably. However, the precipitation of iron did not begin at first. Instead, the dissolved aluminium was fixed to the surfaces of the exchangers, probably releasing iron. Only then, and with a further increase in the pH, was it possible to observe the reduction of iron concentrations in the groundwater.

As expected, sulphate reduction was observed at the more remote groundwater measuring points later than in the first row. However, due to the heterogeneity of the location, groundwater does not flow uniformly to all measuring points.

After initiation of iron precipitation process, the iron levels in the first row of measuring points could be reduced down to 10 mg/L (mean 118 mg/L, starting from 432 mg/L, fig. 3) and the sulphate levels down to 1 mg/L (mean 401 mg/L, starting from 1205 mg/L, fig. 4). Accordingly, with the retracted underground reactor an amount corresponding to 13.5 t Fe/a and 38.3 t SO4/a could be retained.

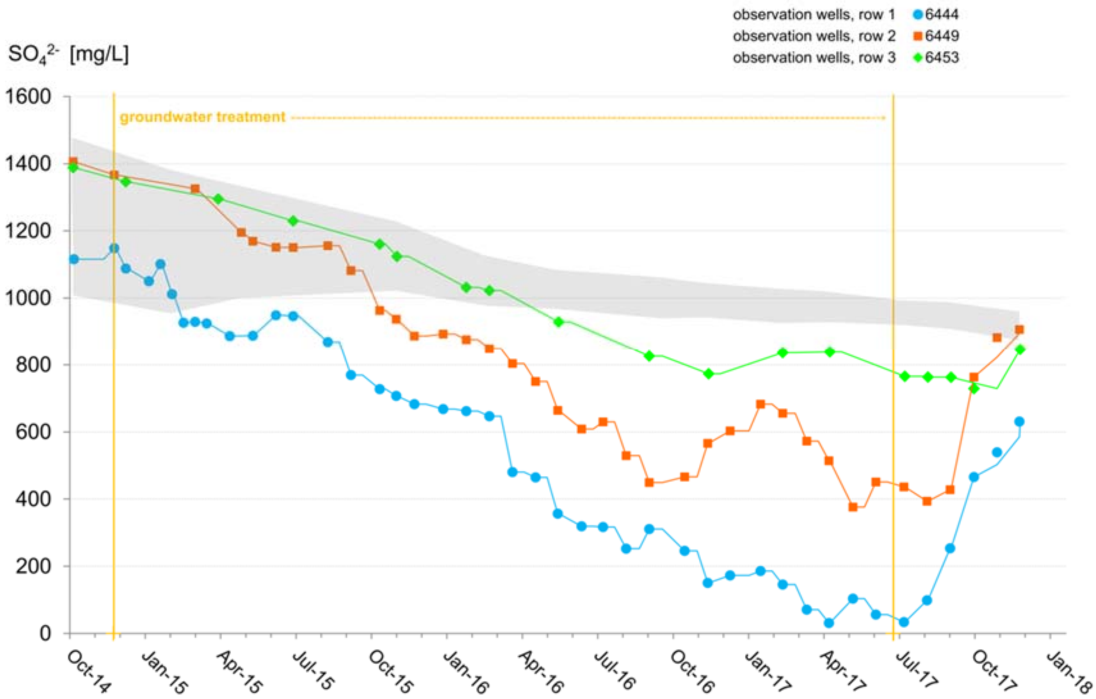

Figure 4 Development of sulphate concentrations at selected groundwater observation wells.

As a measure of the acidity of mining-influenced groundwater, the neutralization potential (Evangelou 1995) can be determined by the acid capacity Ks4,3, taking into account the dissolved iron (II), manganese (II) and aluminium (III) (Schöpke 1999). In fig. 5 we show the neutralization potential of the measuring points against the sulphate concentration. Note the shift of the values from the beginning of our groundwater treatment towards the end of our experiment, representing the desired effect of rising neutralization potential by iron precipitation, also known as "remediation vector".

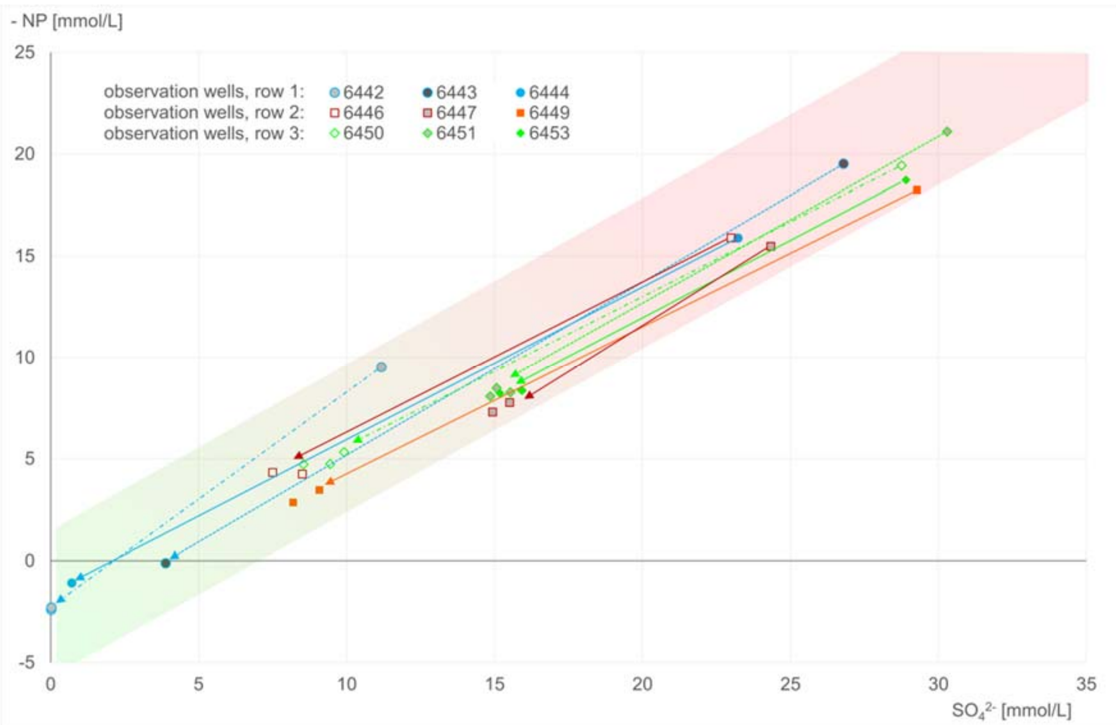

Figure 5 'Remediation vector': development of neutralization potential and sulphate concentration from the start of the experiment to the end, indicated by the arrows.

In the course of our experiment, the injected glycerol was almost completely metabolised by the SRB. Both the glycerol and its incomplete degradation products are measured in the groundwater via the DOC concentration. In the first series of measurement points behind the infiltration line, we were able to measure elevated DOC concentrations compared to the inflow (mean 44.1 mg/L, initial flow 20.4 mg/L). On the other hand, in the last row of groundwater measuring points, the values were again in the range of the inflow (mean 15.1 mg/L). We conclude that surface water was not subject to additional oxygen depletion.

Another important question in the course of our experiment was whether precipitated iron(mono)sulphide would remain in the underground as a monosulphide, or whether (and if so, how quickly) it would be converted to disulphide. We tackled this problem with the help of a liner hole at the level of the first row of groundwater measurement points after completion of the infiltration operation. The analysis of the obtained sediments showed that the measured iron sulphide was significantly increased compared to the values found during measuring points installation. We also found that iron sulphide was predominantly formed as iron disulphide. This is important because with the transformation of iron monosulphide to disulphide, additional alkalinity is generated and thus the pH value is further increased. Above all, however, the iron disulphide formed is more stable to decomposition than iron monosulphide. Therefore, as long as the groundwater level will not drop again, we assume a long-term safe storage of the reaction products.

Concluding, the examination of the sediment samples revealed no evidence of pore space blocking, on the basis of flow tests. Also, from a mathematical perspective, available pore space of 25% is filled only to a small extent, depending on the distance at which the precipitation actually takes place. Complete precipitation near the infiltration points (1.75 m) would require only 1.2% of the pore space per year. If precipitation occurs at a greater distance to the infiltration point, this proportion is correspondingly lower. We infer that the deposition of iron disulphide would not lead to pore space blocking at the Ruhlmühle site even after many years of glycerol injection.

4 Conclusion

Our results show that the presented method is suitable for significantly reducing the levels of iron and sulphate in groundwater. With a well-run underground reactor, iron and sulphate concentrations could be reduced to a low residual concentration according to the stoichiometry of the resulting iron sulphides (reduction by more than 95%).

Acknowledging a slight deflection of flow direction, we successfully could treat groundwater along the entire width of our pilot setup. We note that, for an efficient operation of the process, sufficient time must be scheduled, depending on the location. At our test site, due to the very low local pH values, iron precipitation commenced with delay. In a previous test at higher pH, but on a smaller scale, iron precipitation started much earlier (Gast et al. 2010, Schöpke et al. 2013). Further, the initial adsorption of aluminium associated with the release of iron delayed the onset of precipitation of iron sulphides. As carbonate hardness increased, an acid buffer could establish in the groundwater, too.

Construction and operation of plants for the microbial sulphate reduction are particularly suitable where high concentrations of iron and sulphate are observed in groundwater (hot spots). Permanent fixation of iron and sulphate – even beyond the end of treatment – are the advantageous outcome of our proposed method, presuming no re-aeration. Absolutely no waste, and therefore no disposal costs, is being generated in the process. We stress that the presented method involves an exclusively biological process that features naturally occurring, sulphate-reducing bacteria that already adapted to the extreme site conditions. The construction measures are of limited extent. Wells and infiltration lances are mainly underground, the control and dosing facilities can be set up temporarily as a container unit.

When transferring our method to other locations, the local conditions must be checked. Important are e.g. a sufficiently deep groundwater lamella (no re-oxidation of the iron sulphides formed) and a sufficient distance from surface water bodies, so that the desired reactions can proceed completely (no flow of metabolites in the surface water) and the flow rate and velocity of the groundwater.

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Characterisation and the Potential Environmental Pollution from the Waste Rock Dumps at the Abandoned Edendale Lead Mine

S Lekoadu *Council for Geoscience, South Africa*

K Matshusa *Council for Geoscience, South Africa*

Abstract

The Edendale lead mine was decommissioned before the environmental enforcement related to mining in South Africa. The mine has been left with un-rehabilitated waste materials which are potential environmental hazards. The waste rock materials at the mine site were sampled and analysed for As, Ba, Cr, Cu, Ni, Pb, Se, U, V and Zn in order to determine the potential environmental pollution. The geochemical characterisation of the samples was done through X ray fluorescence (XRF) and X ray diffraction (XRD). The samples were also sent to the laboratory for paste pH, paste electrical conductivity and batch leach test analysis. The leachate were analysed for Al, As, Zn, Pb, Cr and Se using ICP –MS Elan 9000 and for anions using ion chromatography. The XRF results were compared to the Canadian soil quality guidelines for the protection of environmental and human health for industrial land, whereas the leachates from the waste rocks were compared with South African water quality guidelines for the aquatic ecosystem to determine the extent of toxic metal contamination.

According to the XRF results, concentrations of Cr, Ni, Pb and Zn in waste rock dump 1 exceeded the guideline values of 87 ppm, 50 ppm, 600 ppm and 360 ppm respectively. Similarly waste rock dump 2 is also contaminated with Cr, Ni and Zn, whereas waste rock dump 3 and 4 are polluted with Cu, Cr, Ni, Pb and Zn. Therefore, XRF results indicate that the waste rock dumps at Edendale are contaminated with Cr, Ni, Pb, Zn and Cu. The high concentrations of Ni, Pb and Zn could be attributed to the presence of chlorite, Zinckenite and sphalerite, while high concentrations of Cr and Cu require further investigation.

The leachate results indicated that aluminium, lead and zinc could be leached with water from the waste rock dumps. The average leachate aluminium concentration 1.005 mg/L was higher than the target water quality range (0.005 mg/L). The average leachate lead concentrations (88.595) was higher than the target water quality range 0.2 µg/L (soft water), 0.5 µg/L (medium water), 1.0 µg/L (hard water) and 1.2 µg/L (very hard water) while zinc (0.003 mg/L) was slightly higher than the target water quality range of 0.002 mg/L.

Ion chromatography results showed that fluoride (1.1mg/L) in ED – WR 04 was above the target water quality range of 0.075 mg/L. The sulphate and inorganic nitrogen leachate concentrations were below the target values of 500 mg/L and 0.5 mg/L respectively.

Such contamination of the waste rock dumps by Cr, Ni, Pb, Zn and Cu, and leaching of Al, Pb, Zn and Fluoride could negatively affect human health and aquatic life. Therefore, it is critical that measures are taken to rehabilitate the Edendale lead mine.

Keywords: *waste rock dumps, lead, environmental pollution*

1 Introduction

The mining industry plays a critical role in the South Africa's economic, political and social environment. Currently, most of the old mining sites are no longer operational and they threaten public safety and health by creating long lasting environmental hazards. Toxic mine wastes continuously contaminate the soil and the water bodies in the surrounding areas.

The Edendale lead mine is one of the abandoned mine that is located close to Mamelodi township (Foya et al. 2006). The mine was decommissioned before the environmental enforcement related to mining in South Africa, namely the National Environmental Management Act 107 of 1998 and the Minerals and Petroleum Resources Development Act 28 of 2002 (Glass 2006). The mine is situated in the Silverton formation of the Pretoria group which is part of the Transvaal supergroup. The formation consists of carbonate mudrocks which are interbedded with sandstones, chert and dolomite. The main minerals that were mined at Edendale include galena, zinc, sphalerite, chalcopyrite and cerrusite. (Mokone & Wolkersdorfer 2017)

The lead was mined for the manufacturing of bullets. In addition to lead, considerable amounts of silver were also produced at Edendale (Wilson and Anhaeusser 1998). The ore body was processed on the mine site. However the Edendale mine operations were discontinued due to the implementation of the new technology in the arms industry. The mine has been left with un-rehabilitated waste materials which are potential dust and water problems (Foya et al. 2006), since there would have been limited pollution control measures at the time of mining (Glass 2006).

There is a limited establishment of the environmental impacts of the Edendale lead mine (Glass 2006). The current study is aimed at determining the potential environmental pollution that may result from the un – rehabilitated waste rock dumps at the mine site. This is important because there is Edendale primay and high school nearby and the mine is also located adjacent to Edandalespruit where numerous farms and some private residences rely on borehole water that may potentially be polluted (Glass 2006; Mokone and Wolkersdorfer,2017).

2 Methodology

In order to determine the potential environmental pollution, four waste rock materials (figure 1) were sampled at the Edendale mine site. The samples were put in sample bags and labelled ED – WR01, ED – WR02, ED – WR03 and ED – WR04. The samples were sent to the Council for Geoscience laboratory for X ray diffraction (XRD), X ray fluorescence (XRF) and batch leach test analysis. The XRF results were compared to the Canadian soil quality guidelines for the protection of environmental and human health for industrial land.

Figure 1 Distribution of the waste rock samples

The batch leach test was done to assess the constituents which could be leached from the waste rock materials. The procedure by NT Enviro 005 was followed during the batch leaching test. About 20g of the sample was poured into a capped 5L bottles. Approximately 400ml of deionized or distilled water was added to each sample; thereafter the bottles were placed on shaking device for 24 hours. After shaking the samples, the suspended solids were allowed to settle for 15 minutes and the leachates were placed in small beakers for pH and conductivity measurement. The leachates were also filtered into small labeled bottles. After filtering, duplicate samples were made and 3 drops of nitric acid was added to each one of the duplicate bottles for preservation. Then the filtered samples were sent to the chemistry laboratory for the determination of major cations and anions using ICP_MS (inductively coupled plasma mass spectrometry) Elan 900 and ion chromatograph (IC) respectively.

3 Results and interpretation

3.1 X ray fluorescence

XRF analysis was performed to determine the extent of toxic metal contamination. The Canadian soil quality guideline for the protection of environmental and human health were used as a guide in characterising the extent of pollution at the waste rock dumps, because currently there are no established soil quality guidelines in South Africa (Glass 2006). The sample is polluted if the chemical concentration exceeds the standard guideline values. The table below shows the Canadian soil quality guidelines.

Table 1 Guideline for the protection of environmental and human health on industrial land

Element	Guideline for the protection of environmental and human health on Industrial land (ppm)
As	12
Ba	2000
Cr	87
Cu	91
Ni	50
Pb	600
Se	2.9
U	300
V	130
Zn	360

Figures 2-5 below show the comparison of the XRF concentration for the waste rock dumps to the soil quality guidelines. The results for waste rock dump 1 indicate that (Cr, Ni, Pb and Zn) exceed the guideline values of (87, 50, 600 and 360 ppm) respectively. The results for waste rock dump 2 showed that Cr (476 ppm), Ni (141ppm) and Zn (1042ppm) exceeded the guideline value of 87 ppm (Cr), 50 ppm (Ni), 360 ppm (Zn) respectively. However the concentration of lead (191 ppm) was below the guideline value of 600 ppm. Waste rocks dumps 3 and 4 shows concentrations of Cu (638 and 159 ppm), Cr (427 and 728 ppm), Ni (143 and 187 ppm), Pb (1043ppm) and Zn (44900 and 126100 ppm) are also above the guideline values of Cu(91 ppm), Cr (87 ppm), Ni (50 ppm), Pb (600 ppm) and Zn (360 ppm) respectively.

According to these results, waste rock dump 1 is polluted with Cr, Ni, Pb and Zn. Similarly waste rock dump 2 is also contaminated with Cr, Ni and Zn, whereas waste rock dump 3 and 4 are polluted with Cu, Cr, Ni, Pb and Zn. The results indicate the waste rock dumps at Edendale mine did not show pollution from As, Ba, Se, U and V since they fall below the guideline levels.

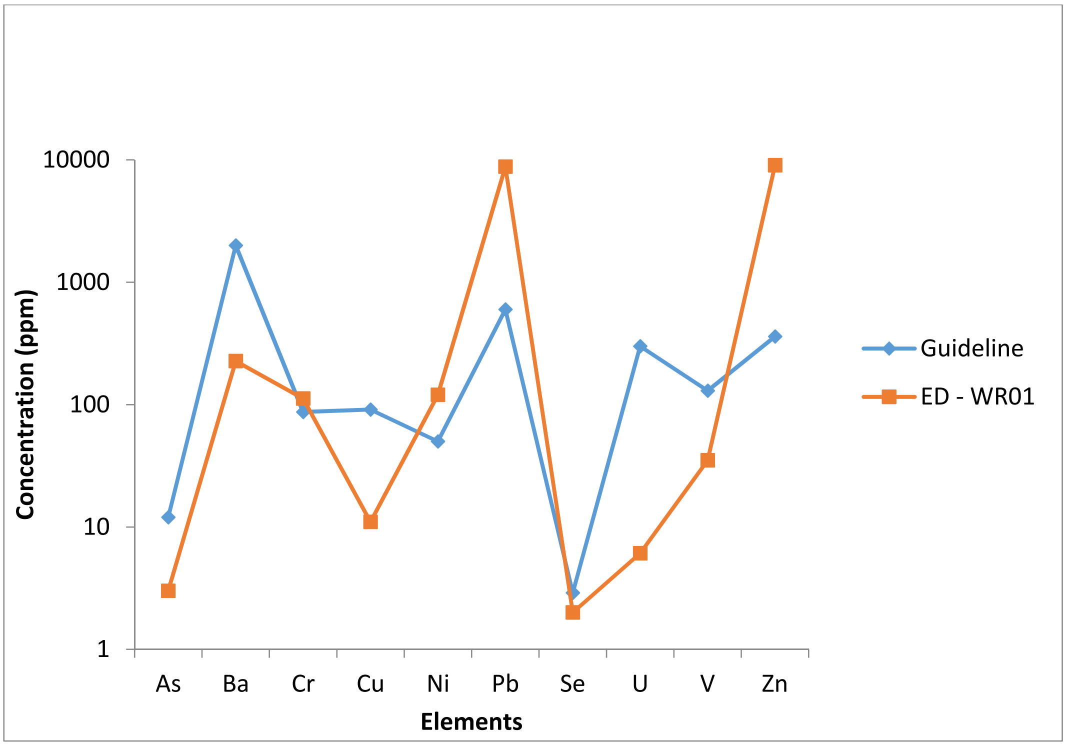

Figure 2 Comparison of XRF results and guideline concentrations for waste rock dump 1

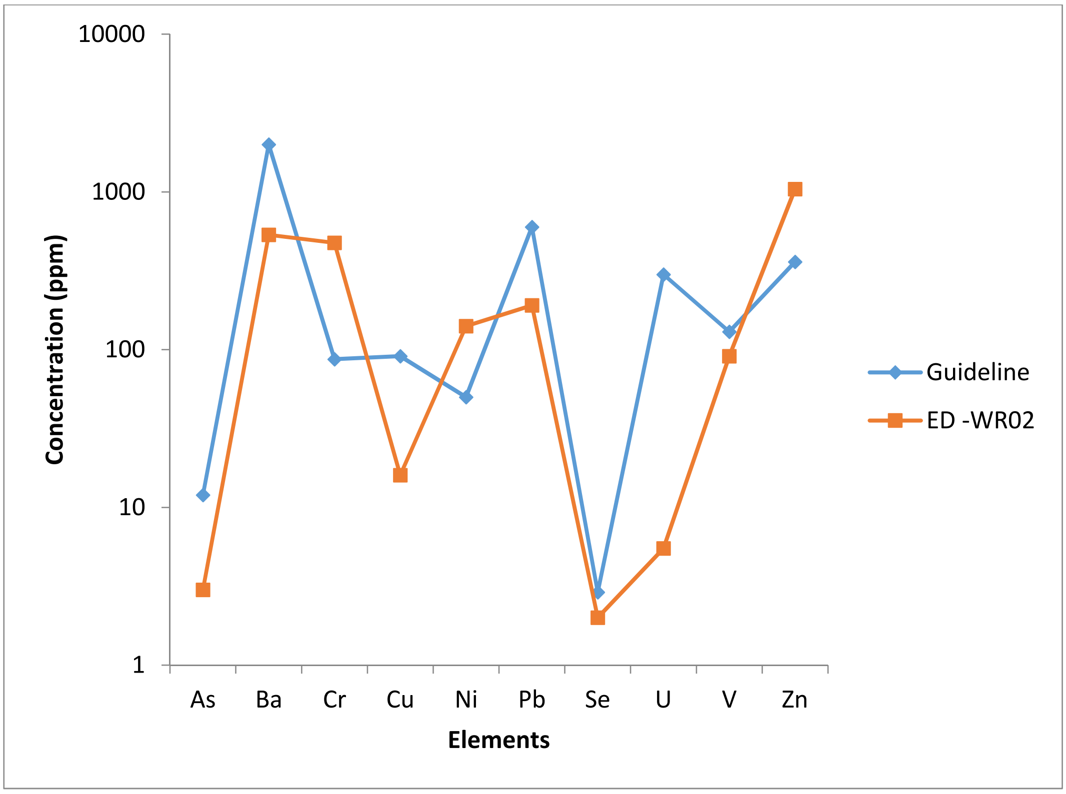

Figure 3 Comparison of XRF results and guideline concentrations for waste rock dump 2

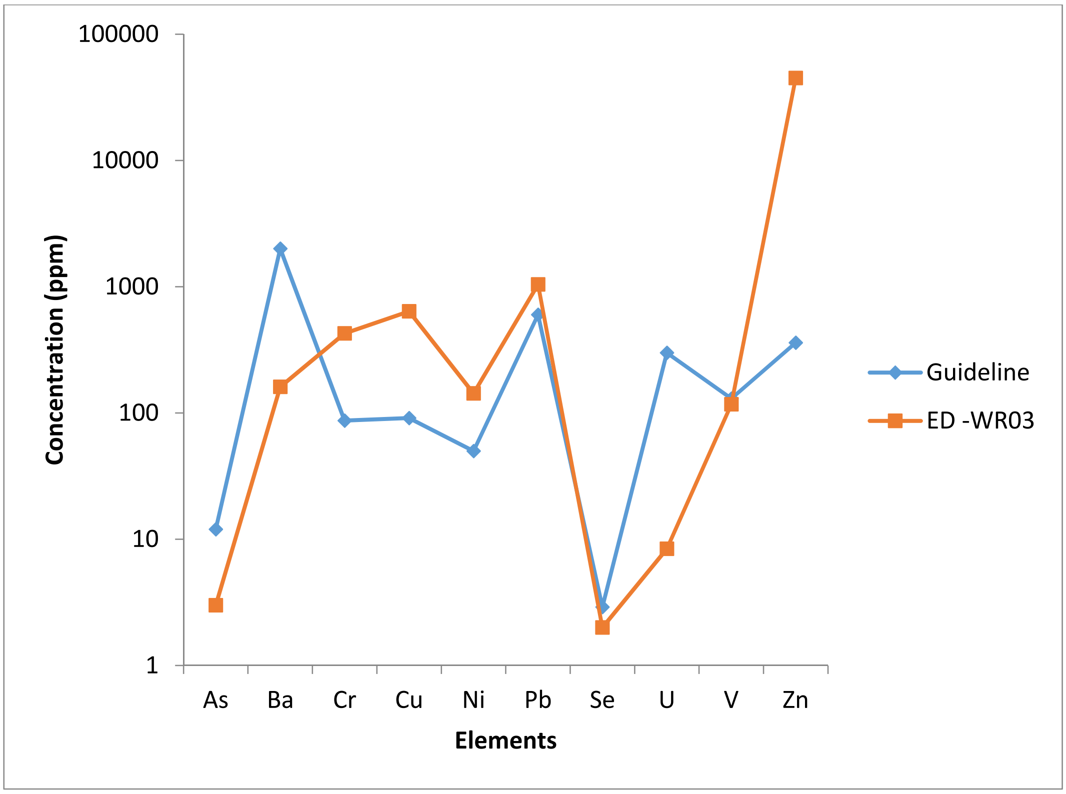

Figure 4 Comparison of XRF results and guideline concentrations for waste rock dump 3

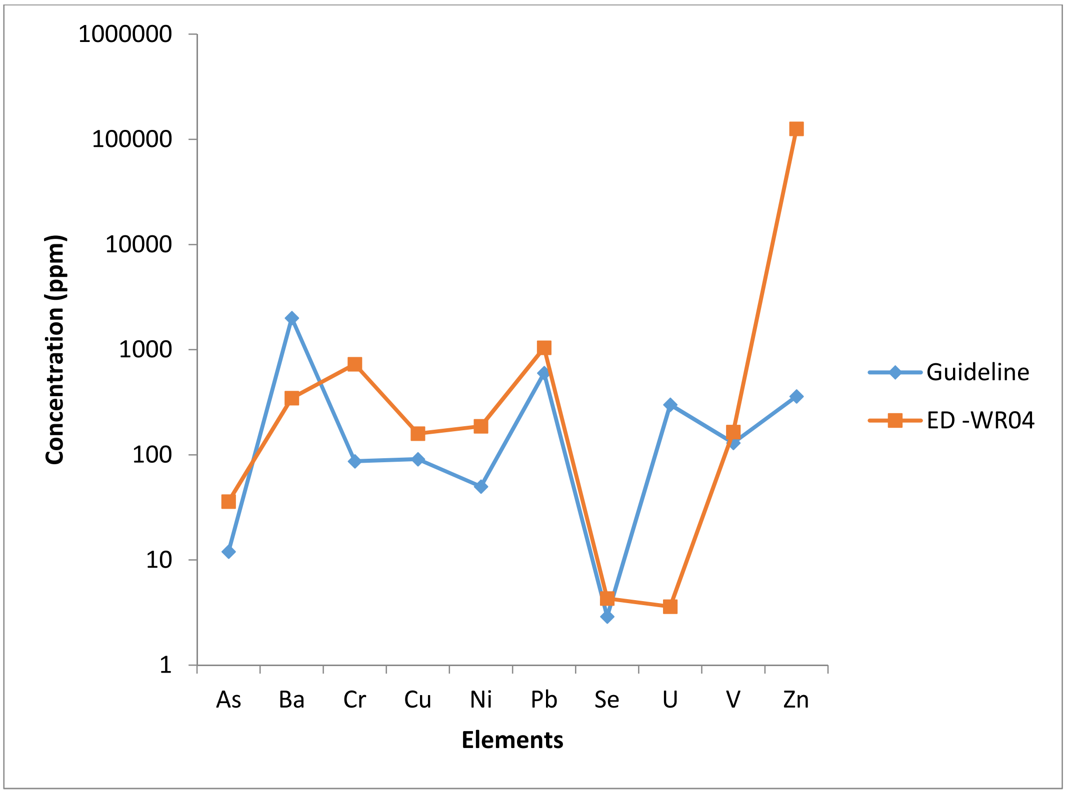

Figure 5 Comparison of XRF results and guideline concentrations for waste rock dump 4

3.2 X ray diffraction (XRD) analysis

All the waste rock dumps are dominated by quartz except the waste rock dump 4 which is dominated by sphalerite (Table 2 and figure 6). The second dominant mineral in the dumps is chlorite. The other minerals that represent small quantities of the dumps are calcite, dolomite, mica, talc and zinckenite. Traces of goethite (Haematite) are present in waste rock dump 4.

Table 2 Mineralogical distribution in waste rocks 1-4

Sample	Calcite	Calcite (magnesium)	Dolomite	Goethite (Haematite)	Quartz	Chloride	Mica	Sphalerite	Talc (Pyrophyllite)	Zinckenite
ED –WR 1	2	3	9	-	59	13	5	5	-	5
ED –WR 2	6	-	-	-	50	26	15	-	3	-
ED –WR 3	4	12	3	-	43	25	2	9	-	3
ED –WR 4	-	-	-	tc	21	13	tc	63	-	-

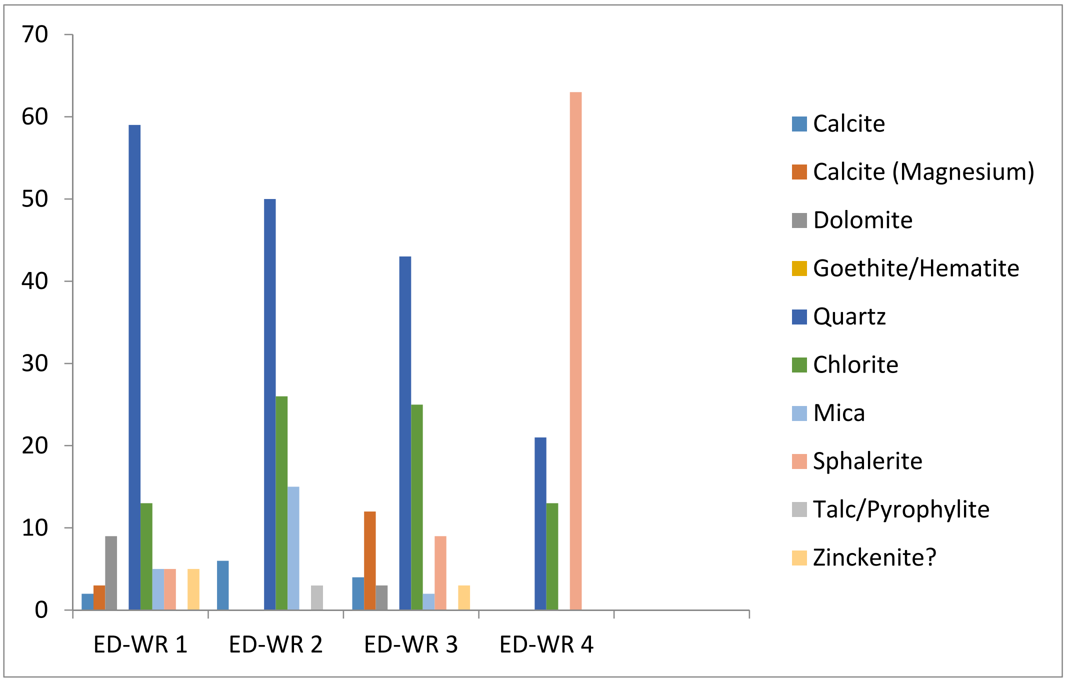

Figure 6 Mineralogical distribution for waste rock dump 1-4

According to (Kgwakgwe 2001), galena, sphalerite and chalcopyrite were found at the old shaft of the Edendale mine. The results of this study are in agreement with Kgwakgwe (2001). The XRD results indicated that waste rocks at Edendale mine are comprised of quartz, sphalerite, mica, chlorite and calcite. This is consistent with studies by (Glass 2006). According to (Glass 2006) the waste rock material of the Edendale contains quartz, mica (muscovite), chlorite and some cerrusite and calcite.

The XRF results were compared with the XRD results in order to determine the main sources of potential toxic elements. In this context the high concentrations of Ni, Pb, Zn and Cu in waste rock dump, could be explained by the presence of chlorite, zinckenite, and sphalerite respectively. However, the high concentrations of chromium in waste rock dumps 1, 2, 3 and 4 together with copper in waste rock dump 3 and 4 need further investigations.

3.3 Paste pH and electrical conductivity of the waste rocks

The paste pH value indicates whether the material contains readily available acidity or alkalinity. The paste pH of the waste rocks is close to neutral to slightly and moderately alkaline. It ranges from 6.92 to 8.85 (Table 3). There must be the presence of reactive carbonates in WR01, WR02 and WR03, since their paste pH values are greater than 7 (Lawrence and Marchant, 1991). This can be explained by the presence of calcite and dolomite in the waste rock dumps.

Conductivity indicates the presence of contaminant salts in the soil. High conductivity levels show that there is a considerable storage of salt, usually sulphates. The paste electrical conductivity (EC) of the waste rock material ranges from 175 – 890 µs/cm. The highest paste EC is observed in ED – WR01 and the lowest paste EC is recorded in ED – WR02.

Table 3 Paste pH and electrical conductivity for waste rocks 1-4

Sample ID	Paste pH	Paste EC (µs/cm)
ED – WR01	7.87	890
ED – WR02	8.85	175
ED – WR03	8.19	324
ED – WR04	6.92	501

3.4 Batch leach test analysis

All the leachates samples were analysed for Al, As, Zn, Pb, Cr and Se using ICP –MS Elan 9000. The leachate from the waste rocks was compared with South African water quality guidelines for the aquatic ecosystem to determine the extent of toxic metal contamination. Toxic metals occur naturally, however activities such as mining result in relatively higher concentrations than those that would occur naturally. High concentrations for toxic metals have detrimental consequences for both humans and animals and can lead to several diseases. (UNEP 2008)The leachate concentrations of different toxic metals were plotted together with the water quality guidelines showing the target water quality range (TWQR), chronic effect values (CEV) and acute effect values (AEV) (Figures 7 and 8).

The target water quality range refers to the concentration levels within which no measurable adverse effects are likely to occur on the health of the aquatic species and assumes long aquatic life exposure. The chronic effect value is the concentration level of a constituent at which measurable chronic effects of up to 5% are expected in the aquatic community and if these effects persist for some time they can lead to mortality of sensitive aquatic species. The acute effect value is the concentration level of a constituent at which significant probability of acute toxic effects of up to 5% is expected in the aquatic ecosystem (DWAF 1996).

The results indicate that the leachate is highly polluted with aluminium (Figure 7) which is 0.92 mg/L, 1.3 mg/L, 0.9 mg/L and 0.9 mg/L in waste rock dump 1, 2, 3 and 4 respectively. These concentrations are extremely higher than the TWQR (0.005 mg/L, CEV (0.01 mg/L) and AEV (0.1 mg/L) in all the samples. Zinc (0.003 mg/L) is slightly higher than the target water quality range (0.002 mg/L), but below the chronic effect value (0.004 mg/L) in ED – WR01 and ED – WR02 samples. High zinc (Figure 8) leachate concentrations (0.12 and 7.4 mg/L) are observed in ED – WR03 and ED – WR04 which are even higher than the chronic (0.004 mg/L) and acute (0.04 mg/L) effect values. There will not be any measurable health effects on the aquatic life due to selenium (0.0005 mg/L) and arsenic (0.0002), because the leachate concentrations for these elements are below the target water quality range of 0.02 mg/L (Se) and 0.01 mg/L (As) respectively.

The aquatic ecosystem guideline values for chromium depend on the type of chromium compound, whether is Cr (III) or Cr (IV) (DWAF, 1996). According to the results the leachate concentration for chromium is below 0.59 µg/L in all the samples and is less than the target water quality ranges for both Cr (III) and Cr (IV) values of 12 and 7 µg/L respectively. Therefore there will be no health effects of chromium on the aquatic life from the chromium leachate. The guideline values for copper and lead depends on the hardness of the water with the guideline values increasing with the hardness of the water for the target water quality range, chronic and acute effect values. The leachate concentration for copper was less than 0.3 µg/L in all the samples which is below the target water quality range (0.3 µg/L , 0.8 µg/L, 1.2 µg/L and 1.4 µg/L) for soft, medium, hard and very hard water respectively.

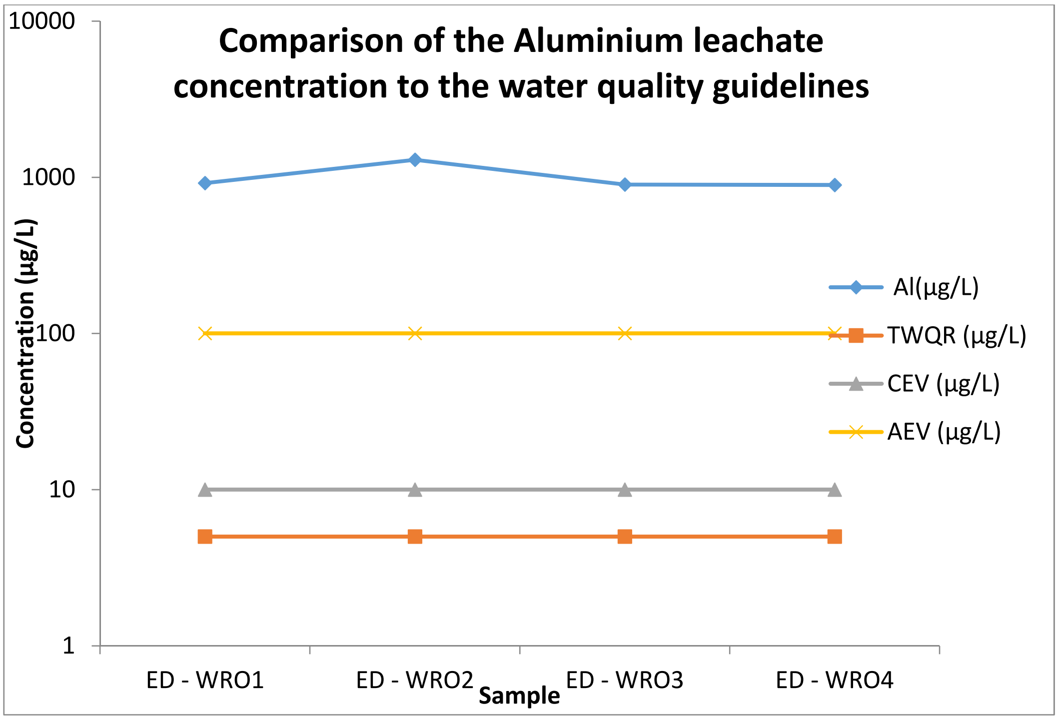

Figure 7 Comparison of concentrations of aluminium leachate with water quality guidelines. Note TWQR (5 µg/L); CEV(10 µg/L) and AEV (100 µg/L)

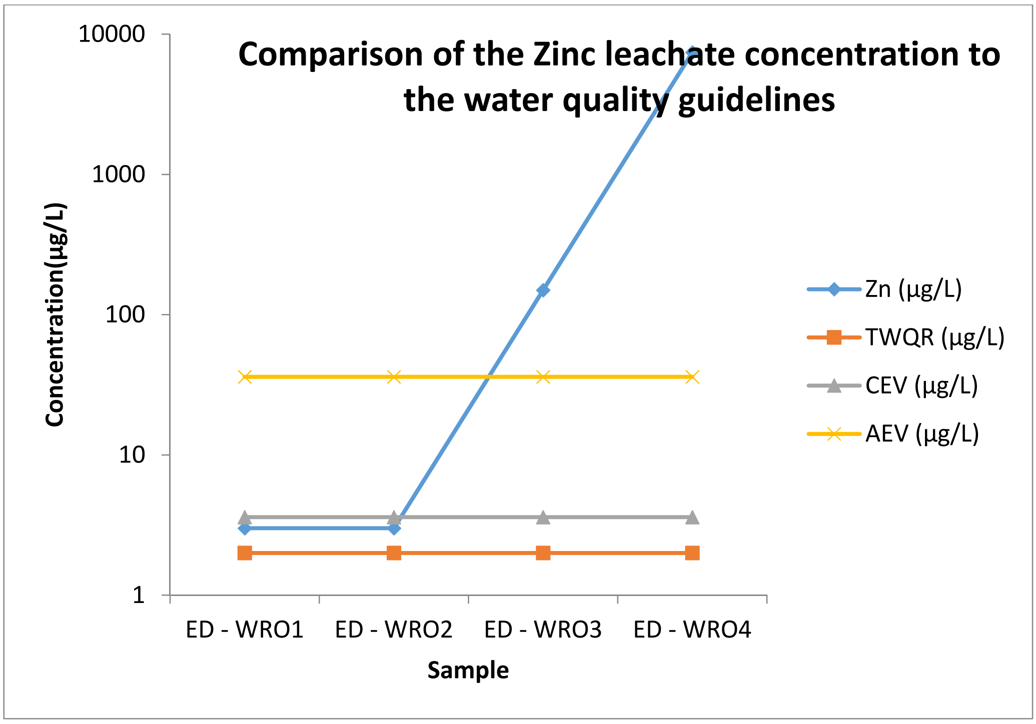

Figure 8 Comparison of concentrations of zinc with water quality guidelines. Note TWQR (2 µg/L); CEV (3.6µg/L) and AEV (36µg/L)

The leachate lead concentration (14.6 µg/L) in ED –WR01 was above the target water quality range 0.2 µg/L (soft water) ,0.5 µg/L (medium water) ,1.0 µg/L (hard water) and 1.2 µg/L (very hard water) and the chronic effect values (0.5 µg/L, 1.0 µg/L,2.0 µg/L and 2.4 µg/L) for all the water types. It is however below the acute effect value of 16 µg/L for the very hard water. The leachate lead concentration (4.10 µg/L) for the ED – WR02 was higher than the target water quality range 0.2 µg/L (soft water), 0.5 µg/L (medium water), 1.0 µg/L (hard water) and 1.2 µg/L (very hard water), chronic effect values 0.5 µg/L (soft water), 1.0 µg/L (medium water), 2.0 µg/L (hard water) and 2.4 µg/L(very hard water) and the acute effect value of 4.0 µg/L for the soft water type. The results indicate very high lead leachate concentration in ED – WR03 (86.05 µg/L) and ED – WR 04 (249.63 µg/L) which is extremely higher than the target water quality range, chronic and acute effect values for all the water types. In general, the lead leachate concentration of all the four samples is above the target water quality range which indicates pollution in the leachate.

3.5 Paste pH, EC and alkalinity of the leachates

The leachate pH was higher than the paste pH for the ED – WR01, ED –WR02 and ED –WR03. In ED- WR04, the paste pH is slightly higher than the leachate pH. The leachate conductivity was less than the paste conductivity in all the samples.

Alkalinity indicates the capacity of a system to buffer against the impacts of acid. Alkaline compounds such as carbonates reduce the acidity by increasing the pH. The results indicate that high alkalinity is linked to a higher pH in ED –WR02 leachate sample, whereas ED – WR04 leachate contain less alkalinity and lower pH (Table 4).

Table 4 Electrical conductivity and pH of leachates

Sample ID	pH	EC (µs/cm)	Alkalinity (mg/L CaCO3)
ED – WR01	8.46	108.8	20.86
ED – WR02	9.04	45.80	45.25
ED – WR03	8.57	61.50	17.10
ED – WR04	6.69	61.80	8.78

3.6 Ion Chromatography analysis

Ion chromatography was used to determine concentrations of anions such as fluoride, chloride, nitrite, nitrate, phosphate and sulphate. The target water quality range for fluoride is 0.075 mg/L (DWAF 1996). The results indicate that the leachate for the ED- WR04 (1.15 mg/L) was above the target value while the fluoride leachate concentration for ED-WR01, ED-WR02 and ED-WR03 was below the target water quality range.

Nitrite and nitrates are the major components of inorganic nitrogen. Nitrite is the intermediate inorganic nitrogen, whereas nitrate is the end product of the oxidation of nitrogen and ammonia and it is more stable and abundant in the aquatic environment. The two nitrogen compounds are usually measured and considered together due to their co - occurrence. These two compounds have stimulatory effect on plant growth and algae (DWAF 1996) All the samples have inorganic nitrogen concentrations below 0.5 mg/L for both nitrite and nitrate which is considered to be sufficiently low to limit eutrophication (DWAF 1996)

Sulphate is a typical constituent found in water and results from dissolution of mineral sulphates and it forms salts with cations such as potassium, calcium, lead and sodium (DWAF 1996). The water quality standard adopted to protect the aquatic life for sulphate is 500 mg/L (Iowa DNR, 2009) and relevant authorities should be notified of sulphate concentrations exceeding this level (INAP, 2003). The sulphate leachate concentrations were below 500 mg/L for all the samples.

4 Conclusion and recommendations

The waste rock dumps at the Edendale mine are generally polluted with Cr, Ni, Pb and Zn and Cu. The high concentrations of Ni, Pb, Zn and Cu in waste rock dump, could be explained by the presence of chlorite, zinckenite, and sphalerite respectively. The leachate results also indicated that high aluminium, lead and zinc could be leached with water from the waste rock dumps. And as a result, there is high potential for these toxic elements to leach into the Edendalespruit and the surrounding environment.

This study recommends that a monitoring system should be conducted on the water and the stream sediments of the Edendalespruit to determine the level of contamination in the stream. The potential for phytoremediation by the grasses and/or plants growing around the Edendale mine site should also be investigated, since they have already adapted and reconditioned themselves to the surrounding pollution.

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In-Lake Technique: 10 Years of Research and Development - Cooperation between TU Bergakademie Freiberg, MOVAB-D GmbH and Industrial Partners

B Merkel *TU Bergakademie Freiberg, Germany*

G Scholz *MOVAB-D GmbH, Germany*

W Rabe *MOVAB-D GmbH, Germany*

D Clauß *MOVAB-D GmbH, Germany*

G Lilja *Movab AB, Sweden*

U Allert *BR Allerts Bulk & Miljökalkning AB, Sweden*

Abstract

Worldwide rehabilitation of acidic pit mine lakes and eutrophic rivers and reservoirs are one of the big challenges with respect to sustainable management of aquatic environments.

On the basis of existing experiences in Sweden in the past 40 years with the treatment of many thousands of acid lakes with ship-based in-lake technique, valuable findings on the application of this technique in Germany were generated with versatile basic investigations at the TU Bergakademie Freiberg and large-scale experiments.

Within the framework of this cooperation federally funded research projects such as OILL (Optimizing In-Lake Liming) and DOPSOL (Development of a P-Elimination System of Lakes) put light on the behavior of different materials for the neutralization of acidic pit mine lakes and man-made reservoirs. Furthermore, knowledge about the restoration of highly eutrophic lakes was gained. A special focus was recording and evaluation of wind induced currents in lakes by means drift bodies and the lake circulation model ELCOM (Estuary, Lake and Coastal Ocean Model).

With numerous series of batch tests, chemical and mineralogical investigations, hydraulic, thermo-dynamic and kinetical modeling and large-scale applications it was possible to prove that especially fine chalk products can play an extraordinary role in the treatment of acidic pit mine lakes in future due to their fine grain size and neutralization properties.

With the commissioning of the water treatment ship of the type BRAHE 3, a highly efficient ship technology for water treatment of contaminated lakes and reservoirs is available.

Keywords: *ship-based In-Lake technique, acidic pit mine lakes, lake circulation, ELCOM, large-scale applications, BRAHE 3*

1 Introduction

The future rehabilitation of the German Lusatian Post Lignite Mining Region is depending on solving many different tasks in the field of the treatment of acid mining drainage (AMD) (Luckner et al. 2017, Kuyumcu 2010, Zschiedrich & Benthaus 2010). The efficiency of in-lake liming of acidic pit mine lakes strongly depends on i) lake water chemistry, ii) the reactant used (CaO, calcite, dolomite), iii) the ratio surface of reactant to volume of water, iv) water temperature and v) flow of acid mine drainage (AMD) into the lake. AMD entering the lake is characterized by low pH as well as elevated SO_4, Fe, Mn, Al and CO_2 concentrations. Under oxidizing lake water conditions and circum neutral pH Fe, Mn, Al will precipitate as hydroxides. CO_2 will exsolve until concentrations of CO_2 equilibrate with atmospheric CO_2 pressure is reached. But the pH of the lake water will getting more and more acid with time and needs neutralization. All parameters have to be considered to achieve the best result at lowest costs. The quality of the used neutralizing reactant as well as the reaction conditions within the lake water, which may strongly vary with respect to time and distribution, have to be taken into account. According to the state of the art, a lime suspension has to be spread into the lake as uniformly as possible using pipelines or boats. However, this approach has to consider wind-induced flow in the lake (Merkel et al. 2016). Within the scope of extensive research activities of the TU Bergakademie Freiberg (TUBAF) in cooperation with the MOVAB-D GmbH, located in Lauta / Saxony and partners of the lime industry, a comprehensive knowledge potential based on laboratory and pilot plant work in large-scale applications was created (Clauß et al. 2010).

Based on more than 40 years of experience in Sweden in the field of lake liming using the special lime ships BRAHE constructed by the Swedish company Allerts Br., located in Skövde and comprehensive research activities at the Hydrogeology Department of TUBAF in collaboration with the German-Swedish MOVAB-D, located in Lauta, Saxonia, it was possible, to develop a unique know how for the efficient treatment of big and small acid mine lakes. The efficiency of lake liming projects is strongly depending of the cost leading factors such as lime quality (in particular grain size), available technology for the lake liming and using the wind induced currents for distribution of the lime added in the whole water body of the mine lake (König et al. 2010, Rabe et al. 2009, Pust et al. 2010, Merkel et al. 2011). The intelligent application of the in-lake technology in general and the modeling of lake water currents as well as the material selection in particular are the decisive key criteria in the generation of economically as well as ecologically acceptable rehabilitation concepts (Merkel et al. 2011). With the spatial and temporal recording of the reaction conditions in the lake body by using online monitoring and model-based prediction of lake currents it is possible to ensure optimal reaction conditions for complete material reaction (Merkel et al. 2011). This is based on data acquisition, model-based process optimization, and targeted liming techniques.

2 Overview on research and development activities

2.1 Reaction kinetics – lake currents

The economics of an in-lake project depends essentially on the consideration of the kinetic processes involved in the dissolution of a lime particle in the acidic environment of a pit mine lake. Fundamental investigations are available from Sverdrup (Sverdrup 1985) from the year 1985. Thereafter, the dissolution of a lime particle takes place always at the particle surface and depends on the ratio surface to water. For any fast reaction, diffusion through the boundary layer is the rate-limiting step. Furthermore, the concentration and activity of H^+ (pH) is important: the lower the pH the faster is the dissolution. Last but not least the grain size of the lime does not only impact the surface to water ratio but as well the sinking speed of particles according to Stokes's law. Thus the target of lake liming is always to ensure that no particle reaches the bottom of the lake. The use of internal lake currents is an indispensable prerequisite for this. ELCOM (Estuary, Lake and Coastal Ocean Model (Hodges et al. 2000) is a very powerful 3d numerical lake model and was used for simulating the distribution of added lime on the lake surface within the research project OILL (Optimizing In lake Liming).

It can be used for simulations of variations in water temperature and quality and for the prediction of time and space depending currents in lakes. Drift bodies were applied on several lakes and were in consequence used to calibrate ELCOM models (Merkel et al. 2011). Thus, it is possible to release lime in those parts of a lake from where wind induced currents will distribute the added lime over the entire lake.

Flow velocities of 100 to 300 m/h in shallow water depth of 0.5 to 4 m were induced by average wind speeds of 3.0 to 6.0 m/s. Figure 1 shows the flow regime in the upper layer of the lake body (depth: 0 – 0.5 m) during westerly wind (3 m/s) of the mining lake Scheibe. Furthermore, the model simulates also vertical currents, which are caused by the morphology of the lake bottom, but also by density convection and/or temperature differences.

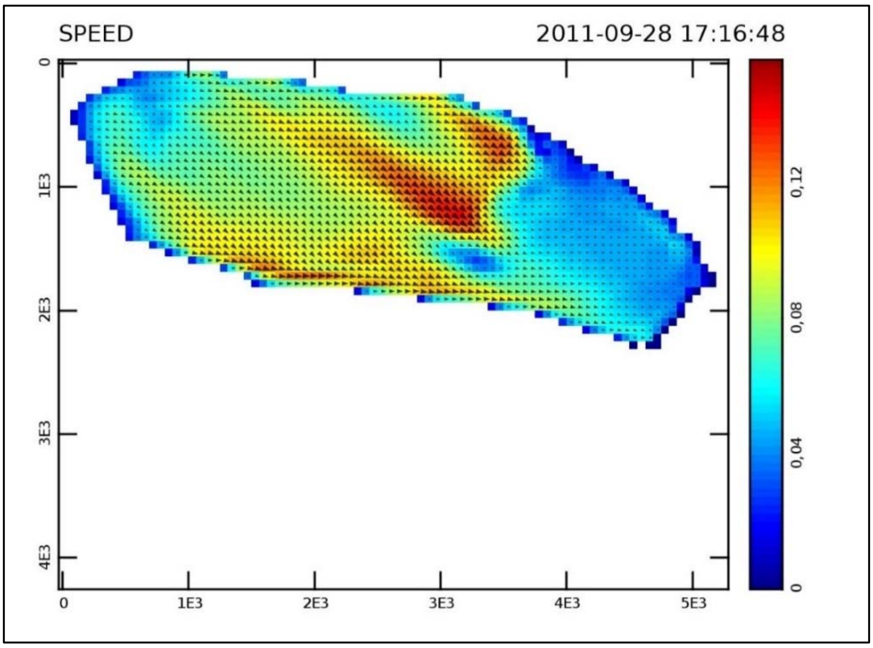

Figure 1 Modelled flow regime (m/s) in the upper layer of the lake body (water depth: 0 to 0.5 m) in the mining lake Scheibe during westerly wind (3 m/s)

Figure 2 and 3 illustrate the advantages of the intelligent use of sea currents in lake liming projects. In an open pit mine lake moderate wind speeds are sufficient to increase the reaction space for the neutralization manyfold.

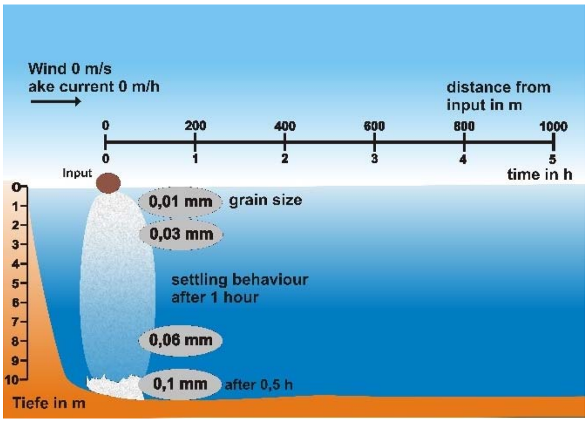

Figure 2 Distribution of calcite particles of different sizes without wind induces currents.

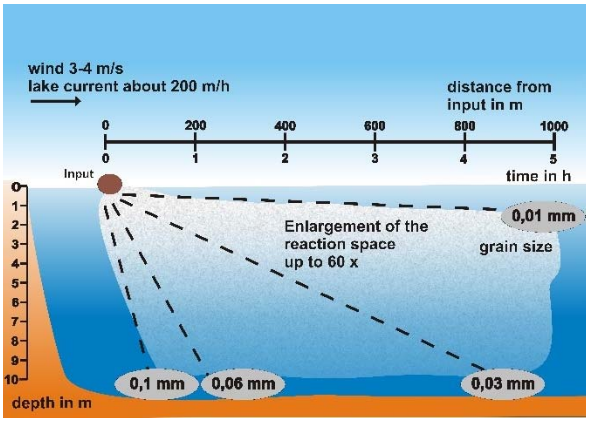

Figure 3 Distribution of calcite particles of different sizes at a wind speed of 3 to 4 m/s and a resulting lake current velocity of ca. 200 m/h

Tracking lengths of particles increase with wind induces lake currents 20 to 60 fold depending on the grain size and the associated sinking speed in comparison to periods without wind. These numbers are simulated on the assumption of spherical particles without considering dissolution. Accordingly, the simulation is a worst case scenario, because in reality the diameter of the particles will decrease with time due to dissolution. On the other side, it is too optimistic, because wind induced currents with this speed occur mainly in the upper part of the lake, while the back-flow in lower parts has a lower speed. In case of shallow water and calm or no wind there is the risk that spreading lime is not completely dissolved before sinking particles reach the lake bottom and will get imbedded in the sediments. In consequence, using ship-based in-lake spreading and wind induced currents only a part of the lake must be treated and costs of applying lime can be significantly reduced. The exact prediction of lake currents, especially in the surface area of a lake are a powerful tool for an effective application of in-lake technologies.

2.2 Lab tests

Since 2009 column experiments have been carried out at TUBAF on behalf of MOVAB-D GmbH in cooperation with the lime industry to optimize the process design / optimization of in-lake projects (figure 4) because the selection of a suitable lime product with a proper grain size is of significant relevance. Series of batch experiments at TUBAF proved that chalk can create a buffer against re-acidification of a treated pit mine lake.

By means of several laboratory experiments different lime products were tested with respect to efficiency and reactivity. Such experiments were performed with original water from the respective pit lake like, because even trace elements may have an inhibiting impact on the solubility kinetics of different products. Only based on these experiments and including the optimized ship application technique, a cost-benefit study can be performed providing the best result for a certain pit lake. Depending on temperature and water composition a buffer capacity of up to 1.5 mmol/l can be obtained by applying chalk. The advantage of chalk products lies in the small particle diameter (mean grain diameter <2 µm) of the individual particles and in the large interior surfaces. Both parameters ensure that these particles stay extremely long in the near-surface water layer and react with acidic groundwater. Results regarding this advantage by using chalk lime have already been proven in previous in-lake projects: In May 2011 the pH of the lake Jahnteich (6 hectar), located next to the town of Weißwasser was increased from pH 4.3 to approx. 7.5 and the buffer capacity was significantly improved during a 3-hour treatment with a fine-grained chalk product (Tab. 1).

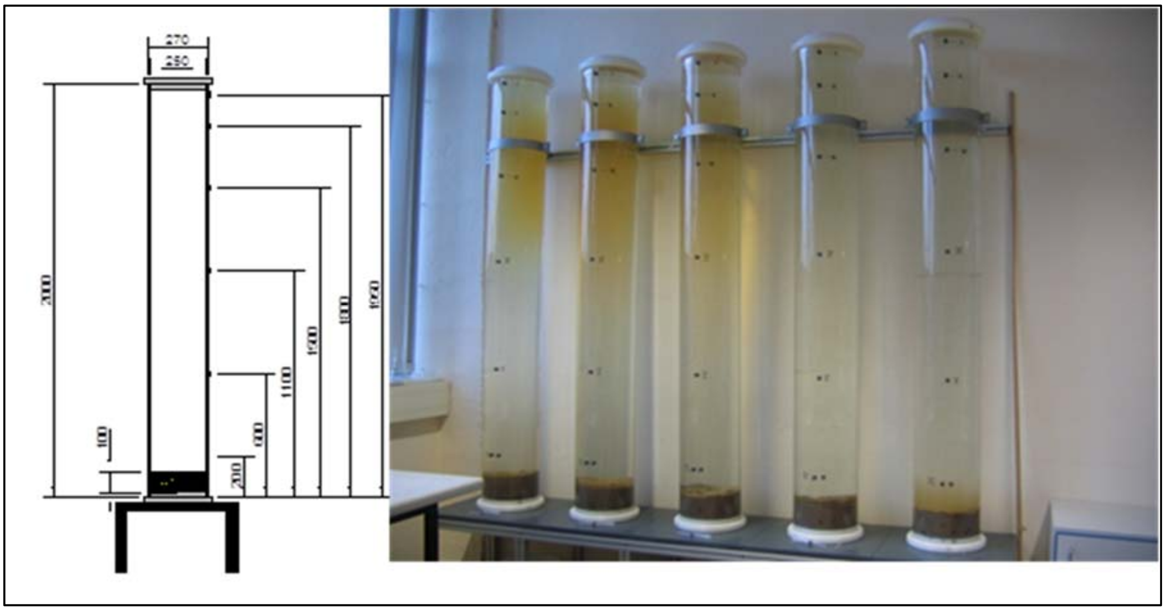

Figure 4 Lab-tests (column experiments) at TUBAF

Table 1 Selected results of the initial neutralization (05/11/2011) of lake Jahnteich, Weißwasser Germany

Sampling date	pH	$K_{S4,3}$	$K_{B8,2}$	Fe	Ca	TIC
dimension		mmol/l	mmol/l	mg/l	mg/l	mg/l
10.05.2011	4.8	0.07	0.45	0.13	46.1	1.6
12.05.2011	7.5	0.4	0.1	0.03	54	5.3
01.06.2011	6.7	0.45	0.17	-	60	-
21.10.2011	6.8	0.81	0.19	1.2	37	10

2.3 Multi-Parameter-Probe

Important equipment for the control of lake liming projects is a multi-parameter-probe to control temperature, electric conductivity, turbidity pH and eH (or oxygen) at different depths and various locations of the water body. In the ideal case multi parameter probes are installed as network at several locations, which radio-transmit data over time. This allows both to optimize spreading of lime during an in-lake liming activity and to find an appropriate time for the next treatment.

By follow up the movement of each lime cloud in the lake it is possible to avoid over-treating parts of the lake and using the shortest way for charging the lime ship at different charging points by using the flexible mobile BRAHE ship equipment. Figure 5 shows the behaviour of a lime cloud over time.

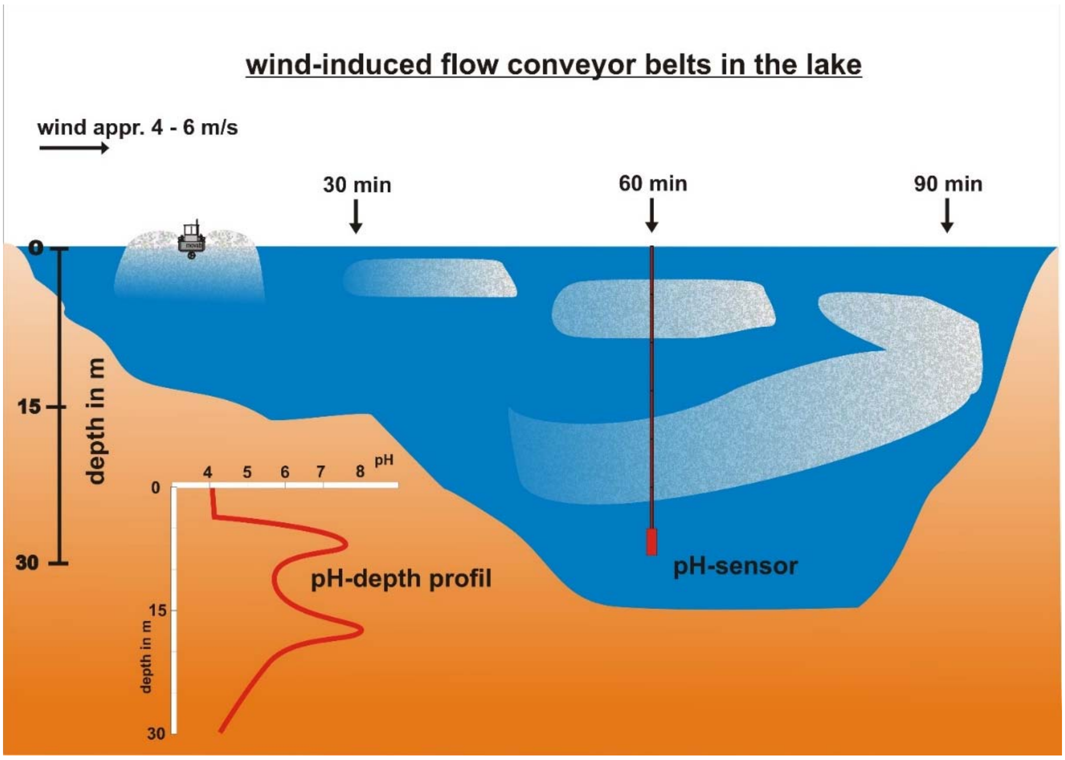

Figure 5 Behaviour of a lime cloud during the neutralizing process in a lake

2.4 Ship-technique

For the efficiency of each in-lake liming project the performance of the ship used is decisive. Within the framework of scientific work in the field of in-lake liming by TUBAF the BRAHE-ship equipment was investigated in detail. The most important advantage of this lake liming ship is the extraordinary flexibility regarding entering of lakes and embankments. Furthermore, this ship has the ability of spreading lime sludge with different content of different lime qualities both above and under the surface of a lake. However, each lake liming project needs a separate approach in order to reach the best result. Figure 6 shows the difference between distribution above and under the lake surface.

Because warm water contains less CO_2 as well the solubility of lime is less. Therefore, a certain part of the applied lime may stay as cloud of very fine grain sized particles as a kind if “physical buffer” which dissolves over time when acid water enters the pit like. Figure 7 and figure 8 shows this effect impressive during in-lake treatment at the lake Tröbitz in April 2016 by using fine chalk lime.

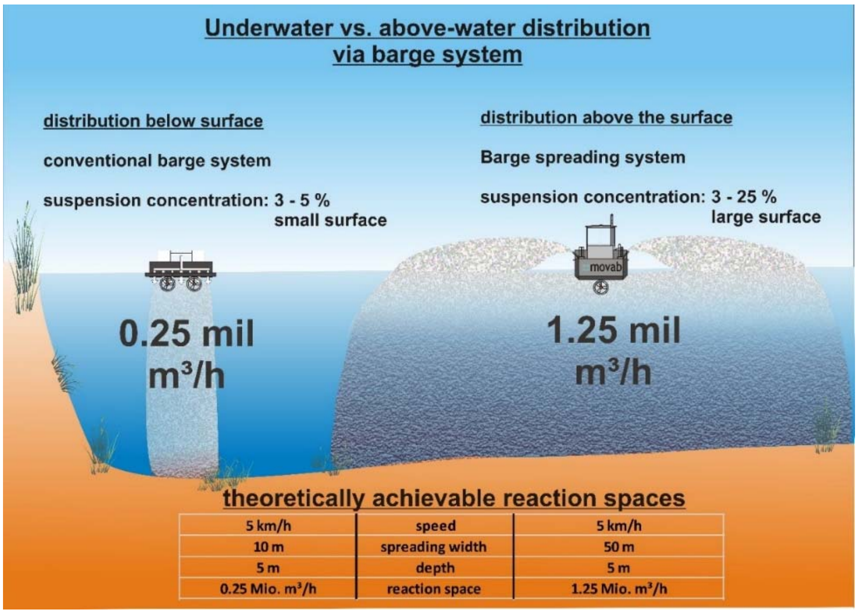

Figure 6 **Comparison of distribution above versus below surface**

Figure 7 **Aerial photo showing the distribution of chalk lime above the surface, lake Tröbitz 08.04. 2016**

Figure 8 **Arial photo showing chalk clouds in the water body of lake Tröbitz, 08.04.2016**

On the basis of the experience in lake liming gathered with lime vessels in Sweden and Germany in recent years, the company Allerts Br. Skövde; Sweden developed and built another powerful ship of the type BRAHE. With the commissioning of the lime ship (BRAHE 3) in March 2017 at the acid mine lake Burghammer, Germany, a high performance ship is available, which is able to spread up to 250 t/day (CaO, $CaCO_3$, $CaMg(CO_3)_2$). The particular advantages of the BRAHE ship technology are the ability to produce on board a water-lime suspension using lake water with a solid concentration of 3 - 20%, which is spread up to 50 m wide above the lake surface or up to 10 m wide below the lake surface. With the special trailer technology for launching and bringing ashore the lime ship without a crane or a ramp further advantages are associated (figure 9). By choosing an appropriate location on the lake´s shore and loading the ship via pneumatics of a silo vehicle with a hose length up to 80 m any kind of lime product can be efficiently distributed without empty running's. For example, with the use of two BRAHE ships and the available know-how it is possible to spread up to 500 t of lime at just one day.

Figure 10 and 11 show the use of BRAHE ship technology in North Sweden. In addition to solid materials, liquid substances can also be used for lake treatment: Figure 12 show the use of BARHE ship technology spreading liquid aluminum sulfate at the artificial reservoir Quitzdorf to combat eutrophication (P-eduction). Figure 13 demonstrated the use of the BRAHE-ship technology at the framework of the RD project DOPSOL

(Development of a P-Elimination System of Lakes) at the artificial reservoir Quitzdorf for the investigation of P-binding effect of FerroSorb to combat algae bloom and cyanobacteria.

Figure 9 Mobile charging point at the lake Tröbitz, 2016

Figure 10 Aerial photo showing the distribution of lime above the surface, AMD treatment, North Sweden

Figure 11 In-lake treatment with 2 ships, distribution above the surface, Sweden

Figure 12 In-lake treatment with liquid AL_2SO_4 in the Quitzdorf reservoir (P-precipitation)

Figure 13 In-lake treatment with a dry iron product at the artificial reservoir Quitzdorf

3 Summary

Utilization of pit lakes in particular for tourism and recreation activities depends on maintaining a good water quality in the long term at affordable costs. As long as AMD drainage cannot be stopped continuous admixing of fresh surface water and/or continuous in-lake treatment is obligatory to maintain neutral pH in these kinds of lakes. In-lake treatment with the flexible BRAHE ship technology using fine grained chalk and wind induced currents as well as profound knowledge and monitoring of water chemistry of the lake with respect to space and time is probably the most economic technology at the time being.

Acknowledgement

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The Geochemistry of Soil and Water Using Drone based Hyperspectral Analysis

J Robinson *SLR Consulting Limited, UK*

P Kingham *SLR Consulting Limited, UK*

S Flagel *SLR Consulting Limited, UK*

A Iwanoczko *Harris Geospatial Solutions UK Limited, UK*

A Adams Satelytics Inc, US

J Martin Satelytics Inc, US

Abstract

Geochemical analysis through field samples and laboratory testing is a well-trodden method to understanding the composition of environmental media. The limitation of this approach is in the spatial extrapolation of these diagnostic point-location samples. Over large areas such as mine sites, sampling can be labour intensive and present potential Health, Safety and Enviromental protection issues relating to the sampling team's activity in very old mine sites. Hyperspectral image analysis has been shown to identify an object's spectral composition and discretise it from its surroundings. SLR, Harris Geospatial Solutions UK Ltd (Harris Geospatial)) and Satelytics (US) have, in collaboration, been developing a methodology to assess the chemistry of soil and water using mounted hyperspectral sensors and combine these to provide greater accuracy and precision insights across sites with known contamination. The use of UAV-mounted Visible Near Infrared (VNIR) and Short-Wave Infrared (SWIR) sensors aims to deliver superior spatial and spectral resolution outcomes, compared to multispectral satellite or manned fixed-wing airborne hyperspectral acquisitions. Through the use of case studies in Ireland and the US, the team will demonstrate the application of hyperspectral analysis and also provide insight into the potential problems associated with the technique and how these may be overcome. The case studies will demonstrate real data which has been successfully correlated with ground based analysis to such an extent that large areas can be surveyed. Preliminary studies compared RBG data with hyperspectral data to demonstrate the difference which can be seen beyond the naked eye. In addition, interpretation of the data provided an initial assessment of elements which might be present in the waste rock and tailings, subject to the ground truth observations. The studies have shown that the use of drone based hyperspectral sensors show an excellent potential for the surveying of areas such as those exposed to a legacy of mining. The surveys provide benefits in supporting soil and water geochemical investigation at active and historic mining sites both in data acquisition and also survey coverage.

Keywords: *geochemistry, hyperspectral analysis, UAV, mine closure, contamination*

1 Introduction

The assessment of mining sites using geochemical and hydrochemical assessment is well established and can involve a variety of different analytical techniques. Similarly the use of multispectral and hyperspectral analysis of soil/rock has been undertaken over a number of years through the use of satellite and fixed wing aircraft to aid mineral exploration (e.g. Cudahy et al. 2001; McConachy et al.2007; Rajakumar et al. 2009) and in the interpretation of dominant geochemical regimes such as acidic and metalliferous mine drainage (e.g. Zabic et al.2014) and Quental et al. 2013) and land contamination issues (e.g. Maya, 2014). It is a passive non-intrusive analytical technique that can reveal alteration patterns that cannot be seen by the human eye. SLR Consulting Limited (SLR) examined the information relating to the area of multi spectral and hyperspectral analysis and concluded that the use of drone technology could be a viable alternative when investigating mining sites. In particular it was seen as a useful method for assessing old and abandoned mine sites where acidic mine drainage is present. Furthermore, time variant studies were seen as a valuable addition to existing mine closure monitoring schemes. It is not the purpose of this paper to review the existing techniques for aerial hyperspectral analysis of soil and water, but rather to present the value-added application of using drone technology in the identification and monitoring of contaminated mine sites. This includes:

- Development of the approach;
- Brief presentation of VNIR and SWIR technology and its use;
- Typical issues with using aerial assessment tools;
- Presentation of preliminary studies in the Ireland and US which demonstrate successful use of the technology and value-added application; and
- Next stages of assessment.

There were two main hypotheses tested in the study. These involved considering hyperspectral surveys of areas where:

- the formation of minerals associated with pyrite oxidation such as those shown in Figure 1 below are dominant. This presents opportunities to understand wider scale geochemical environments at areas of the mine; and
- non-sulfidic mine areas such as lead zinc mines in carbonate host rock.

The objective has been to establish if the combined hyperspectral sensor and drone platform survey approach can integrate the geochemistry successfully such that informed decisions regarding long termed sampling, monitoring and management plans can be put in place.

2 Geochemistry

Recent studies have shown that by understanding certain mineral assemblages using the hyperspectral analysis, the likely dominant geochemical environment controlling the solubility of the metals can be theorized. This is exemplified below where other authors have successfully used hyperspectral imaging to understand the geochemical environment. In particular, the review of such hyperspectral imaging demonstrates how identification of the different iron mineral assemblages may provide an indication of acidity generation in an area which has implications. Zabic et al (2014) presented predicted pH maps for mining impacted areas based on the iron mineral assemblage which showed a strong correlation to the measured soil pH. The second consideration was those mine sites typically not involving sulfide ores such as lead zinc ores in carbonate host rocks. In Ireland it was possible for the authors to assess preliminary metalloid concentrations in tailings and these results are presented in Figure 3 below. This included consideration of a range of lead and zinc minerals, some of which are described in Table 1 below.

In addition, the risk posed from metalloids such as arsenic can be more fully appreciated by understanding its spatial distribution in the soil over a wider area, compared to traditional soils sampling and interpolation alone An example of this is presented below. A review of the Table 1 and literature shows:

- There are a number of lead and zinc compounds which might be present at such mine sites
- Some of these may not be visible with the naked eye but may exhibit diagnostic spectral reflectance characteristics in certain abundances
- Knowledge of the likely dominant metal form from the local geology and potential weathering assemblage is very important as it refines the mineral which might be present form a potential huge list
- A number of the reflectance spectra overlap and emphasizing the importance of ground truth observations to accurately correlate and decorrelate the surveys with relevant geochemical analysis (XRD, XRF etc)

Notwithstanding the above, it is anticipated that a UAV-mounted hyperspectral survey can, depending on the mine site in question:

- Aid the understanding of the metal concentration across mine site areas;
- Provide information concerning the dominant geochemical environment; and
- Consequently enhanced interpretation of the risk posed by the metal presence can be theorized and applied though a source-pathway-target relationship.

The additional benefits are that the proposed acquisition technique can cover larger areas of the mine sites; enable access to areas which might otherwise be considered too hazardous to foot/vehicle access by the ground-based sampling teams; and allow for the identification of areas of greatest contaminant concentration, therefore providing more accurate characterisations of the survey areas than through random field sampling and interpolation alone.

Table 1 Zinc Minerals with Associated Spectral Reflectance (after McConachy et al. 2007)

Name	Formula	Colour	Spectral Reflectance
Common Minerals			
Smithsonite	$ZnCO_3$	White	Red peak, broad depression at 800-1200nm
Hydrozincite	$Zn_5(CO_3)_2(OH)_6$	White, grey, yellow	Peak at 600nm
Cerusite	$PbCO_3$	White	Peak at 800nm
Name	**Formula**	**Colour**	**Spectral Reflectance**
Rare Minerals			
Adamite	$Zn_2(AsO_4)(OH)$	Clear – yellow if iron present	Peak at 650nm (red)
Linarite	$PbCu(SO_4)(OH)_2$	Azure blue	Sharp peak at 450nm(blue); broad depression at 550-1050nm
Zinc melanterite	$(Zn,Cu,Fe)SO_4.7H_2O$	Yellow green	Peak at 515nm; broad depression at 700-1100 nm with minimum at 790 nm.
Tsumehite	$Pb_2Cu(PO_4)(SO_4)(OH)$	Green	Peak at 580nm (green)

3 Hyperspectral Imaging

Hyperspectral sensors collect hundreds of contiguous bands of reflected and emitted energy. Unique signatures or finger prints are created by the collected wavelengths where the reflectance is related to the composition of different materials in the ground. In the case of mine sites, the molecular structure of a minerals' surface generates the distribution of its reflectance and associated absorption; the resulting spectral signature serves as a unique fingerprint in the identification its composition (Headwall, 2016).

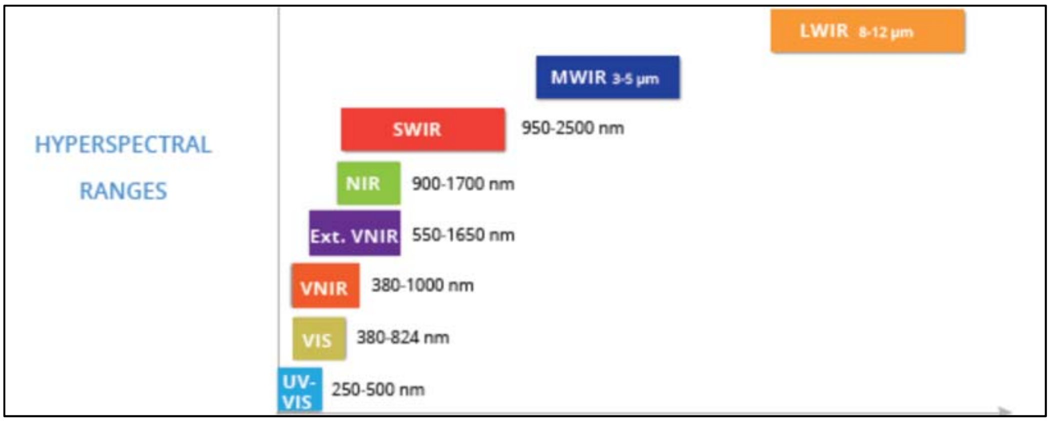

Figure 1 Hyperspectral Ranges Source: 'Airborne Hyperspectral and Ground Truth Technologies' (Headwall, 2016)

The infrared region of light is considered a good mineral detection wavelength range because of the associated wide range of minerals that can be identified. The infrared extends from (as shown in Table 2 above):

- the visible and near-infrared (VNIR, 0.4- 1µm),
- through the short-wave infrared (SWIR, 1-2.5µm), and
- mid-wave infrared (MWIR, 3-5µm) to the long-wave infrared (LWIR, 7-13µm)

The value of each infrared wavelength range to any application is determined by its detection capabilities of the targeted minerals. Electronic and vibrational ('exciting' of the elements) processes associated with bonded elements within minerals cause characteristic wavelengths in the infrared ranges, which enable identification of mineral species and in certain instances mineral chemistries. This results in the ability to identify mineral composition is therefore significantly enhanced (Terracore Geo, 2017). The detection capabilities of the VNIR, SWIR and LWIR are illustrated in the summary table of mineral classification – refer to Table 2 below. These are the wavelength ranges where the most mineral detection capabilities are achieved.

Table 2 Detection Capabilities of VNIR, SWIR and LWIR for Minerals. (Source: Terracore Geo, 2017)

	Structure	Mineral Group	Example	VNIR Response	SWIR Response	LWIR Response
Silicates	Inosilicates	Amphibole	Actinolite	Non-Diagnostic	Good	Moderate
		Pyroxene	Diopside	Good	Moderate	Good
	Cyclosilicates	Tourmaline	Elbaite	Non-Diagnostic	Good	Moderate
	Nesosilicates	Garnet	Grossular	Moderate	Non-Diagnostic	Good
		Olivine	Forsterite	Good	Non-Diagnostic	Good
	Sorosilicates	Epidote	Epidote	Non-Diagnostic	Good	Moderate
	Phyllosilicates	Mica	Muscovite	Non-Diagnostic	Good	Moderate
		Chlorite	Clinochlore	Non-Diagnostic	Good	Moderate
		Clay Minerals	Illite	Non-Diagnostic	Good	Moderate
			Kaolinite	Non-Diagnostic	Good	Moderate
	Tectosilicates	Feldspar	Orthoclase	Non-Diagnostic	Non-Diagnostic	Good
			Albite	Non-Diagnostic	Non-Diagnostic	Good
		Silica	Quartz	Non-Diagnostic	Non-Diagnostic	Good
Non-Silicates	Carbonates	Calcite	Calcite	Non-Diagnostic	Moderate	Good
		Dolomite	Dolomite	Non-Diagnostic	Moderate	Good
	Hydroxides		Gibbsite	Non-Diagnostic	Good	Moderate
	Sulphates	Alunite	Alunite	Moderate	Good	Moderate
			Gypsum	Non-Diagnostic	Good	Good
	Borates		Borax	Non-Diagnostic	Moderate	Uncertain
	Halides	Chlorides	Halite	Non-Diagnostic	Uncertain	Uncertain
	Phosphates	Apatite	Apatite	Moderate	Non-Diagnostic	Good
	Hydrocarbons		Bitumen	IUncertain	Moderate	Uncertain
	Oxides	Hematite	Hematite	Good	Non-Diagnostic	Non-Diagnostic
		Spinel	Chromite	Non-Diagnostic	Non-Diagnostic	Non-Diagnostic
	Sulphides		Pyrite	Non-Diagnostic	Non-Diagnostic	Non-Diagnostic

Case Study #1: Alaska Tundra Water Bodies

On behalf of our client, SLR supported collection of hyperspectral data using airborne hyperspectral cameras and ground based spectrometers to evaluate metals concentrations in tundra water bodies in Alaska. The characteristics of the hyperspectral sensor and surveying platform acquiring the data greatly influence the amount and quality of information available within each pixel. Consideration of the required scale of assessment determines both the spatial and spectral resolution of the sensor used, and also the altitude of the platform used to conduct the survey. For regional-scale assessments i.e. over large areas, a sample spacing of 20 or 30 meters, such as that which can be acquired from Sentinel and Landsat satellite data may be adequate. However, when greater resolutions are preferred, more accurate, near-ground assessments are needed.

For the Alaska project, where some water bodies in the project area were significantly smaller than 30-meters in diameter, greater resolution was required. To achieve the project objectives, a hyperspectral camera was flown across the area, at a flight height of c.1,500 metres, by fixed-wing manned aircraft at an elevation designed to achieve 2-metre pixel resolution (sample spacing). Concurrently, a ground-based crew was deployed to collected surface water samples and spectral readings from selected tundra water bodies along the flight lines. The SLR team in Anchorage designed an innovative method for simultaneously collecting water samples and spectral data safely from the shore. The Lake Sampling Device (LSD), designed by SLR, eliminated the need to transport a boat across sensitive tundra and mitigated the risk of collecting samples from a boat in cold and windy conditions – see Figure 3. Using the water analytical results and ground based spectral data, Satalytics, SLR project team partner, developed algorithms for estimating dissolved phase metal concentrations. The algorithms were then used to process the airborne hyperspectral data and develop metal concentration maps (2-meter resolution) for hundreds of tundra water bodies across the project area.

Figure 2 Examples of Field Sampling to Support Hyperspectral Analysis

Traditional data collection methods involve sensors mounted on satellites (20-30 metre resolution) and manned aircraft (2 – 10 metre spatial: 10 – 20 nm spectral resolution). Sensors with medium to low resolution provide data adequate for regional and large-scale assessment such as the tundra water body study in Alaska. However, large pixels produce spectral signatures that represent a mixing of many independent real-world objects, each with their own inherent reflectance spectra characteristics, rendering the image unreliable for most detailed land use or other thematic classification requirements. Sub-metre resolution is preferred when more accurate ground assessment is needed. As an example, the results for iron and barium analysis are presented via the satelytics.io platform in Figures 3 and 4 below.

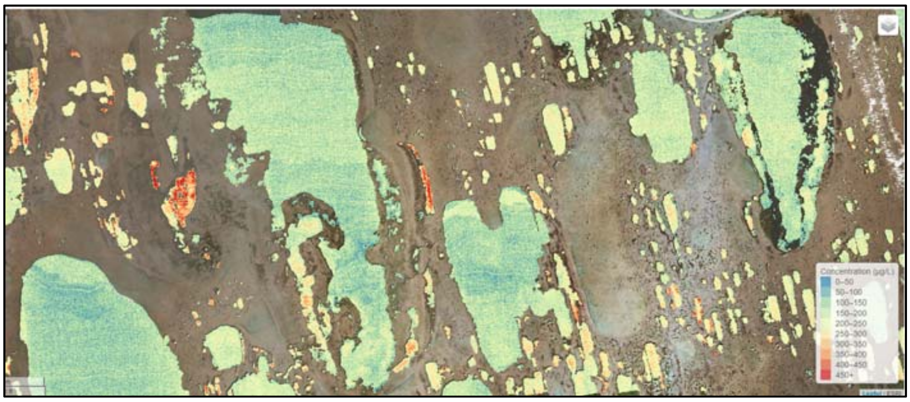

Figure 3 Barium Concentration across Survey Area.

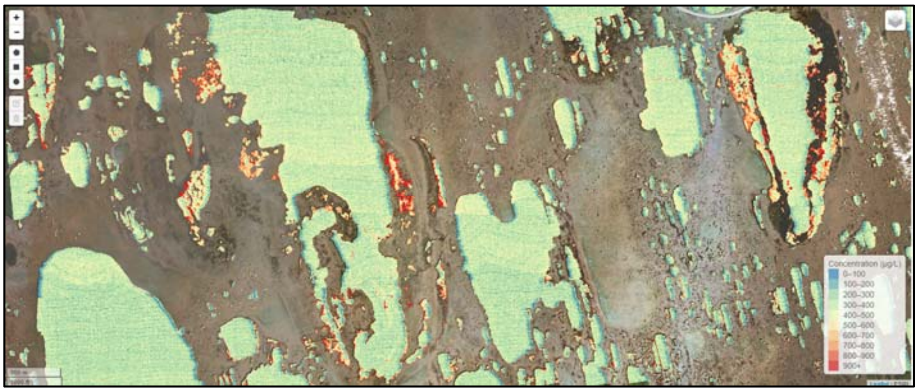

Figure 4 Iron Concentration across Survey Area

Case Study #2: UAV mounted Hyperspectral Survey – Irish Mine Investigation

Due to advances in technology, smaller and lighter hyperspectral sensors are being mounted on unmanned aircraft systems allowing hyperspectral data to be collected at a higher temporal and spatial resolution. Following the Alaskan case study described above and the limitations identified, SLR decided to explore the use of Unmanned Aircraft Vehicles (UAVs) for improving the data collection method to complement the use of more traditional methods.

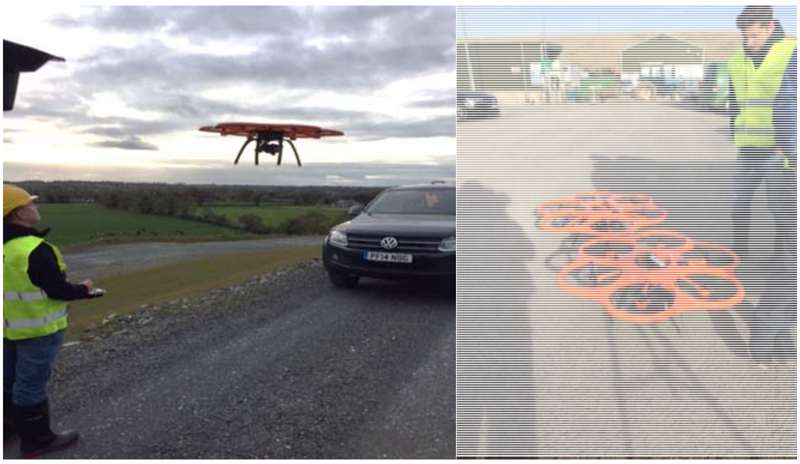

Figure 5 Drones Used in the Study

Following a review of available systems at the time (Summer 2016) it was decided to use this system:1 x Aibot X6 V2 and hyperspectral sensor (VNIR only) **Sensor Specification: Headwall (VNIR)** (Spectral bands: 272, Spectral Range: 400-1000 nm, Spectral Resolution: 2 nm; Spatial Resolution (GSD): 5cm,). The field work, consisting of the UAV mounted sensor only (no ground truth observations) was carried out in November 2016 at an active mine site in Europe. An area of c. 2 Hectares was covered at a flight height of 50 metres producing data of 5 centimetres resolution, with 1 battery. This 10 minute flight produced c. 10 gigabytes of hyperspectral data as we collected data across the full spectral range. The case study above (Alaska Tundra Water Bodies) produces data at c. 2 metre resolution using a manned aircraft and was flown at c. 1,500 metre flight height. Interpretation of hyperspectral remote sensing requires specific algorithms able to manage high dimensional data compared to multispectral data. The collected data was processed by Harris Geospatial using ENVI image analysis software and by Satelytics using their proprietary algorithms. Results were processed to allow feature extraction for thematic purposes, using standard algorithms, leading to a spatial pattern and spectral identification pixels within the scene displayed as a map – refer to Figure 6 below that shows the processed hyperspectral data compared to RGB imagery (i.e. visible to the human eye).

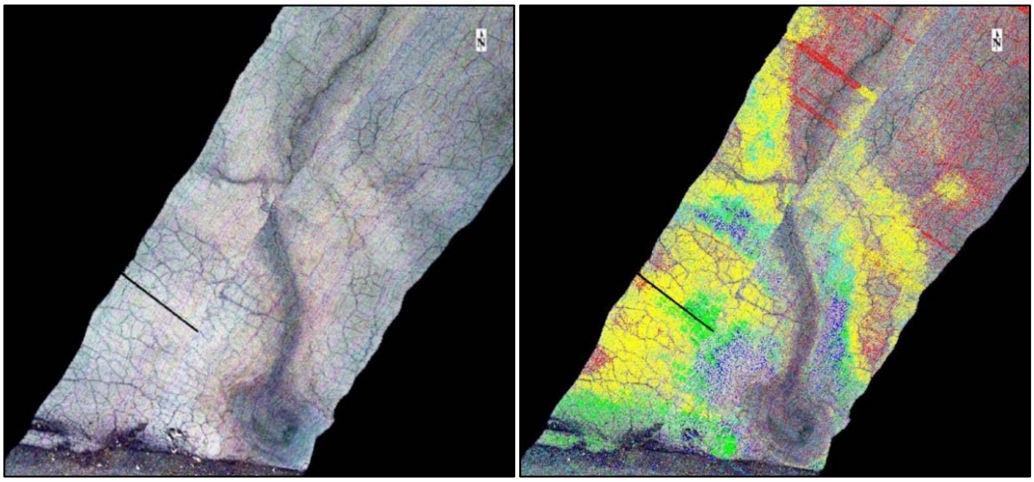

Figure 6 RGB Imagery Compared to Processed Hyperspectral data

The information presented demonstrates that the hyperspectral imaging and processing provided a diagnostic means by which to identify and separate discreet classes based on the reflectance spectra characteristics across the VNIR wavelength range and with further preliminary interrogation some elements in the soil are delineated. For example the distribution of relative concentrations of arsenic is present in Figure 7 below.

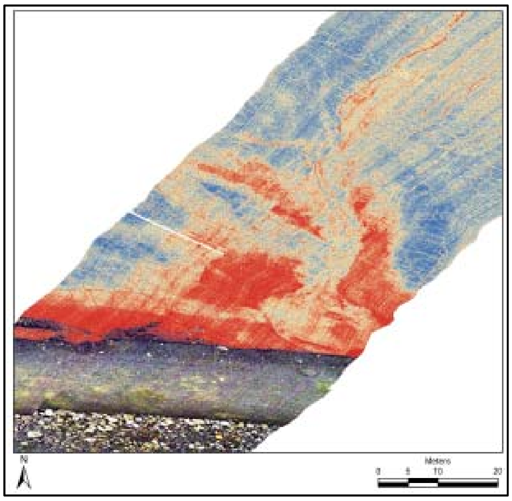

Figure 7 Relative Concentration fo Arsenic in Tailings Dam (red – high concentration, blue- low)

Learnings identified during the data collection stage included the usual issues with UAV's including limited battery life allowing a limited flight time, variable wind speeds, and inconsistent lighting conditions. The data size of the captured spectrum was also a limitation factor due to the gigabite size and associated transfer of data and associated storage. A number of challenges of working with the UAV collected hyperspectral data were identified by Harris Geospatial when processing the data, including, systematic noise in the direction of acquisition, variable speed of acquisitions and poor ortho-rectification. Awareness of these issues from the outset will dramatically improve the success of future surveys.

4 Next Stages of Assessment

The VNIR provides significant diagnostic value in the identification of minerals and is especially important for iron compound identification, which can be a useful area of study at sites producing acid mine drainage. UAV systems are now available with coupled VNIR and SWIR sensors providing additional diagnostic and characterisation potential and SLR is currently developing methodologies to use these systems on a number of active and legacy mine sites in Europe. The combination of these sensors will improve the detection capabilities of the process for the required minerals / contaminants, both in terms of the number of contaminants able to be detected an in improved accuracy of class separation. The next field study will include additional ground based sampling to enable correlation and decorrelation of the UAV-collected data.

5 Conclusions

There are benefits of using UAV mounted hyperspectral sensors for monitoring a range of environments e.g. active and legacy mine sites, contaminated land etc. In the mining sector there are particular benefits in using this technology for mine closure monitoring and management (providing an invaluable tool for environmental evaluation and temporal / spatial change analysis). Hyperspectral data, when used in combination with other monitoring methodologies, can assist in optimising the time and cost required for long term management and monitoring programmes. Experience in data collection, complementary analysis methodologies, hyperspectral data processing and geochemical interpretation are key to producing accurate and reliable results.

Acknowledgements

We would like to thank the support of the SLR Management Team in progressing this applied research initiative. The help and technical skills of Julian Deeks, Aibotix, Headwall, Harris Geospatial and Satelytics are also greatly appreciated for the successful collaborative working on these and other SLR projects to date.

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7. Geotechnical aspects

Satellite Remote Sensing to Monitor Surface Deformation Over Closed Mines

V Velasco *TRE ALTAMIRA, Spain & Italy*

F Meloni *TRE ALTAMIRA, Spain & Italy*

D Colombo *TRE ALTAMIRA, Spain & Italy*

Abstract

The mining activity is a temporary step in the exploitation of natural resources that may last from a few years to decades. When an operation faces a temporary or a permanent stop, a new phase of the mining life-cycle begins: the closure process. The mine closure is a procedure that consists of several steps and is required by the regulations of many countries. While the administrative procedure may change depending on the country, environmental and geotechnical monitoring are often implemented in order to monitor and mitigate the hazards associated to the abandoned mine sites. Abandoned sites risks vary from ground collapse to water recharge or gas accumulation. In general, a broad range of the post-closure phenomena affects ground surface stability.

Satellite-based interferometry has a proven track of successful applications in the mining industry and beyond. In fact, the broad coverage, the high resolution and the millimetre precision makes it a perfect tool to perform long term stability assessment and to spot any early-evidence of ground deformation over wide areas. As the InSAR technology is effectively used in many active operations, we deem it a fundamental and cost-effective mean to complement the monitoring network of an abandoned mine, extending both in space and time the accuracy of the hazard characterization. Due to its unique features, satellite interferometry has the potential to meets, or even exceed, the HSE performances required by national regulations, without compromising the economic feasibility of the closure activities management.

The present paper presents some case-studies related to the advanced application of InSAR techniques to abandoned mines.

Keywords: *monitoring, InSAR, satellite, radar, subsidence, slope stability*

1 Introduction

Safety critical monitoring in active mines is implemented to mitigate risk and ensure viable production. Several technologies are applied on site, employing both geotechnical instrumentation and several remote sensing technologies. Satellite InSAR is applied frequently together with other solutions in order to assess the deformation occurring all over the mine site, taking into account the operative area (as the pits) and the waste facilities (as the tailings dams or the waste piles). In underground mining, InSAR is used as the elective tool to complement survey when measuring wide scale subsidence. When the mine reaches the end of life, and near real time alarming is not anymore a crucial, the maintenance of expensive monitoring stuff is not anymore becomes not affordable; InSAR, as per its intrinsic capacity to work without any need of in situ instrumentation proved to be a cost effective solution to cover most of the problems related to further instabilities induces by old mining works.In this article, after a brief description of the methodology and an overview of the application of such monitoring in active mines, several cases of InSAR monitoring over abandoned mines are shown.

2 InSAR in active mines; a tool to complement safety critical monitoring

Currently, critical mine areas are monitored for geotechnical stability with the deployment of expensive ground based monitoring equipment. The cost of equipment and management of the complex data from multiple systems limited full mine and mine infrastructure coverage. Interferometric Synthetic Aperture Radar (InSAR), has always shown promise to provide full mine site monitoring, however the poor resolutions (10 and 20 m) and long repeat pass times (24-, 35-, and 46-day repeat) severely hampered this technique from becoming a commonly applied tool in the mining industry. The availability of modern Synthetic Aperture Radar (SAR) satellites with revisit times down to 4-days and ground resolutions commonly down to 3 metres, has brought InSAR technology back to the forefront of mine site deformation monitoring.

While modern satellites provide improved spatial and temporal resolutions, InSAR processing techniques have also improved to exploit the full benefit of these robust data sets. InSAR services are delivered by means of frequent reports upon the reception of an updated image, or -every quarter or semester – allowing the measurement of displacement down to a few mm. As the orbit of the satellite is almost north-south, InSAR measurement are sensitive to vertical and horizontal east-west displacement. InSAR provide most benefits when coupled with in situ geotech sensors or alarming-prone instrumentation like radars and lasers.

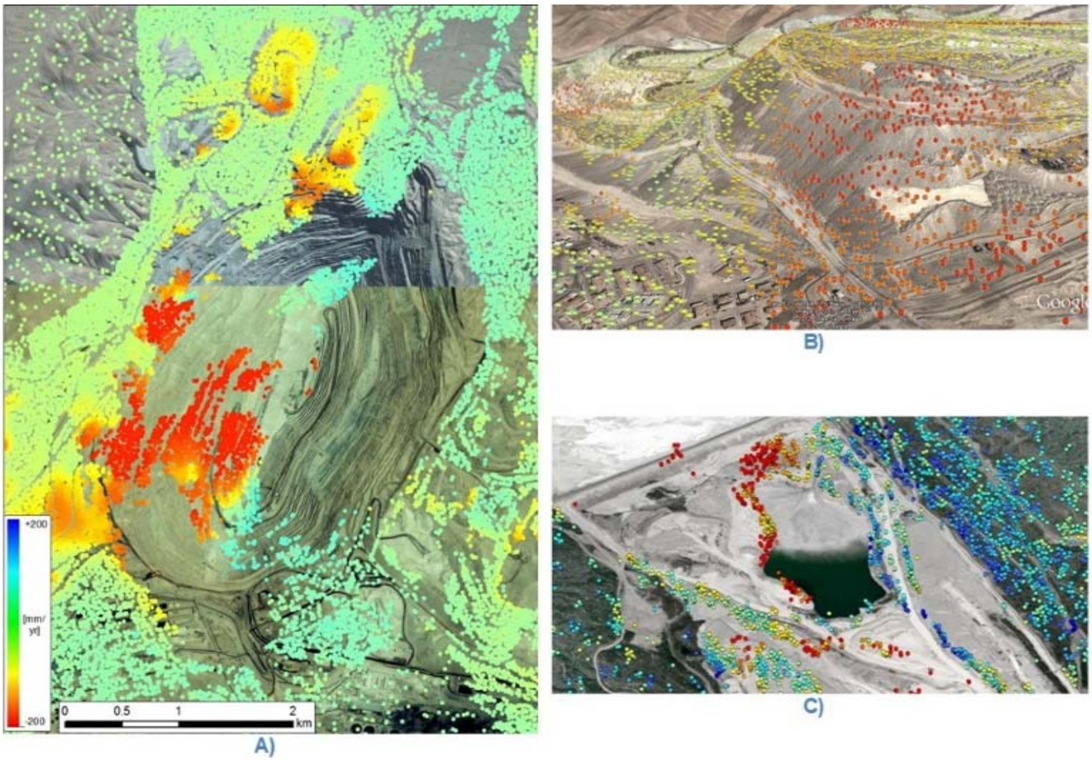


Figure 1 InSAR displacement maps over operative mines. Green points represent stability, red and blue displacement A) displacement in a vast open pit operation B) differential displacement on a waste pile C) differential displacement on a tailings dam

3 Monitoring surface displacement in closed mines

3.1 Site specific monitoring over abandoned open pit

Amiantifera S.p.A. in Balangero was incorporated in 1951 and soon became Italy's leading asbestos producer and exporter. As early as the 1960s, however, there was a growing awareness of the hazards of the material. Production continued until 1990, when Amiantifera S.p.A. went bankrupt. Two years later, Italian Law no. 257 banned asbestos and its derivatives throughout Italy, and decontamination plans for the Balangero and

Corio mines were drawn up. In 1994, RSA S.r.l., a company for the environmental reclamation and development of the former asbestos mines in Balangero and Corio, started work on the site, which in future will be used for photovoltaic electricity production. The company plays an important role in raising awareness about environmental issues.

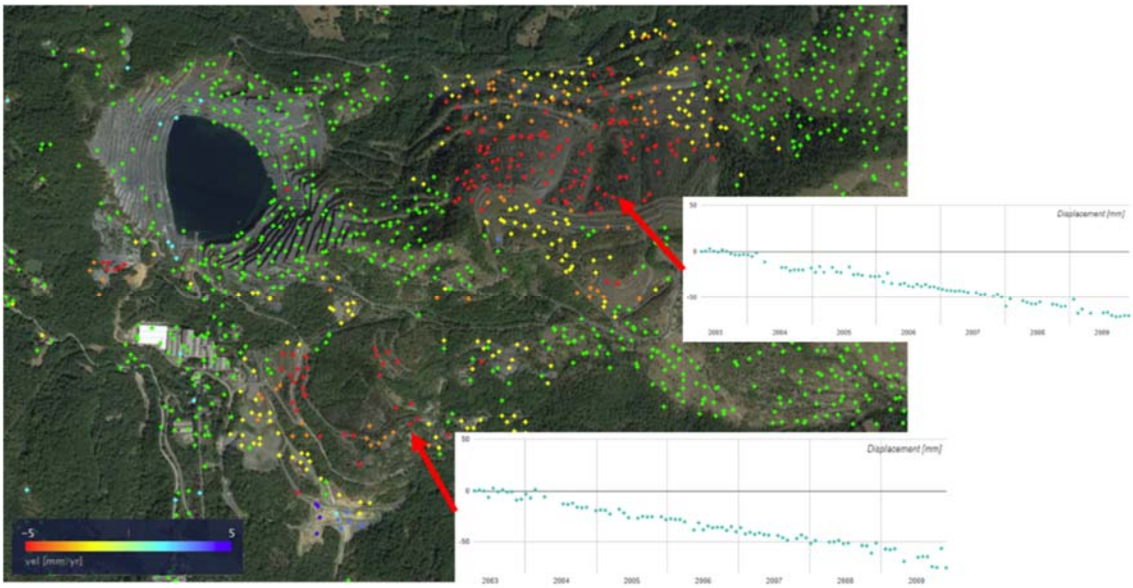


Figure 2 Displacement field on the surroundings of the abandoned Balangero open pit. Monitored period: 2003-2009

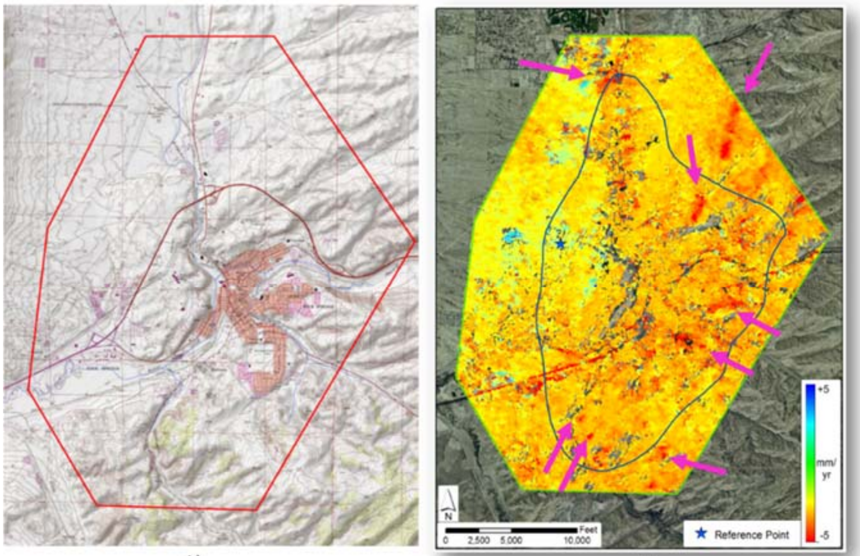
Figure 2 shows a displacement map calculated by means of satellite data acquired between 2003 and 2009. For a basic reading, green points represent stable targets reflecting towards the satellite, while red ones shows movement away from the sensor itself, typically associated to vertical settlement or east-west slips. As per the intrinsic character of remote sensed data, all the measurement point are calculated without the need of any instrument installed on the ground (avoiding local inspections), but just as the consistent backscatter towards the satellite of exposed rocks and man made structures. Moreove, as shown in Figure 2, each point is correlated with a time series of displacement. The pit shows no significant displacement in the period. On the other hand, most of the waste disposal area shows displacement. The northern waste piles shows quite a vast displacement area; almost all the time series of displacement shows a very clear linear behaviour. Displacement in this area reaches 30 cm in 7 years. Other areas in motion are identified quite close to the pit and on the southern side of the waste piles. In that particular case, the upper side of the waste pile shows evidences of compaction going on (settlement here is slower, up to 7 cm in 7 years), while the toe shows some heave, likely induced by a deformation phenomenon which is not purely vertical compaction. The application of InSAR in a similar cases would allow to understand which areas are in motion; moreover, as SAR satellites are continuously acquiring, such maps can be updated every 3 or 6 months, thus being an elective tool to detect subtle instabilities without the need of any visit.

3.2 Site specific monitoring over abandoned underground mines

Intrinsic to any assessment of subsidence hazards associated with abandoned underground mines, is an understanding of where subsidence has occurred previously and where active movements are occurring as these areas represent the highest risk for future damage. With trough subsidence, deformation often consists of broad gentle warping that can encompass large areas where identifying active ground movements requires careful measurement and monitoring. Where the undermined area is limited, subsidence monitoring can be accurately and cost effectively performed using conventional surveying equipment to periodically measure a series of monument points established throughout the area in question. However, for larger areas, this approach quickly becomes very time consuming and cost prohibitive.

The case of RockSprings, WY

InSAR has been applied to overcome this difficulty in Rock Springs, Wyoming, where a significant portion of the city is undermined. The area had been mined for coal since the late 1860, last mine closed in 1963. The availability of historical dataset (in that case dating back to the 90s) makes it possible to perform back analysis of events happened several years ago, while new satellites orbiting allow to frequently update the deformation map. In this article, we discuss the main findings associated with the processing of a set of SAR images acquired between 1992 and 2000. Figure 3 shows an overview of the overall displacement measured in 8 years. As is it visible, apart from the evidence of compaction corresponding with a recent railway line, one the western side of the map signatures of linear subsidence are clearly visible and highlighted with the purple arrows.



A) B)

Figure 3 A) Area of interest. B) 1992-2000 cumulative displacement

Figure 4 shows some surface evidences of such processing in action both in the urban area (image B) and outside of the town (see tension cracks in image A). Figure 5 presents the measurement obtained over a structured damaged with evident cracks.

A) B)

Figure 4 Evidences of surface displacement A) Surface cracks. B) Cracks in a building at Wyoming street

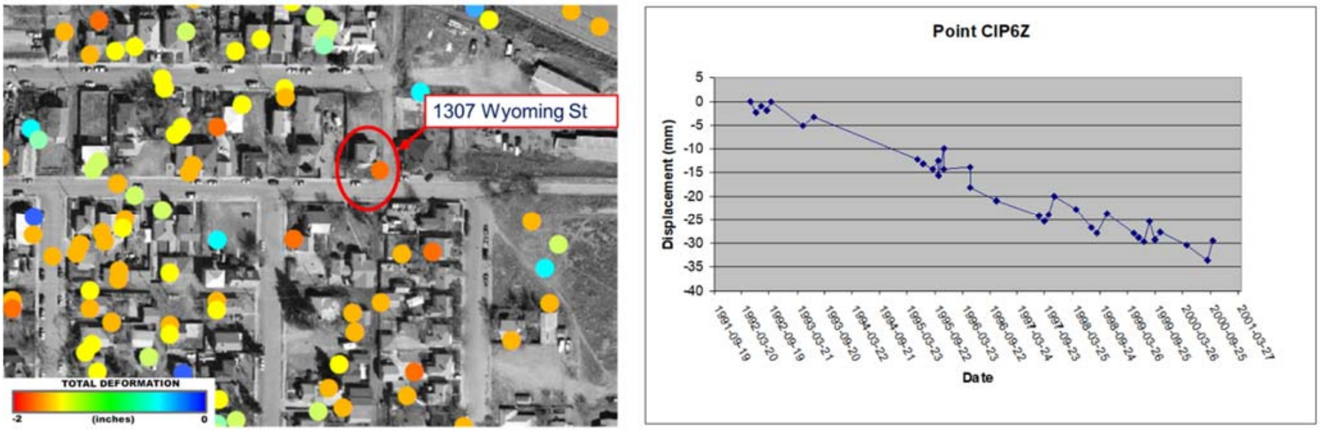


Figure 5 Subsidence map and time series measured over a building in Wyoming street, Rock Spring

3.3 Wide area monitoring and sensor-less detection of instable areas

InSAR – as per its intrinsic remote sensing capability – can be applied over vast areas. As satellites are tasked to cover all the land (worldwide), this makes InSAR the eligible tool to timely detect incumbent unknown subsidence and slope instabilities. As an example, Figure 6 shows the displacement field of an entire nation (Italy) where several signatures are easily visible: the red area in the Po Plain in northern Italy relates to ground subsidence induced by water withdrawal, and volcanic activity is visible in Sicily. More than 14,000 landslides had been mapped thanks to such dataset. Indeed, Italy is not a mining country, but such example shows the capability to have bird's eye view assessment of the displacement, without the need of field inspections or instrument positioning.

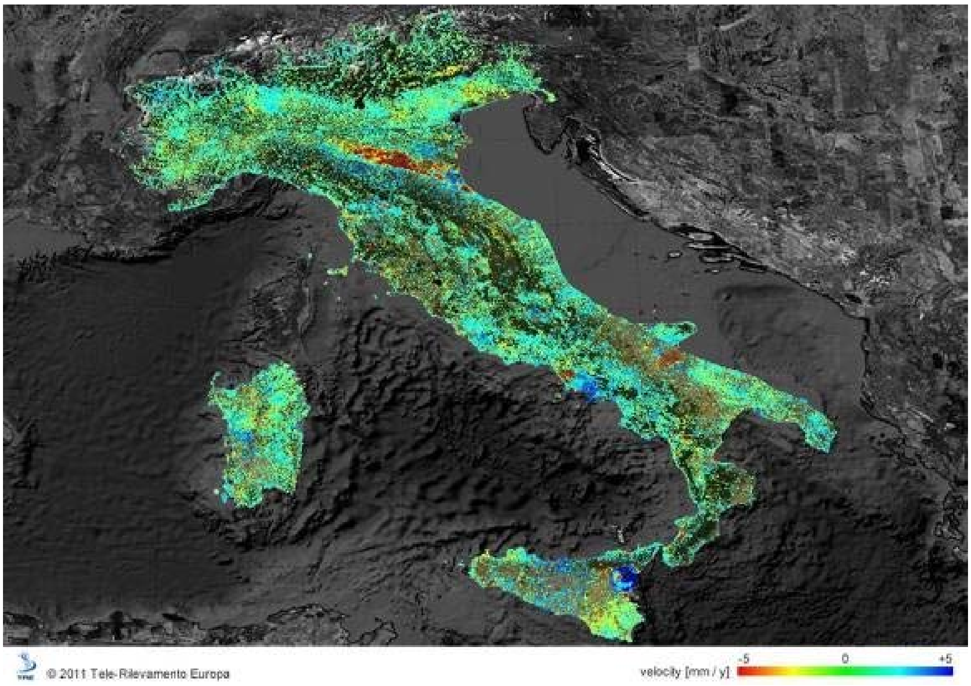


Figure 6 Displacement map of Italy, reference period 1992-2000

Such approach provide significant measurements when applied on mining areas. The Silesian Coal basin had been studied with InSAR to map subsidence and uplift induced by mining. The region is still quite active (with long wall coal mining) but most of the seams have been already exploited. The Upper Silesian Coal Basin (USCB) is located in the south-western Poland and the north-eastern Czech Republic. The USCB basin forms the western part of the Silesia-Cracow Upland and peripheral part of the Silesian Beskids.

Coal mining activity in the USCB has been conducted since seventeenth century. In 2012 in Upper Silesian Coal Basin about 79,2 million tons of hard coal was mined. At present in this region are 30 active coal mines. Average depth of coal extraction is about 700 metres below surface and the longwall mining method with caving or hydraulic stowage are used. In the USCB, hazardous ground deformations are caused primarily by mining workings and operations, The subsidence in this region reaches velocities of a few centimetres per month but in some cases can reach even 5 millimetres per day. Figure 7 shows a significant pattern of subsidence bowls. Most of the displacement measured in the Southern section of the colliery is to be related to expected subsidence due to active mining. This is not the case of the northern patch, where still subsidence is evident (there are both big scale phenomena and small ones on the north eastern side). Also, uplift (shown in blue) is visible. After a field investigation with the Polish Geological Institute, such uplift had been explained as the result of water recharge in the lower levels of the mine – likely associated to a stop in dewatering operaitons.

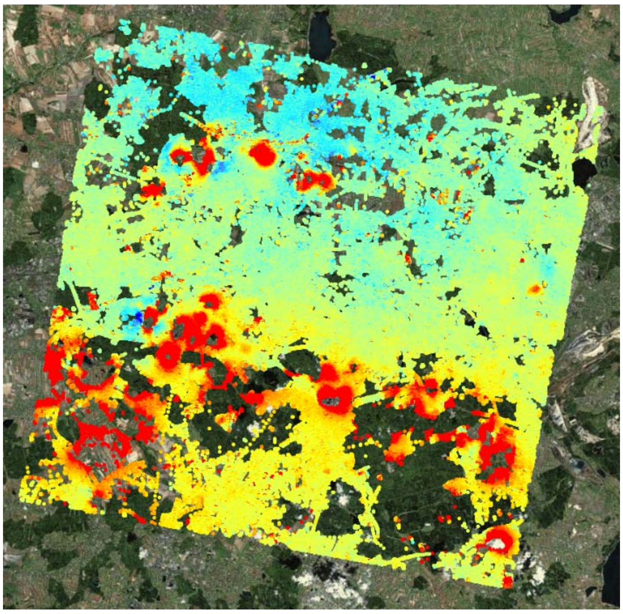


Figure 7 Displacement map, Sileasian Coal basin, reference period 2011- 2012

4 Conclusion

Modern constellation of satellites, together with improved capabilities, make InSAR a viable technology to remotely detect potential instabilities affecting old mining areas.

As it had been shown, subsidence and slope instabilities does not cease after the operation stops, while frequently it is not doable to carry on with expensive monitoring instrumentation. Being scalable to different resolution, and potentially providing weekly updates of the displacement maps, InSAR is a powerful tool to decrease the uncertainty when extensive and proactive monitoring is requested.

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Relevance of Seismic Risk Assessment in Abandoned Mining Districts: the Case of the Gardanne Coal Mine, Provence, France

JL Kinscher *Ineris, Institut National de l'Environnement Industriel et des Risques, France*

D Namjesnik *Ineris, France*

I Contrucci *Ineris, France*

P Dominique *BRGM, Bureau de recherches géologiques et minières, France*

E Klein *Ineris, France*

Abstract

Mining shutdowns have increased significantly in last century, but seismic risk in post- mining districts and consequent damage from ground shaking is still poorly understood. Large induced seismic events with M > 5 are known from active mining districts. Their origin is widely directly linked to stress perturbations related to mining activity. In post-mining districts, especially when they are flooded, the bandwidth of potential seismic source origins is comparatively large and has been observed in the context of partial underground collapses, fluid induced redistribution of the environmental stresses, and reactivation of pre-existing fault structures next to the mining district. The estimation of the associated seismic hazard is quite challenging, depending on many complexly interacting factors, such as the mine geometry and geological constitution, its long-term alteration behaviour (modified by the presence of fluids), meteorological impacts and climate changes, triggering from regional or global natural earthquakes, and the presence of pre-existing fault structures and tectonic stresses.

Such challenges are today encountered in the case of the underground flooded, abandoned coal mine at Gardanne in the Provence region (in SE France). Local microseismic monitoring highlights the presence of significant periodic seismic swarming activity, including events of magnitudes close to 2 which have been several times felt by the nearby living population. Seismic analysis demonstrates that most of the events appear to be located below the excavated, flooded mine workings and seems to be spatially and temporally correlated with the flooding evolution, controlled by meteorological conditions and active pumping operations. Results from source mechanism analysis showed that swarming activity is probably related to rupture along a network of pre-existing fault structures, which are favourably oriented with respect to the local tectonic stress field. Based on these observations, we suggest that some mine workings (especially room and pillar) act as a very efficient "anthropogenic" aquifer, whose water level fluctuations trigger reactivation of these faults, e.g. via a poroelastic effect or pore pressure increase. The nature of the detailed triggering mechanism remains however speculative and is part of currently ongoing investigations. This example shows the necessity and relevance of the understanding of this mechanism in order to reason if variations of the mine water level might potentially trigger larger local tectonic events, as recorded in the past (Mw 3.6, 1984), or simply episodes of swarm activity associated to small transient creep. In the light of these developments, seismic hazard analysis in post-mining risk assessment, which is non-standard today, could be assessed.

Keywords: *Flooded post-mining, seismic risk, microseismic and hydrological monitoring, source analysis*

1 Introduction

The closure of mines may pose significant environmental problems related to ground and surface stability. These problems can affect public safety and the sustainable development of mining regions. When mines are abandoned, ground water pumping is usually stopped, such that water floods residual voids. Such water intrusion may affect the mechanical stability of the underground structures and perturb the local state of stress sometimes leading to different forms of mine collapses. In France, these events have been a great concern for the population of the Lorraine region (France) after the closure of iron mines in the 90's (Didier, 2008). Surface subsidence due to mine collapses reached two meters in some places and more than five hundred buildings have been damaged due to these disorders.

In contrast to such well known static deformation phenomena, the potential seismic risk in flooded, post-mining districts and consequent damage from ground shaking is poorly understood. Large seismic events with M > 5 are known from active mining districts. These events are often directly induced by mining activity and thus, could be in some cases anticipated from local seismic monitoring. In flooded post-mining districts, seismic events have been observed in the context of partial underground collapses, fluid induced redistribution of the environmental stresses, and the reactivation of pre-existing fault structures next to the mining district (e. g. Miller, et al., 1988; Miller, et al., 1989; Ogasawara, et al., 2002; Goldbach, 2009; Srinivasan, et al., 2000; Senfaute, et al., 2008; Wetmiller, et al., 1993; Dominique, et al 2012). The estimation of the associated seismic risk is quite challenging, depending on many complexly interacting factors, such as the mine geometry and geological constitution, its long-term alteration behaviour (modified by the presence of fluids), meteorological impacts and climate changes, triggering from regional or global natural earthquakes, and the presence of pre-existing fault structures and tectonic stresses.

Such a degree in complexity is today encountered at the abandoned and flooded Gardanne coal mine in the Provence region in SE France, where close living habitants frequently feel seismic ground motions. With this case study, we would like to attract attention to the need of further developments and progress in knowledge of proper seismic hazard and risk assessment in post-mining management.

1.1 Gardanne mine: flooding history and seismicity

The Gardanne coal mine basin has been exploited for over more than a century and was finally shutdown in 2000. Main parts of the exploited lignite deposit occurred in the so called Grande-Mine (GM) layer, dipping from the East to the West, covering an area of more than 100 km^2(Figure 1). A wide area has been exploited by room and pillar technique between50 m and 700 m depth, which has left residual, potentially unstable voids with possible surface impact. A residual zonation was obtained (by GEODERIS), distinguishing zones of low hazard (subsidence, eventual limited damage to buildings), generally located westward beyond 250 m depth, and areas of surface subsidence collapse hazard located generally to the East in areas where the exploited layer extends up to 250 m (Figure 1).

Associated risk zones have been monitored in real time since 2008 by a network of 5 seismic stations (boreholes equipped with4.5 Hz–40 Hz geophones from 2m to 250 m depth) installed by the CENARIS (National Monitoring Center created by Ineris; http://cenaris.ineris.fr) at the request of the BRGM-DPSM (Figure 1). With the cessation of mine water pumping in 2003, these mine workings flooded progressively from the West towards the East of the mine basin. In 2010, the flooding front reached the mining sector of Regagnas, located about 2 km West of the Fuveau monitoring station (located at the NE of the basin), what coincided with the birth of a spatially concentrated periodic seismic activity called the "Fuveau swarm". A total of more than 1,500 seismic events have been since recorded from the monitoring network, which mainly occurred in form crisis, notably in 2010, 2012, 2014, 2016 and lately in 2017 (Figure 2). Largest events reached local magnitudes close to almost 2 (regional SiSMOAZUR network) and have been significantly felt by local population. Seismic activity seems to be generally linked to water level variation in the mine working controlled from seasonal rain fall and active pumping at the Gerard well towards the Mediterranean Sea via an old mining gallery (Galerie de la mer, Figure 1). Most of the seismic crisis appeared in rather wet periods associated with significant rainfall events, as demonstrated by a good first order correlation of shallow aquifer level recorded at the Fuveau Rognacian well at 7m depth and the number of recorded seismic events (Figure 1 and 2). In contrast, a seismic crisis has been recently observed during a dry period in August 2017, indicating that water level changes and rainfall are probably not the only determining factor generating seismic activity (Figure 2). Unfortunately, today there are no in-situ measurements of the mining water level available in the seismic active area allowing to precisely understand in detail the link to seismicity.

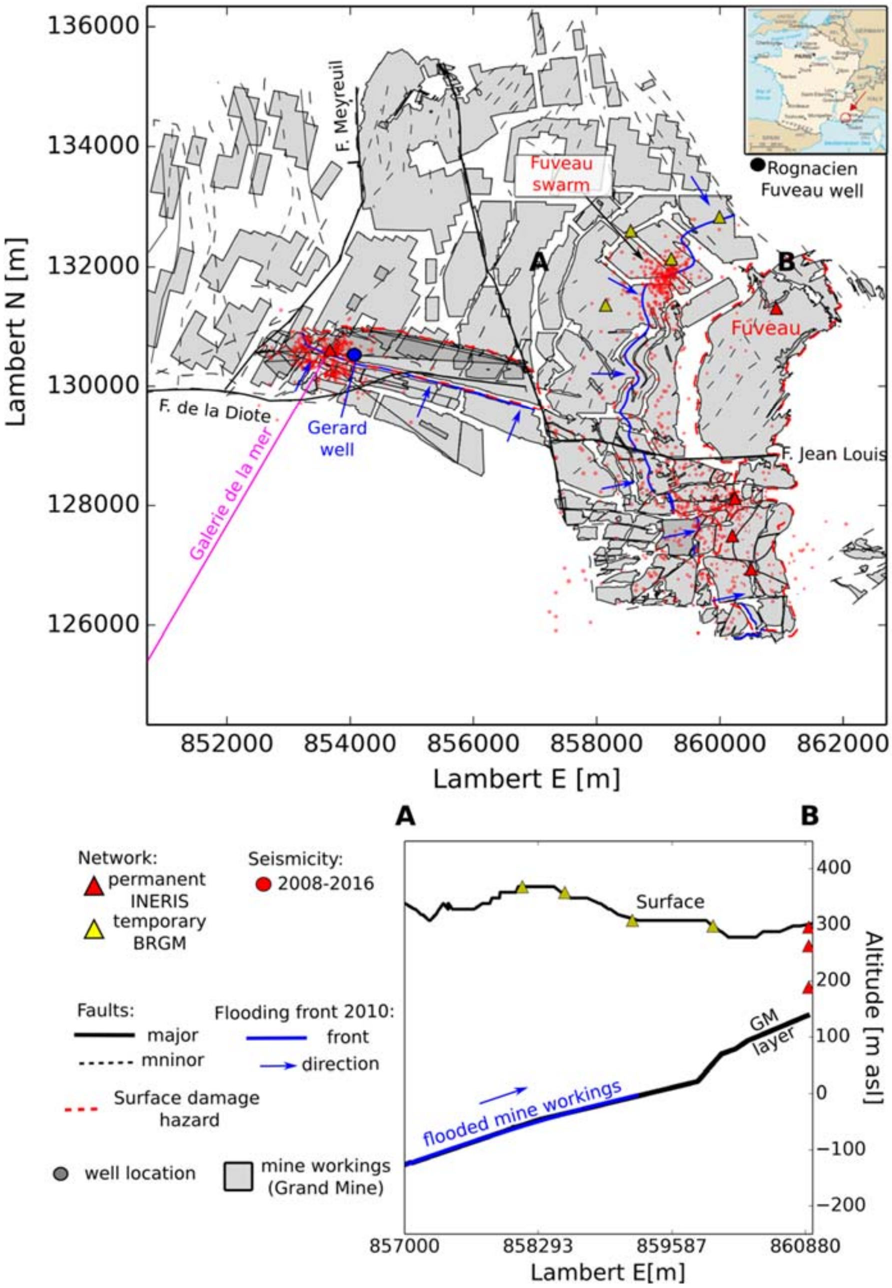

Figure 1 Microseismic monitoring of the Gardanne coal basin. The flooding front (blue lines) at the level of the mine workings (gray polygons) progressed from west to east, towards the center of the basin and was accompanied by microseismic events recorded by the permanent network (red triangles) from 2008 to 2016. The flooding front is represented by the intersection of the mine workings with the water level (-10 m asl) measured at the beginning of 2010 at the Gerard well (gray circle). The set of faults is taken from Gaviglio (1980). Permanent Ineris network, installed in 2008, is composed of high-frequency (4.5 Hz and 40 Hz) geophones (red triangles) installed in boreholes. Temporary BRGM network, installed in 2013, (yellow triangles) is composed by 3-component of 1 Hz accelerometers.

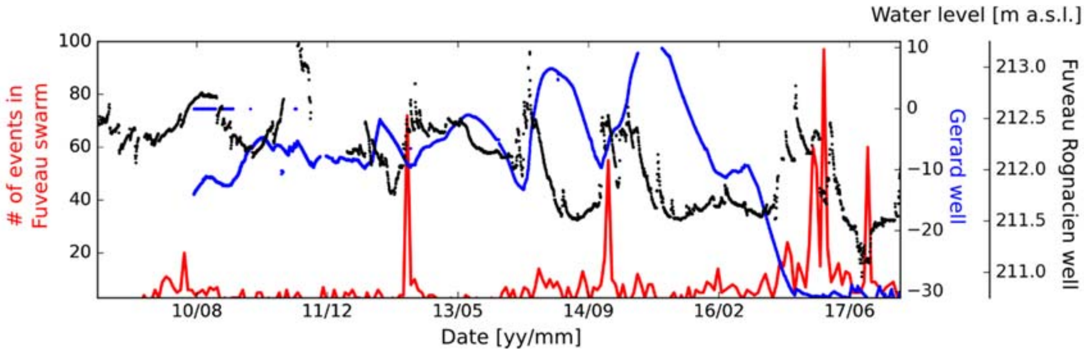

Figure 2 Seismicity (red curve) and water level changes recorded at the Gerard well (blue curve), connected to the Grande Mine layer at the west of the basin and the Fuveau Rognacian well (black curve) reaching 7 m depth

2 Seismic source analysis

2.1 General characteristics from 2010-2016

Based on the data from the permanent monitoring station Fuveau (Figure 1), we estimated moment magnitudes for strongest events by using Brune's model (Brune, 1970) and source spectral fit method (e.g. Kinscher, 2015) which ranged between 0.6 to 1.4 (Figure 3). Magnitudes for smaller events do not respect Bath's law (Bath, 1965) indicating absence of typical main shock-aftershock sequences as known from natural earthquakes, which is typical for seismic swarms (Malone et al. 1975; Mogi 1963). Seismic wave forms for strongest events do not show similarities indicating significant differences in source location and mechanism. In addition, partially events represent multi shock (Figure 3b) and double shock (Figure 3a) signature (multiple superposed P and S wave phases) indicating complexities in the rupture mechanism.

Although waveforms for strongest events are not alike, almost every event is associated with "multiplet" occurrences, i.e. events of lower magnitudes with very similar waveforms. Multiplets have been observed in many contexts, tectonic (Poupinet, et al., 1984; Augliera, et al., 1995), volcanic (Lees, 1998), geothermal (Moriya, et al., 2002), mining (Maisons, et al., 1997; Gibowicz, 2006), or during fluid injections (Baisch& Harjes, 2003) and are generally indicative for multiple stress release on the same seismogenic structure (fault) (Geller & Mueller, 1980, Poupinet, et al., 1984, Moriya, et al., 2002). An example of a multiplet is shown in Figure 4. These events are associated with the Mw 0.9 event of the 28th of July 2012 shown in Figure 3. The events corresponding to this multiplet group appeared over almost the entire duration of the Fuveau swarm from 2011 to 2016. The origin of this multiplet family is likely related to a fault segment, which ruptured gradually over a period of approximately 5 years.

2.2 Detailed source analysis for the 2014 crisis

Seismic sources have been analysed more in detail in terms of location, source mechanism and source parameters for events recorded during the seismic crisis in December 2014 by a temporary network installed by the BRGM in 2013 (Dominique 2015, Figure 1 and 5). Locations have been refined for a total of 140 events, recorded between 1st and 28th of December 2014 using double difference based relocation technique (Matrullo, 2015). Location results outlined a microseismic cloud in the southern part of Regagnas sector with a NW-SE alignment (Figure 5), being consistent with the orientation of the geological faults and mining sector. The depth of these events varies between 500 m and 900 m with an average of 700 m. The average depth of 700 m lies below the mine workings, which are at a depth of about 300 m (Figure 5).Sensitivity tests on the velocity model, polarization angle analysis and detailed seismogram simulation showed that source location below mine working is most probable, however, seismic event occurrences within or above the mine workings cannot be completely excluded.

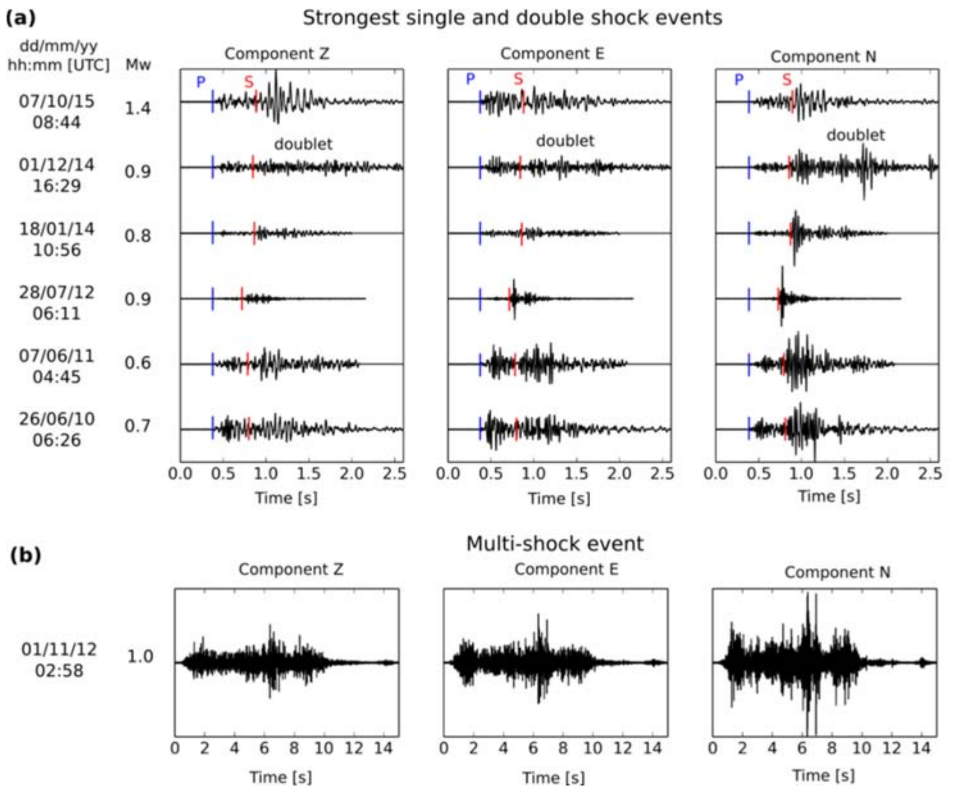

Figure 3 **(a) Seismograms for the six strongest events recorded from Fuveau monitoring station between 2008 and 2016. (b) example of a multi-hock event**

Source mechanisms have been investigated using a classical "double-couple" source model, representing shearing along a fault. The choice of a shear model is generally justified by the presence of multiplet families and significant fraction of SH wave energy relative to the P and SV waves (see N component in Figure 3), which is indicative for a significant shearing component in the mechanism. Two methods were used to estimate the double-couple mechanism, namely: (i) wave form inversion for the five strongest events and (ii) a composite method based on the spectral ratio of P and S waves applied to a set of 60 events with very similar wave forms and thus likely to be associated with a similar source mechanism. Both approaches followed methodology as used by Kinscher (2015) and Kinscher et al (2016). Results from both approaches demonstrated coherently convergence to a normal faulting mechanisms with main orientation N120-160 ° (NW-SE)being in agreement with pre-existing faults documented at the north of the Regagnas sector (Figure 5).

Source parameters in form of seismic moment and source radius have been determined for 60 events using a spectral fit approach (Kinscher, 2015) and Brune's models (Brune, 1970). Obtained moment magnitudes vary between -0.2 and 1.2 which is consistent with magnitudes obtained from Fuveau monitoring station. Obtained source radii vary between 10 m and 90 m.

3 Results and discussion

3.1 Origin of seismic sources

Summarizing results of the preceding chapters we conclude that:

(i) seismic activity at the Fuveau swarm is characterized by low magnitude (Mw < 1.4) events that are spatially constrained and appear in form of periodic crisis which seems to be linked to variation in the mine water level;

(ii) seismic sources seem to be mainly located below the mining works, between 400 m and 900 m depth;

(iii) the vast majority of seismic events seem to be related to rupture along NW-SE oriented normal faults, consistent with normal faults documented by in situ geological observations further north of the sector;

(iv) the characteristic size of these faults was estimated at a few tens of meters.

Results suggest that seismicity is linked to the reactivation of a network of faults, constituted by different discrete segments of small dimension (a few tens of meters). In addition, the presence of "multiplet" type events (Figure 4) indicates repetitive rupture on distinct segments partially over periods of at least 5 years. An origin of seismicity related to occurrences of disorders in the mine workings itself seems thus less likely, but cannot be totally excluded. Indeed, previous geotechnical studies suggest that the abandoned mining area is rather in a "post-collapsed" state where most of the overlying formations, composed of resistant calcareous beds, are probably widely plasticised (free of elastic energy). Nonetheless, the presence of some non-collapsed areas cannot be completely excluded as potentially able to produce significant seismic activity.

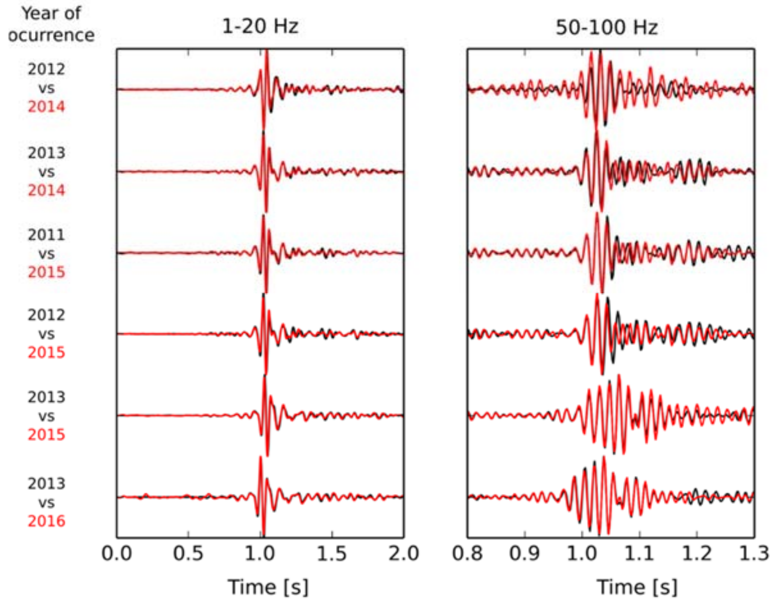

Figure 4 Normalized seismograms of multiplet group corresponding to the Mw 0.8 event of the 28th of July 2012 (Figure 3) recorded by Fuveau monitoring station.

3.2 Triggering mechanism

Next to the water level variation in the mine workings, we believe that the natural tectonic regime plays a major role in the triggering of seismicity. Indeed previous studies have shown that regional tectonic stress has played an important role in the generation of several rockburst events during the exploitation of the Gardanne coalfield(Jarlier, 1925;Josien, 1980;Gaviglio, 1985).The maximum horizontal compressive stress SH is expected to be approximately NW-SE oriented(Baroux, et al., 2001;Heidbach, et al., 2008) (Figure 5). Measurements of in situ stress at a depth of 390 m in the Sainte Victoire sector to the north of Regagnas confirm this conclusion (Gaviglio, 1985). Main horizontal stress orientation is in agreement with NW-SE normal faulting (Anderson, 1905). Hence, it seems that regional tectonic stress contributes significantly to the shear stress applied to the normal faults in the Regagnas sector, due to their favourable orientation. As a result, these faults have been possibly already close to rupture before flooding of the mine workings which finally provoked minor stress changes sufficiently high to trigger seismicity.

The interpretation of the detailed relationship between the hydrological and seismic system remains highly speculative. The difficulty of this analysis comes from the fact that hydrological measurements are not made directly in the mining sector where seismicity is observed. Interpretation from the data of the Gerard well is not feasible without having a precise knowledge of mine water circulation which seems rather complex (Chalumeau, 2000; Dheilly& Brigati, 2015). Indeed, curves between Rognacian Fuveau and the Gerard well seem to be shifted in the order of months, which might indicate complexities in the water transport from the East to the West of the mine, maybe as a result of damming effects from the backfilled mining parts (Figure 5). Furthermore, there seems to be a remarkable spatial correlation of the area marked by the minimum and maximum flooding front level which seems to clearly constrain the spatial area where seismicity is observed (Figure 5).

Hence, it seems evident that water level variation triggers seismicity; however the exact triggering mechanism remains unknown. We suggest that the temporal occurrence of seismicity is determined by an overload and depletion effect of the aquifer formed by the unfilled (room and pillar exploited) part of the Grande Mine layer during very wet/saturated and dry periods, respectively (Figure 5b-c).These hydraulic load modifications can result in two potentially seismic triggering processes either (i) by vertical loading and unloading by the water column or (ii) by an increase in pore pressures reducing the normal stress and causing slips along fault planes (e.g. McGarr, et al.2002; Bell & Nur, 1978). Apart from fault reactivation hypothesis, remobilization of already demolished area in mine workings and overburden cannot be completely excluded as seismic source origin.

3.3 Implications for seismic hazard

At this stage of the study, it is difficult to estimate the seismic hazard, which depends heavily on the precise knowledge of the triggering mechanism of the observed seismicity. Seismic hazard and the generation of larger events will mainly depend on the nature and distribution of pre-existing faults (depth, tectonic role) releasing either (i) minor stresses in form of transient tectonic creep (earthquake creep) at shallow depth or (ii) release significant tectonic stress along larger deeper structures (Johnston & Linde, 2002). Both models bear very different consequences in terms of seismic hazard.

Assuming the case of transient creep, the Fuveau swarm will be interpreted as a network of small fault segments, which react progressively to external stresses not being able to accumulate significant and sufficient stresses that would be released by a single seismic event with a magnitude much greater than the magnitudes already observed and felt. Although this model explains the vast majority of the results obtained by this study, it is not entirely compatible with the observation of an apparent increase of magnitudes of recently recorded events (October 2016 - February 2017). Increases in magnitudes may potentially indicate stress increase and/or a growth of active fault segment sizes.

The Provence region represents one of the most active seismic zones in France and has experienced a major earthquake in history (e.g. Lambesc earthquake, 1909, Mw = 5.7). Also, the Gardanne region is known for moderate earthquakes, e.g. Ml 3.5 in April 1969, Ml 3.0 in October 1973 and the Ml 3.6 (Io = VI) Mimet event of the 19thof February in 1984 (Haessler, et al., 1984), which indicates the presence of an active fault segment being in the order of one kilometer long. Exact fault location and mechanism of this event are highly uncertain as demonstrated by fairly ambiguous previous results (Haessler, et al., 1984; Nicolas et al., 1990, Figure 5). So location of larger structures are not very well known, which implies significant uncertainties for seismic hazard assessment. Also rupture events along well known main fault structures as the Diote and the Meyreuil fault (several km long) have clearly the potential to generate larger events as already observed.

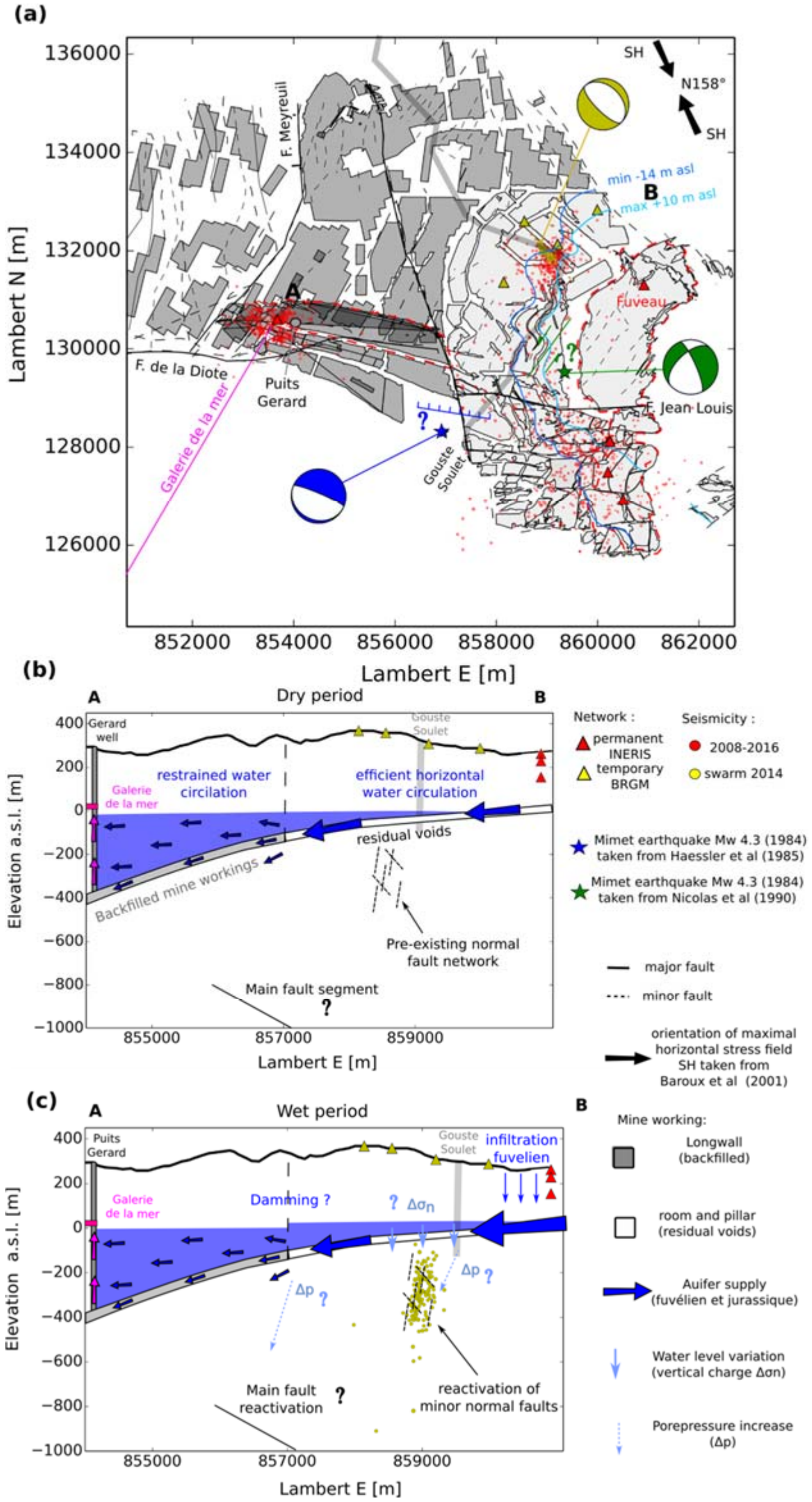

Figure 5 Synthesis of data (a) and final model (b) - (c), describing the origin of recorded seismicity. The dominant normal fault source mechanisms is shown for the Fuveau swarm (yellow beachball) and two different mechanisms and locations proposed for the Mimet Mw3.6 earthquake in 1984 by Nicolas et al., (1990) (green beachball) and Haessler et al (1985) (blue beachball), as well as their tectonic interpretations (green arrows and blue lines respectively). The regional stress measurements, represented by the maximum horizontal stress SH (black arrows) adapted from Baroux et al. (2001). The flooding fronts is approximated and are represented by the intersections of the mine workings with the minimum water level (-14 m asl) and maximum water level (10 m asl) measured since 2010 at the Gérard well (gray circle).

4 Conclusion

During monitoring in the Provence region at Gardanne (in SE France), we experience the high degree of complexity in which an abandoned, flooded mine can interact with its local tectonic setting. In this case, excessive and long-term excavation has led to the formation of very efficient "anthropogenic" aquifer which, especially in wet periods seems to modify the local state of stress, resulting in induced seismicity. The modification of the hydrogeological system seems to be the today's cause of significant seismic swarming activity, including local magnitudes close to 2 that have been several times felt by the nearby living population. Seismic source analysis suggests that swarming activity is related to the reactivation of minor fault segments being favourably oriented with respect to the local tectonic stress field. However, It remains still unknown if the meteorologically and active "anthropogenic" pumping operations controlled variations of the mine water level, might potentially trigger larger local tectonic events, as recorded in the past (Mw 3.6, 1984), or if swarming represents simply episodes of small transient creep. Further seismic and hydrological measuring campaigns and investigations are planned to understand in detail the triggering mechanisms, evaluate potential reactivation of larger fault segments and to exclude presence of other potential source origins located within and above the mine layer. This study case clearly underlines the importance of seismic hazard assessment studies (ground motion hazard) in flooded post-mining regions which are today mostly not taken into account in local risk analysis.

Acknowledgement

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Probabilistic Assessment of Tailings Dam Performance Using Bayesian Network

ZQ Liu *Norwegian Geotechnical Institute, Norway*

BG Kalsnes *Norwegian Geotechnical Institute, Norway*

F Nadim *Norwegian Geotechnical Institute, Norway*

S Lacasse *Norwegian Geotechnical Institute, Norway*

Abstract

In view of recent tailings dam failures with devastating consequences, there is need for a critical evaluation of the methodologies used for analysing tailings dam stability and for improving the procedures for their reliability assessment. The paper presents an approach for performing probabilistic assessment of tailings dam stability. The purpose of the probabilistic assessment is to quantify the probability of non-performance of the dam, which, combined with the expected consequences, provides a measure of the risk associated with unsatisfactory performance. Multiple plausible triggering factors and failure mechanisms were investigated in an example study. The probabilistic analyses were conducted with both the event tree and the Bayesian network approaches. After a screening of the triggering factors and the plausible failure modes for the tailings dam, the occurrence probabilities and annual probability of dam breach were evaluated for different scenarios. The Bayesian network models were built based on the input from a risk analysis workshop. The Bayesian network analyses were supplemented with Monte Carlo simulations to obtain the statistics of the probability of dam breach in terms of the mean (expected value) and higher bound and lower bound estimates of annual probabilities of failure. The Monte Carlo simulations used the probability bounds set by the experts participating in the risk analysis workshop. The analysis results showed that the best estimate for annual probability of non-performance causing catastrophic consequences for the example study was approximately 10^{-4}. The new Bayesian network analyses provided in addition the most plausible range of probabilities of failure. This is very useful information when the stakeholders need to make decisions regarding rehabilitation and closure of the tailings dam.

Keywords: *Probabilistic analysis, tailings, dam stability, Bayesian network*

1 Introduction

Tailings dams are built to store waste tailings from mining activities. Currently, thousands of tailings dams exist around the world. The stored tailings are often highly toxic and even a minor breach of a tailings dam could have catastrophic environmental consequences. Therefore the correct approach to long-term tailings dam management is crucial to the success, and reputation, of the mining industry as a whole. Tailings dam are more vulnerable to failure than water storage dams due to the following factors: (1) embankments usually formed by locally derived fills (soil, coarse waste, overburden from mining operations and tailings); (2) sequential dam raise along with an increase in effluents; (3) lack of appropriate monitoring including water level and pore pressure measurements; (4) the high cost of remediation works following the closure of mining activities (Rico et al. 2008). The failure of a tailings dam and the uncontrolled release of the impounded waste can have serious consequences for the public safety, the environment and the owner or operator. Since 1960, the consequence of tailings dam failure has become increasingly greater (Bowker and Chambers, 2015). Probabilistic methods are increasingly being used to handle the uncertainties associated with various factors, such as hydrologic variability and the variability of material properties, and to do quantitative risk analysis to provide support for decision-making, such as dam rehabilitation priorities and increasing the storage volume.

This paper presents the probabilistic analyses of the potential non-performance of a tailings dam. The dam is about 100 m high and is planned to be raised by 57 m in two phases. In the first phase, the dam crest will be raised by 4 m. The probabilistic assessment in this paper focused on the dam configuration after the first stage of raising the tailings dam.

2 Probabilistic methods used in the study

The probabilistic analyses were carried out with two approaches (Liu et al. 2017): (1) Event tree analysis; (2) Bayesian network combined with Monte Carlo simulations. In both cases, the probabilistic assessments were done in a workshop assembling specialists with experience with the dam and/or probabilistic assessment.

2.1 Event tree analysis (ETA)

An event tree analysis (ETA) follows the potential course of events as they move from an initiating event to non-satisfactory performance or failure. A probability of occurrence is assigned to each event. ETA is useful for both early design s or later to remedy to events that have occurred. The probability of failure for one event tree is the sum of the probabilities of failure on this tree, and the total probability of failure is the sum of the probabilities for all trees of plausible scenarios that can lead to tailings dam failure. The values in Tables 1 and 2 were used to assign probabilities to the different events. Table 1 lists the "traditional" guidelines (Høeg 1996; Vick 2002) as used in Norway, whereas Table 2 is an adaptation of the Intergovernmental Panel on Climate Change (IPCC, 2012) recommendation, where a range of probabilities is used to reflect an uncertainty in the verbal probability estimates.

Table 1 Estimate of probabilities and verbal description used in the event tree analyses

Probability	Verbal description
0.001	*Virtually impossible*, due to known physical conditions or process that can be described and specified with almost complete confidence.
0.01	*Very unlikely*, although the possibility cannot be ruled out on the basis of physical or other reasons.
0.10	*Unlikely*, but it could happen.
0.50	*As likely as not*, with no reason to believe that one possibility is more or less likely than the other.
0.90	*Likely*, but it may not happen.
0.99	*Very likely*, but not completely certain.
0.999	*Virtually certain*, due to know physical conditions or process that can be described and specified with almost complete confidence.

Table 2 Estimate of probability ranges and verbal description used in the event tree analyses

Probability	Verbal description
~0.0 – 0.005	*Virtually impossible*, due to known physical conditions or process that can be described and specified with almost complete confidence.
0.005 – 0.02	*Very unlikely*, although the possibility cannot be ruled out on the basis of physical or other reasons.
0.02 – 0.33	*Unlikely*, but it could happen.
0.33 – 0.66	*As likely as not*, with no reason to believe that one possibility is more or less likely than the other.
0.66 – 0.98	*Likely*, but it may not happen.
0.98 – 0.995	*Very likely*, but not completely certain.
0.995 – ~1.0	*Virtually certain*, due to known physical conditions or process that can be described and specified with almost complete confidence.

2.2 Bayesian network analysis

A Bayesian network (BN), also called belief network, is an emerging method for reasoning under conditions of uncertainty and for modelling uncertain domains.

Each variable in the network is defined in a discrete and finite outcome space (discrete random variable) or as a continuous outcome space (continuous random variable). One important property of the BN is that the joint probability function of all random variables in the network can be factored into conditional and unconditional probabilities in the network (Jesen 2007). The probability descriptors in Tables 1 and 2 were used for the BN analyses to evaluate the probabilities for the different events in the Bayesian network.

3 Non-performance scenarios and consequences

A non-satisfactory performance of the tailings dam and its appurtenant structures could have consequences that range from minor damage, which could be repaired quickly, to an uncontrolled release of tailings and water from the dam over a period of time. The release could be due to a breach of the dam or overtopping without dam breach.

The participants in the workshop agreed to classify the potential consequences of a non-performance into four consequence classes (Table 3). In the event tree and Bayesian network analyses, the annual probabilities of the events leading to "non-performance" of the dam and/or its appurtenant structures were calculated.

Table 3 Simplified list of consequences

Consequence Class	Description
1 – Minor	Minor physical damage requiring some repairs; no tailings or water escaping; mining operations not affected.
2 – Significant	Significant physical damage to dam and/or its appurtenant structures requiring major repairs; small amount of tailings and water escaping; mining operations would have to be stopped for a few days or a few weeks.
3 – Major	Significant material damage and contamination downstream, that may include trans-boundary effects if the released volumes are very large. Millions of dollars in repair costs. Mining operations have to be stopped for months.
4 – Catastrophic	Many casualties downstream. Physical damages of the order of millions of dollars. Significant contamination downstream with major long-term impact on the environment. Reputation of the owner or operator and the consultants involved in the project would be severely damaged. Mine would be shut down permanently.

Following an initial failure mode screening, five scenarios leading to unsatisfactory performance were considered most critical and/or relevant by the participants in the workshop. Event tree analyses were done for these five modes:

- Scenario 1: Strong earthquake leading to liquefaction of tailings, instability of downstream slope and breach of the dam.
- Scenario 2: Failure of concrete plug in the tunnel of one of the old "ventanas" (concrete structures for gathering the surficial water and draining them away through a drainage tunnel), or collapse of a pipeline under the right abutment of the dam.
- Scenario 3: Overtopping and failure of the downstream slope of the dam leading to dam breach during an extreme precipitation and flooding event.
- Scenario 4: Piping in the dam along an existing crack that occurred during construction or after the dam is raised.
- Scenario 5: Earthquake-induced rockslide impacting the existing "ventana" in operation today.

4 Results of event tree analyses

Figure 1 shows an example event tree for Scenario 4: Piping in dam at location of crack during or after construction.

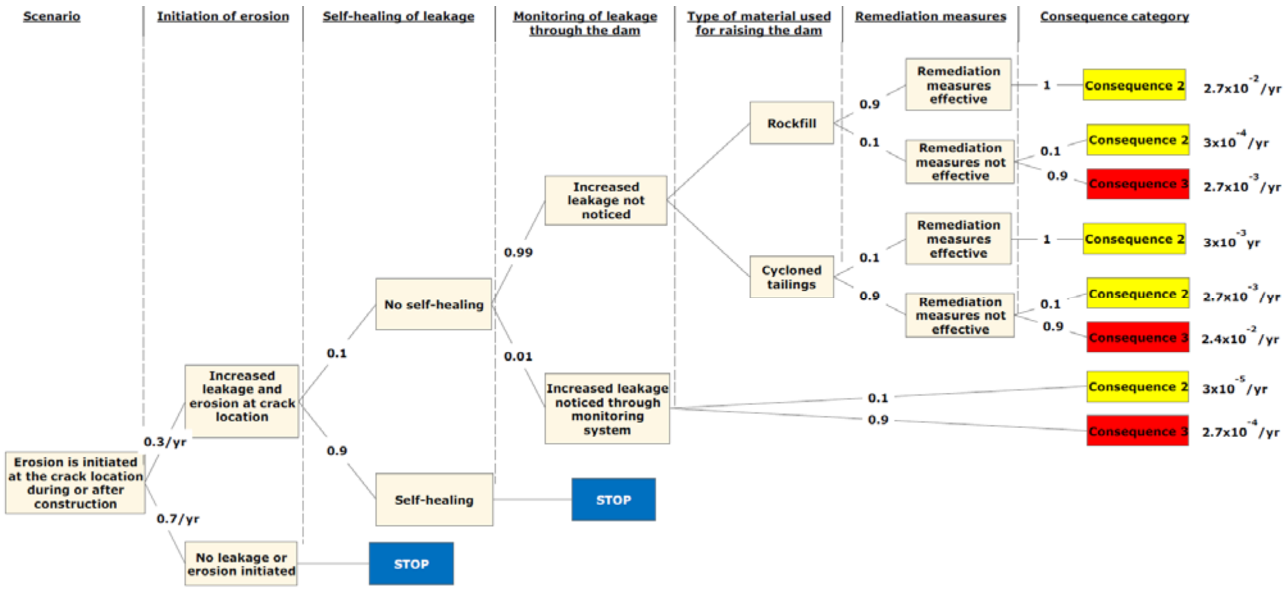

Figure 1 Event tree analysis of Scenario 4: Piping in dam along existing crack

Tables 4 presents the results of the probabilistic analyses using event trees. Several important uncertainties were believed to be significant to estimate the probability of each scenario, including:

- Scenario 1: The estimated annual probability of non-performance leading to catastrophic consequences was $4{\cdot}10^{-5}$/yr under earthquake loading. The main uncertainties governing the risk are to what extent the tailings will liquefy during the earthquake and whether the downstream slope of the dam remains stable.
- Scenario 2: The probabilities derived for this scenario should not be interpreted as annual values. The estimated high probability of non-performance is dominated by epistemic uncertainty (lack of knowledge). The probabilities can be greatly reduced through inspection and verification that concrete plugs are in good shape and functioning well.
- Scenario 3: A dam built with rockfill has much lower probability of non-performance with catastrophic consequences (Consequence Class 4) than a dam built with cycloned tailings. The latter is much more susceptible to erosion in case of overtopping and it is strongly recommended that erosion protection in form of a layer of rockfill with filters is provided on the downstream slope if the dam is built with cycloned tailings.
- Scenario 4: Rockfill dam has much lower probability of non-performance with major consequences (Consequence Class 3) than a dam built with cycloned tailings. The latter is much more susceptible to erosion in case of leakage through the crack and subsequently possible loss of freeboard, which may lead to overtopping. The estimated probability of non-performance for this scenario may be lowered through a programme of monitoring and contingency plans.
- Scenario 5: The joint planes in the rock cliff behind the existing ventana dip down and away from the cliff surface, making it extremely unlikely that an earthquake-induced rockslide would take place at the location of the existing ventana.

Table 4 Annual probabilities for different consequence classes for the five scenarios considered

Non-performance Scenario	Annual probability of non-performance for three consequence levels		
	Consequence 2 Significant or worse	Consequence 3 Major or worse	Consequence 4 Catastrophic
1- Extreme earthquake event	$6.8 \cdot 10^{-4}$	$4.1 \cdot 10^{-4}$	$4.1 \cdot 10^{-5}$
2- Leakage through buried ventanas and around tunnel plugs	0.50 (A)	0.225 (A)	$< 10^{-7}$ (B)
3- Extreme precipitation and flooding event	$9.3 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	$2.7 \cdot 10^{-5}$ (C) $2.4 \cdot 10^{-4}$ (D)
4- Piping through the dam in the cracked section	$3 \cdot 10^{-2}$	$3 \cdot 10^{-3}$ (C) $2.4 \cdot 10^{-2}$ (D)	$< 10^{-7}$ (B)
5- Earthquake-induced rockslide at location of Ventana 13	$< 10^{-7}$ (B)	$< 10^{-7}$ (B)	$< 10^{-7}$ (B)

(A) This high probability reflects the complete lack of documentation about the positions and conditions of earlier "ventanas" and their plugged tunnels that are now buried within the body of the dam.

(B) Not analyzed. Annual probability too low to be of interest for risk analysis

(C) Dam raised by 4 m using rockfill

(D) Dam raised by 4 m using cycloned tailings

5 Probabilistic analyses of the tailings dam using Bayesian network

The Bayesian network analyses were run for Scenario 4 where the tailings dam is raised by a 4-m high rockfill. The Bayesian network analyses first verified the result of the event tree analyses with the probability descriptors in Table 1. Thereafter, the Bayesian network analyses were supplemented with Monte Carlo simulations to obtain the statistics of the probability of the tailings dam non-performance (for Consequence 2) in terms of the mean and lower bound and upper bound probabilities of failure.

5.1 Best estimation of failure probability

The BN for the Scenario 4 and 4m rockfill raise is presented in Figure 2. Calculation with best estimate probabilities from Table 1 for each event were done using Hugin Lite (Hugin Expert 8.6, 2018).

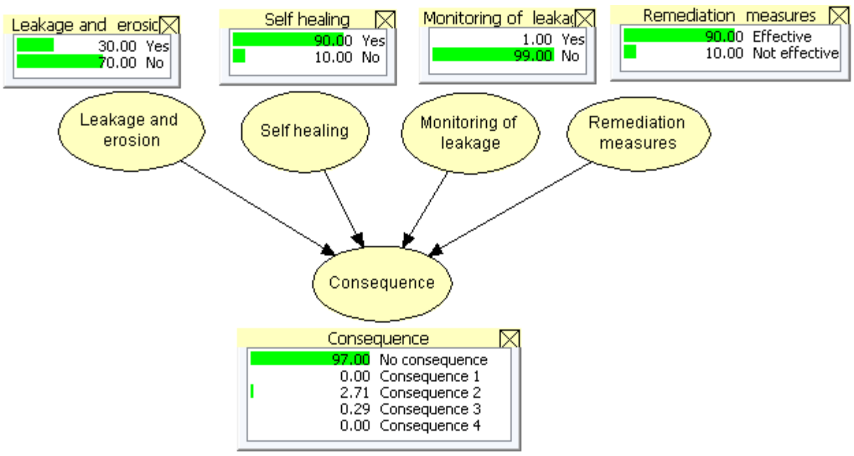

Figure 2 Bayesian network for estimating the non-performance probability due to 'Piping in dam along existing crack': mean and lower and upper bound estimates (probabilities listed as percentage point)

5.2 BN analyses enhanced with Monte Carlo simulations

Using the probabilities in Table 2, each event was assigned a range of probabilities to reflect an uncertainty in the probability estimates in Table 1. In the Monte Carlo analysis, a Beta distribution was selected for the probability of each event because the Beta probability density function (PDF) is suitable to model the behaviour of events limited to intervals of finite length (e.g., values between 0.33 and 0.66).

The Monte Carlo simulations provided the statistics of the probability of non-performance leading to the consequence classes in Table 2 for the tailings dam. The combined Bayesian network-Monte Carlo analyses were run for the Scenario 4 and Consequence Class 2 'Significant damage1 with the BNT toolbox in MATLAB (Murphy, 2001).

Figure 3 presents the results of the Monte Carlo simulations for the Scenario 4, with a histogram of the probability of Consequence Class 2. A mini-table on the figure summarizes the statistics of the annual probability distribution with the Mean ($3\cdot10^{-2}$), Standards deviation (SD), Coefficient of Variation (COV)[8], N (number of simulations), and p-value. The best fit of the histogram with a lognormal distribution is also shown. The p-value is obtained from the Kolmogorov-Smirnov goodness-of-fit test. A significance level of 5% is commonly used for this test. The p-values were greater than 5% for all parameters. Thus, the hypothesis of a lognormal marginal distribution for the probability of Consequence Class 2 is not rejected at the 5% significance level.

The probability of non-performance for the tailings dam leading to Consequence Class 2 ('significant damage') for the case of ''piping in dam along existing crack'' is with a mean of $2.7\cdot10^{-2}$/yr. The mean estimate was the same as the best estimate probability from the ETA analysis for the same scenario. The standard deviation is very high (COV of 57%) for this scenario with relatively high probability of non-performance, and reflects the uncertainty in the estimates, and the wide range of values suggested in Table 2.

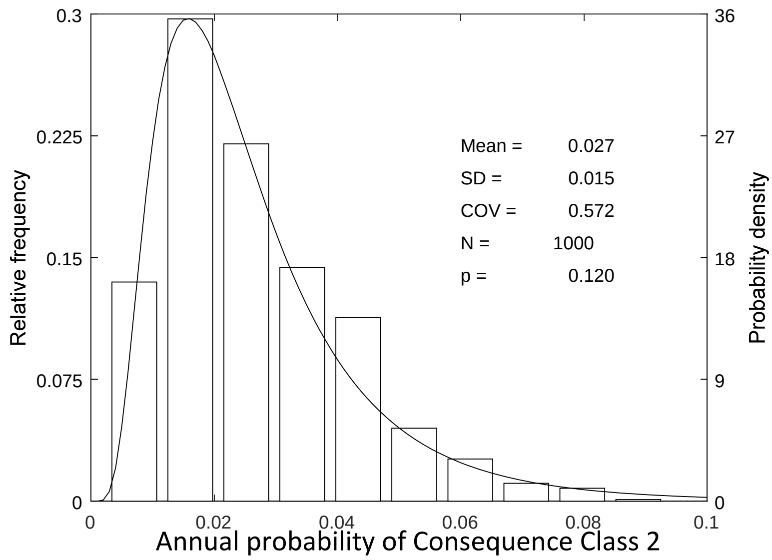

Figure 3 Distribution of probability of non-performance for the tailings dam leading to Consequence Class 2 ('significant damage') for the case of ''piping in dam along existing crack''.

[8] The coefficient of variation is the ratio of the standard deviation to the mean: COV = SD/mean

6 Conclusion

The application of probabilistic methods can be useful for ensuring safe and cost-effective tailings dam design. The annual probability of non-performance of the tailings dam leading to catastrophic consequences was found to be $4 \cdot 10^{-5}$/yr for the earthquake-induced dam failure scenario to $2.4 \cdot 10^{-4}$/yr for the extreme precipitation and flooding event. The total probability for catastrophic consequences was about $2.8 \cdot 10^{-4}$/yr. The total probability for major consequences and for significant consequence were about 0.225/yr and 0.5/yr, respectively, due to the complete lack of documentation about the positions and conditions of earlier "ventanas" and their plugged tunnels that are now buried within the body of the dam . The last two probabilities are so high that rehabilitation and mitigation measures are required.

The new approach, the Bayesian network combined with Monte Carlo simulations included a wide range of uncertainty in the probability estimates for each of the events in the chain of events that could lead to unsatisfactory performance of the tailings dam.

The probabilistic estimates are very useful information to have when the stakeholders need to make decisions regarding rehabilitation and, eventually, closure of the tailings dam.

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8. Biodiversity and ecological aspects

Long-term Effects of Trace Element Contamination and Tree Species on Soil Microbial Biomass and Enzyme Activities

M Gil-Martínez *Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS) - CSIC, Spain*

MT Domínguez *University of Seville, Spain*

CM Navarro-Fernández *Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS) - CSIC, Spain*

H Crompot *Haute École Condorcet, Belgium*

M Tibbett *University of Reading, United Kingdom*

T Marañón *Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS) - CSIC, Spain*

Abstract

Phytostabilisation technology in post-closure metal-mine industry may be a feasible reclamation solution to avoid the transfer of trace elements to adjacent systems and to provide long-term benefits increasing the functionality of the reclaimed ecosystem. In a contaminated and remediated area in SW Spain, we determined the long-term effects of different tree species on soil functionality. After the Aznalcóllar mine-spill, a large-scale phytostabilisation plan was launched including sludge and soil removal, amendment addition and native tree species afforestation. We selected two areas in the Guadiamar Green Corridor, the North and South fields, due to their different soil properties and contamination levels. Both fields were affected by the spill and were afforested by a mixed plantation pattern with specimens of the same age. Three native tree species were selected for this study: white poplar (Populus alba), stone pine (Pinus pinea) and wild olive (Olea europaea), and compared with adjacent treeless areas.

Nineteen years after the phytostabilisation implementation, we measured soil physical-chemical parameters and available and total trace element concentrations. For functional measurements, we analysed the microbial biomass C and N as well as a varied enzyme activities to measure the hydrolysis of assimilated products of C, N and P. A long-term marked contamination effect was still significant along the Guadiamar Green Corridor. The North field, closer to the mine tailings, presented contamination concentrations above the Lower Guideline Values for total As, Cu, Pb and Zn. Tree afforestation was found to be positive for the increase of soil fertility and microbial biomass on trace element contaminated soils. The studied tree species were found to affect differently the soil chemistry and microbial communities. White poplar and stone pine were the tree species with the greatest effects on soil. Soils under white poplar presented less acidification and more N content, while soils under stone pine were acidified and presented the highest C:N ratio. Regarding microbial biomass, stone pine was found to reduce the biomass growth. Regarding enzyme activities, tree species had different effects depending on the specific enzyme; however soil acidification and contamination were the main factors affecting them. In conclusion, our study demonstrates the importance of properly planning the post-closure reclamation according to the nature of the mining activity and the local conditions and properties of the mine location. When phytostabilisation technology is selected, the effects of tree species should be taken into account to improve reclamation success and develop a self-sustaining ecosystem.

Keywords: *Aznalcóllar mine-spill, functional ecosystem, phytostabilisation, post-closure, species-specific effect*

1 Introduction

Post-closure operations comprises reclamation and long-term stabilisation of mining areas. The reclamation success of the affected areas will depend on the planned closure and sequential land use developed during the production stage and the posterior implementation after closure (DIIS 2011). Therefore, post-mining land use planning should be addressed carefully and take into account the nature of the mining activity and the local conditions and properties of the mine location.

Metal-mine reclamation generally transforms post-mining landscapes through tree afforestation or phytostabilisation, which is the most feasible technology for the recovery of large areas contaminated by trace elements (Mendez & Maier 2008). The advantages of phytostabilisation are multiple: in situ technique, cost effectiveness, aesthetic value and potential for restoring overall ecosystem function (Garbisu et al. 2002). The use of trees may be a feasible reclamation solution to avoid the transfer of trace elements to adjacent systems and it could also provide long-term benefits, increasing the functionality of the reclaimed ecosystem. In order to develop the maximum functionality within the reclaimed ecosystem, the settlement and survival of planted trees is essential as well as reaching the optimal soil functionality to create a long-term self-sustaining ecosystem.

We expect that different tree species will have differential effects on soil functionality in terms of soil chemical properties, nutrient cycling and microbial activity performance (Aponte et al. 2013; Mitchell et al. 2010). Regarding soil chemistry, tree species inducing soil alkalinisation will produce the reduction of trace elements bioavailability and will be more effective for trace element phytostabilisation (Domínguez et al. 2009). Moreover, each tree species will produce a specific leaf litter quality which, through its decomposition, will have an effect on soil nutrients concentrations. It is also known that variations in C, N and P cycling drives changes in microbial communities (biomass, composition and physiological properties) (Berg & McClaugherty 2008; Orozco-Aceves et al. 2014).

We hypothesised that different tree species, through their species-specific effect on soil, will have a varied effect on soil microbial biomass as well as a varied enzymatic hydrolysis of assimilated products of C, N and P measured as beta-glucosidase, acid phosphatase, N-acetyl-glucosaminidase and leucyl aminopeptidase activities (Sinsabaugh et al. 2009). Moreover, we measured the oxidoreductase enzyme dehydrogenase as a general indicator of the soil microbial activity under different tree species (Trevors et al. 1982).

In a contaminated and remediated area in SW Spain, we determined the long-term effects of different tree species on soil functionality. Nineteen years after the afforestation of the contaminated area, we analysed soil fertility, contamination and microbial activities in two areas located at different distances downstream from the mine-spill.

2 Methodology

The studies reported here were carried out at the Guadiamar Green Corridor, located at 37.3916°N, 6.2255°W, in SW Spain. The climate is Mediterranean, with mild rainy winters and warm dry summers. Average annual temperature is 19°C and annual rainfall is 448 mm. The area was affected by a large mining accident in 1998, which left the soils severely contaminated by trace elements. After the Aznalcóllar accident, a large-scale phytostabilisation plan was launched including sludge and soil removal, amendment addition and native shrub and tree species afforestation. The restoration process mitigated the residual pollution and improved soil structure (more information in Madejón et al., 2018a).

We selected two areas in the Guadiamar Green Corridor, the North and South fields, due to their different distance from the Aznalcóllar mine tailings and, therefore, their different soil properties and contamination levels (Fig. 1). Both fields were affected by the spill and were afforested by a mixed plantation pattern with specimens of the same age. Three native tree species were selected for this study: white poplar (*Populus alba*), stone pine (*Pinus pinea*) and wild olive (*Olea europaea*), each of them with different mycorrhizal symbioses. Wild olives are symbionts of arbuscular mycorrhizal fungi, while stone pine and white poplar may form symbioses with ecto- and arbuscular mycorrhizal fungi. Soil was sampled at a depth of 0-5 cm under the tree species and in adjacent treeless areas, in March 2017. In each area 7 replicates per tree species and treeless were sampled.

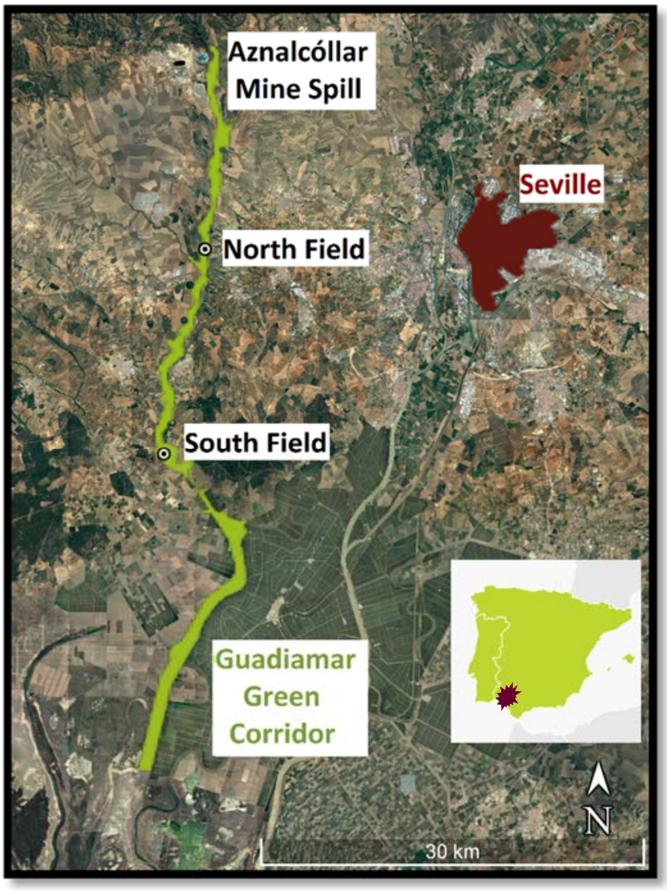

Figure 1 Situation map of the Guadiamar Green Corridor in SW Spain and location of studied sites.

A fraction of the soil samples were air-dried and sieved to <2 mm for physico-chemical analyses. Soil pH was measured in a 1:2.5 soil-water suspension by using a pH meter (CRISON micropH 2002). Total C and N content was determined using a Flash HT Plus elemental analyser. Olsen P (Olsen et al., 1954) was analysed for available P estimation in the South field, with neutral and basic soils, and Bray P was analysed in the North field, with acidic soils (Bray & Kurtz, 1945). Pseudo-total trace element concentrations in soil samples (ground to <60 µm) were determined by digestion with *aqua regia* in a Digiprep MS block digestion system (SPS Science). Bioavailability of selected trace elements was estimated by extraction with 0.01 M CaCl2 solution (Ure et al. 1993). Trace elements in both extracts were determined by ICP-OES (Varian ICP 720-ES).

A fraction of fresh soil samples were kept at 4°C for one week and soil was sieved to <2 mm for microbial analyses. Microbial biomass C and N were extracted in fumigated and non-fumigated samples with 0.5 M potassium sulphate solution (Vance et al. 1987). Microbial biomass was determined by the fumigation-extraction method modified by Gregorich et al. (1990). Different enzyme assays were carried out to determine the maximum potential enzymatic activity in soil. Soil enzyme activities, including beta-glucosidase, acid phosphatase, N-acetyl-glucosaminidase and leucyl aminopeptidase, were measured using a microplate fluorimetric assay (Marx et al. 2001). The substrates for beta-glucosidase, acid phosphatase and N-acetyl-glucosaminidase enzymes were conjugates of the fluorescent compound 4-methylumbelliferyl (MUB) and 50 mM sodium acetate buffer was used for optimal pH 5.5 (Tabatabai, 1982; Tabatabai & Bremner, 1969). The substrate for leucyl aminopeptidase was L-Leucine-7-amido-4-methylcoumarin (AMC) and 50 mM TRIS buffer was used for optimal pH 7.8. These activities were expressed in units of nmol g^{-1} h^{-1}. Dehydrogenase activity was determined in a 1 M TRIS–HCl buffer for optimal pH 7.5 (Trevors, 1984). The iodonitrotetrazolium formazan (INTF) produced was measured spectrophotometrically at 490 nm and was expressed in units of nmol INTF g^{-1} h^{-1}.

3 Results

3.1 Soil characteristics

3.1.1 Field effect

The North field was closer to the mine tailings; consequently its soil was highly affected by the spill contamination (Table 1). Significantly higher concentrations for all available (except As) and total trace elements (except Cd) were found in the North field compared to the South field. The contamination produced by sulphides had an acidification effect on the North field which showed a soil pH significantly lower to the neutral soils of the South field. Available P and total N were not significantly different among fields. However, total C was significantly higher in the South field soils, which explained the significantly higher C:N ratio in these soils (Table 1).

Table 1 Mean and SE results of soil variables and available and total trace elements in the two Field sites, and ANOVA results. Significant results ($p \leq 0.05$) are highlighted with bold letters. $^{\Delta}$Non-parametric Kruskal-Wallis chi-square. *Log-transformed data. Units: P and trace elements, mg kg^{-1}; N and C, %. Lower Guideline Values (LGV) for contaminated soils are according to MEF (2007).

Variable	North field		South field		*F*	*p value*	LGV
	Mean	SE	Mean	SE			
pH	5.9	0.3	7.4	0.03	36.00$^{\Delta}$	**<0.001**	
Avail. P*	16.06	2.06	19.42	3.35	1.41	0.241	
Total N*	0.257	0.022	0.241	0.013	0.62	0.434	
Total C	2.16	0.28	3.13	0.277	16.89	**<0.001**	
C:N	8.19	0.60	12.81	0.66	74.61	**<0.001**	
Avail. As	0.201	0.049	0.169	0.044	0.66	0.419	
Avail. Cd	0.054	0.019	0.003	0.001	19.32$^{\Delta}$	**<0.001**	
Avail. Cu	0.385	0.181	0.057	0.011	30.87$^{\Delta}$	**<0.001**	
Avail. Pb	0.159	0.037	0.089	0.030	6.11	**0.017**	
Avail. Zn	5.54	2.35	0.134	0.045	32.06$^{\Delta}$	**<0.001**	
Total As	146.8	18.17	36.54	5.53	39.19$^{\Delta}$	**<0.001**	50
Total Cd	0.707	0.169	0.699	0.096	0.01	0.941	10
Total Cu	186.6	12.18	57.91	3.33	290.72	**<0.001**	150
Total Pb	241.8	32.36	72.84	13.32	37.16$^{\Delta}$	**<0.001**	200
Total Zn	286.7	25.18	235.6	15.74	8.31	**0.006**	250

3.1.2 Species effect

Tree species did not show a significant difference in soil pH or available P. However, soil total N, C and their ratio C:N were significantly different between species (Table 2). Total N was higher under *Populus alba* species than *Pinus pinea* species and treeless, while total C was higher under *Populus alba* and *Pinus pinea* species than treeless. Soil C:N ratio were significantly higher under *Pinus pinea* and *Populus alba* species in comparison to treeless. No significant differences were found between tree species for any available or total trace element (data not shown).

Table 2 Species factor one way ANOVA, mean and SE results of soil variables. Significant results ($p \leq 0.05$) are highlighted with bold letters. Units: P and trace elements, mg kg^{-1}; N and C, %.

Variable	*Olea europaea*		*Populus alba*		*Pinus pinea*		Treeless		*F*	*p value*
	Mean	SE	Mean	SE	Mean	SE	Mean	SE		
pH	6.8	0.2	6.7	0.4	6.3	0.5	6.9	0.3	0.69	0.562
Avail. P	17.77	2.57	22.14	3.15	14.75	1.41	16.30	3.39	1.89	0.143
Total N	0.259**ab**	0.011	0.286**a**	0.023	0.229**b**	0.016	0.221**b**	0.014	4.37	**0.008**
Total C	2.60**ab**	0.29	3.09**a**	0.30	2.90**a**	0.35	1.98**b**	0.23	3.79	**0.016**
C:N	9.88**bc**	0.89	10.90**ab**	0.86	12.40**a**	1.02	8.83**c**	0.81	4.05	**0.012**

3.1.3 Field and species effects

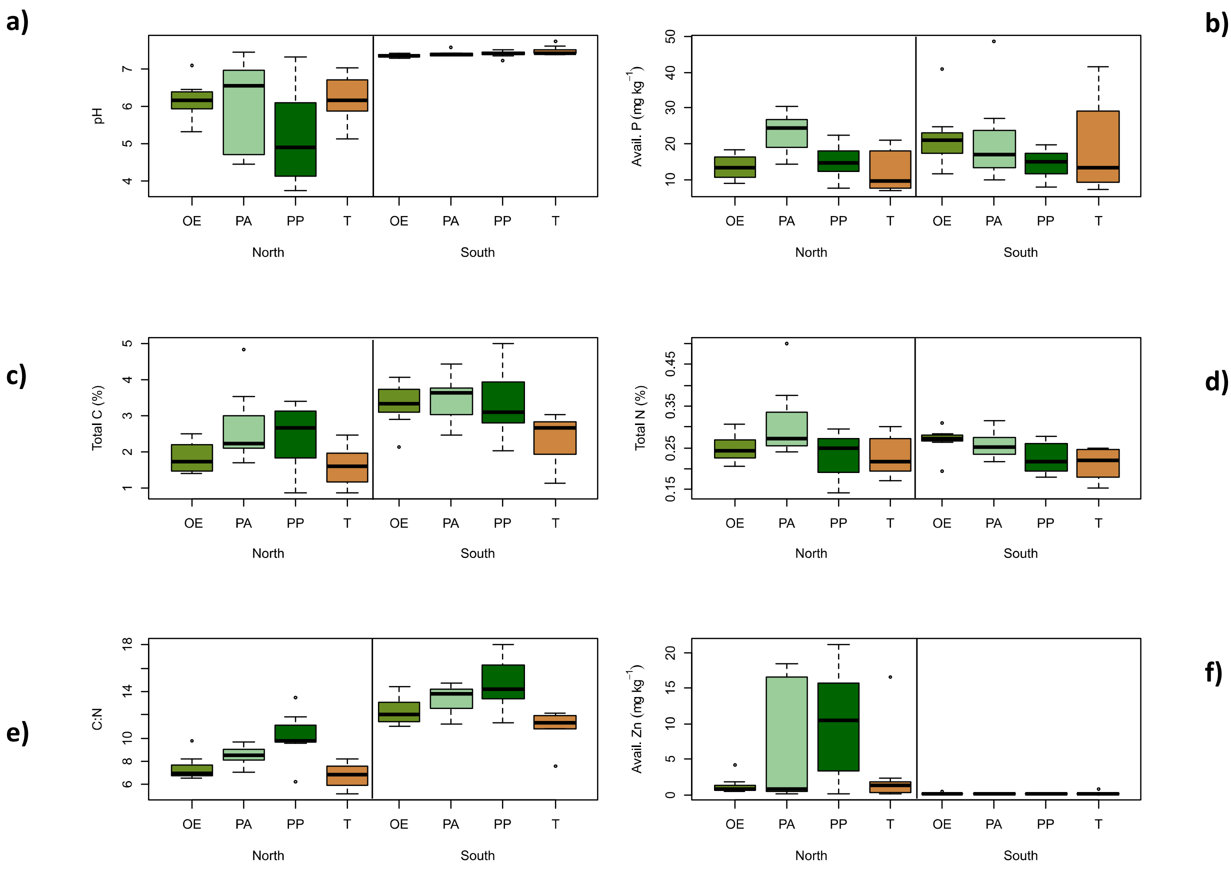

Figure 2 Soil variables under the studied tree species (OE, PP, PA) and treeless (T) in North and South fields. Box edges represent the upper and lower quartile with median value shown in the middle of the box, whiskers represent minimum and maximum, and circles show suspected outliers. a) pH; b) Available P (mg kg^{-1}); c) Total C (%); d) Total N (%); e) C:N ratio; f) Available Zn (mg kg^{-1}). OE: *Olea europaea*; PP: *Pinus pinea*; PA: *Populus alba*; T: treeless.

Soil variables were analysed by both field and species factors, however none of them presented a significant interaction effect (Fig. 2). Soil pH was significantly higher in the South field (Fig. 2a) while available Zn was significantly higher in the North field (Fig. 2f). Total C and C:N ratio were found significantly higher in the South field and under *Populus alba* and *Pinus pinea* species (Fig. 2c and 2e). Total N was not affected by field factor but was found significantly higher under *Populus alba* species (Fig. 2d). Available P were not significantly different in any case (Fig. 2b).

3.2 Microbial biomass and enzymatic activities

3.2.1 Field and species effects

Soil microbial biomass C and N were significantly different between tree species, and N was also significantly different between the North and South fields (Table 3). Some soil enzyme activities were highly influenced by both factors: beta-glucosidase, N-acetyl glucosaminidase, leucyl aminopeptidase and dehydrogenase. Moreover, leucyl aminopeptidase and dehydrogenase presented a significant interaction between factors. Acid phosphatase activity was significantly different among fields (but not among tree species) but showed an interaction of factors effect.

Table 3 Results of the generalized linear models applied to microbial biomass and enzyme activities across tree species and field. Significant results ($p \leq 0.05$) are highlighted with bold letters. Cmic, Nmic, BGL, ACP and LAP were analysed with gamma distribution and "inverse" link function. NAG was analysed with gamma distribution and "log" link function. DH was analysed with Gaussian distribution and "identity" link function. Cmic: microbial biomass carbon; Nmic: microbial biomass nitrogen; BGL: beta-glucosidase; ACP: acid phosphatase; NAG: N-acetyl-glucosaminidase; LAP: leucyl aminopeptidase; DH: dehydrogenase; D^2: adjusted model deviance.

Variable	Species	Field	Interaction	D^2
Cmic	**0.001**	0.513	0.248	0.28
Nmic	**0.004**	**0.037**	0.418	0.31
BGL	**0.006**	**<0.001**	0.634	0.42
ACP	0.091	**<0.001**	**0.011**	0.81
NAG	**0.002**	**<0.001**	0.170	0.65
LAP	**0.001**	**<0.001**	**<0.001**	0.54
DH	**<0.001**	**<0.001**	**0.047**	0.57

Tree species and field effects were studied in detail for each microbial variable and results are shown in Figure 3. Tree species effect was found in microbial biomass C and N where treeless soils registered the lowest biomass in both the North and South fields (Fig. 3a and 3b). Enzymes with their optimal activity at pH 5.5 (beta-glucosidase, N-acetyl glucosaminidase and acid phosphatase) showed increased activity in the North field. Regarding the differences between tree species, beta-glucosidase activity was slightly higher under *Populus alba* species (Fig. 3c), and N-acetyl glucosaminidase activity was higher under *Pinus pinea* species (Fig. 3e). Acid phosphatase was significantly higher under *Pinus pinea* species than treeless areas in the North field, however no significant differences were found in the South field (Fig. 3d). Leucyl aminopeptidase activity was significantly higher under *Populus alba* and *Pinus pinea* species but only in the South field (Fig. 3f). Dehydrogenase activity was significantly higher under *Olea europaea* and *Populus alba* species in the South field, and significantly lower under *Pinus pinea* species in the North field (Fig. 3g).

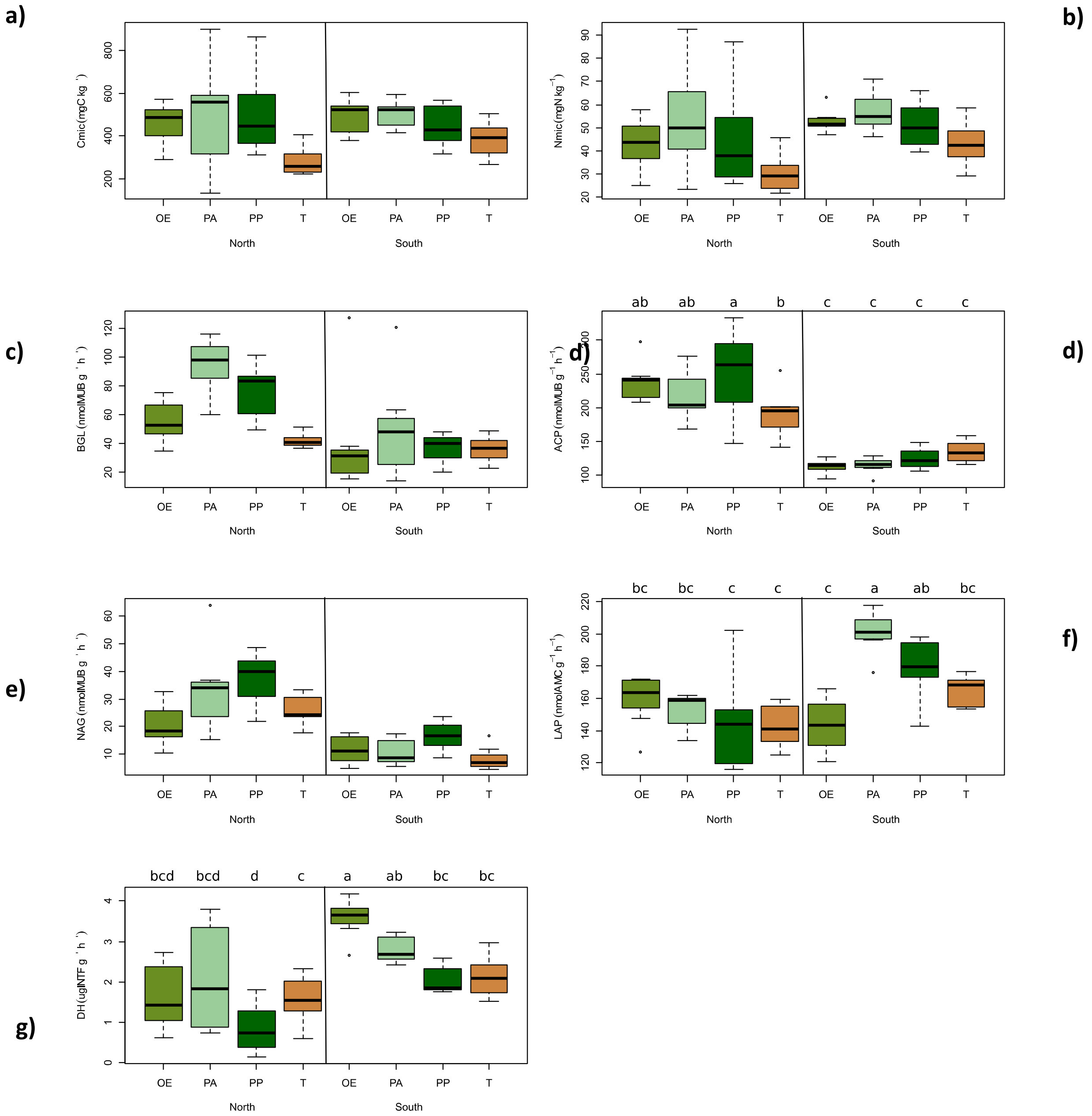

Figure 3 Soil microbial activity under the studied tree species (OE, PP, PA) and treeless (T) in North and South fields. Different letters above species indicate significant differences when interaction factors effects exist. Box edges represent the upper and lower quartile with median value shown in the middle of the box, whiskers represent minimum and maximum, and circles show suspected outliers. a) Microbial biomass carbon (mgC kg^{-1}); b) Microbial biomass nitrogen (mgN kg^{-1}); c) Beta-glucosidase activity (nmolMUB g^{-1} h^{-1}); d) Acid phosphatase activity (nmolMUB g^{-1} h^{-1}); e) N-acetyl glucosaminidase activity (nmolMUB g^{-1} h^{-1}); f) Leucyl aminopeptidase activity (nmolAMC g^{-1} h^{-1}); g) Dehydrogenase activity (μgINTF g^{-1} h^{-1}). OE: *Olea europaea*; PP: *Pinus pinea*; PA: *Populus alba*; T: treeless.

3.3 Soil, microbial biomass and enzymatic activities relationships

All microbial biomass and enzyme activities were highly correlated to soil pH (Table 4). Microbial biomass C and N increased with pH, while enzyme activities presented different trends. Beta-glucosidase, acid phosphatase and N-acetyl glucosaminidase activities showed higher values in acidic soils, while leucyl aminopeptidase and dehydrogenase activities correlated positively to pH. None of the microbial variables correlated to available P. Soil total N had a positive effect on microbial biomass N, beta-glucosidase and N-acetyl glucosaminidase. Soil total C positively correlated to microbial biomass C and N but negatively to acid phosphatase. Soil C:N ratio correlated positively to microbial biomass N, leucyl aminopeptidase and dehydrogenase activities, and negatively to acid phosphatase and N-acetyl glucosaminidase activities. Available Zn contamination showed a high correlation to all microbial variables. Microbial biomass C and N was reduced in higher contaminated areas as well as leucyl aminopeptidase and dehydrogenase activities. However, contamination was positively correlated to beta-glucosidase, acid phosphatase and N-acetyl glucosaminidase activities.

Table 4 **Results of the bivariate correlations between microbial biomass and enzyme activities with the soil variables. Significant results ($p \leq 0.05$) are highlighted with bold letters. Asterisks indicate the significance level (* $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$). Bio C: biomass carbon; Bio N: biomass nitrogen; BGL: beta-glucosidase; ACP: acid phosphatase; NAG: N-acetyl-glucosaminidase; LAP: leucyl aminopeptidase; DH: dehydrogenase.**

Variable	Cmic	Nmic	BGL	ACP	NAG	LAP	DH
pH	**0.313***	**0.508*****	**-0.449****	**-0.868*****	**-0.684*****	**0.482*****	**0.695*****
Avail. P	0.062	0.118	-0.090	-0.204	-0.179	0.127	0.150
Total N	0.196	**0.375***	**0.304***	0.08	**0.353***	-0.017	0.046
Total C	**0.294***	**0.465*****	-0.024	**-0.386****	-0.055	0.264	0.254
C:N	0.238	**0.349***	-0.256	**-0.587*****	**-0.349***	**0.379***	**0.309***
Avail. Zn	**-0.316***	**-0.432****	**0.424****	**0.668*****	**0.573*****	**-0.377****	**-0.582*****

4 Discussion

4.1 Soil characteristics

Nineteen years after the Aznalcóllar mine-spill there is still a marked contamination effect along the Guadiamar Green Corridor. The North field, closer to the mine tailings, is significantly more contaminated than the South field, presenting contamination concentrations above the Lower Guideline Values for total As, Cu, Pb and Zn (Table 1). Lower Guideline Values indicate that the North field area may still present an ecological and/or health risk (MEF 2007) while in the South field the risk is lower. In a previous study, Domínguez et al. (2016) found that at the most contaminated areas in the Guadiamar Green Corridor there was a strong soil acidification due to the oxidation of the remnants of sulphides deposited during the mine-spill. Therefore, mine-spill contamination may be responsible for the North field acidification.

An acidification effect was expected on soils under stone pine (Sariyildiz et al. 2005; Swift et al. 1979) and a consequent higher availability of trace elements (Domínguez et al. 2009; Madejón et al. 2018b). Surprisingly, there was no significant effect of the tree species on soil contamination neither available nor total concentrations. However, an incipient effect was visible as Zn availability under stone pine was highly variable among replicates and a higher availability trend was found in the North field (Fig. 2f). Moreover, a previous study in the North field (Madejón et al. 2018b) registered a lower soil pH and higher trace element availability under stone pine.

A marked species-specific effect through a chemical footprint in topsoil was found. On one hand, trees are acting as ecosystem engineers modifying the soil properties (Jones et al. 1994; Mitchell et al. 2010) probably through their root exudates and leaf litter quantity and quality. On the other hand, the decomposition of roots and leaf litter is producing an effect on the ecological processes such as nutrient and carbon cycling, contributing to the maintenance of soil fertility (Kara et al. 2014). Low-quality litter for decomposers is generally suggesting a high litter C:N ratio (Chomel et al. 2016) and we found a species litter quality footprint in the studied soils. Treeless soils, covered by herbaceous species, presented the lowest soil C:N ratio in comparison to soils under trees, which is in line with the general understanding that herbaceous habitats have higher-nutrient and lower-recalcitrant compounds in comparison to forested ones (Strickland et al. 2009). Moreover, herbaceous species are known to produce lower litter quantities and accumulation than trees (Donath & Eckstein 2008) which could explain the lowest soil total C and N contents in treeless areas. In previous studies, coniferous species were found to produce lower quality litter compared to broadleaf species (Chomel et al. 2015; Cornwell et al. 2008; Pérez-Harguindeguy et al. 2000) and our soils corroborated this litter effect on soils as the stone pine was the tree species with the highest soil C:N ratio among the three studied species.

4.2 Microbial biomass and enzymatic activities

Soil biological parameters may have a potential as early and sensitive indicators of soil ecological stress and restoration (Dick & Tabatabai 1992) and we support here the importance of studying microbial activities as soil quality and bioremediation success indices (Burns et al. 2013; Wang et al. 2007). Microbial activity and soil fertility are related due to the mineralization of the organic nutrients by the microbial communities (Frankenberger & Dick 1983). Therefore, contamination and tree species effects on soil properties may have an effect on microbial activity and, indirectly, on the biochemical processes in our studied soils.

Microbial biomass C and N was found to correlate negatively to contamination levels (Table 4) which is in line with previous evidence that trace elements decrease microbial biomass C (Brookes 1995; Wang et al. 2007). However, tree species effect was greater than the field effect on microbial biomass (Table 3). Treeless soils presented significantly lower biomass in comparison with afforested soils which may hinder microbial growth due to nutrient availability limitation or lower litter quantity input.

Soil enzyme activities are considered sensitive and early indicators of natural and anthropogenic disturbances (Giller et al. 1998). We agreed with the previous findings about trace element contamination, which has a major effect as bioavailable concentrations rather than as total concentrations on enzyme activities (Pérez-De-Mora et al. 2006). Thus, Zn availability negatively correlated to leucyl aminopeptidase and dehydrogenase activities. However, unexpected positive correlations were found for beta-glucosidase, acid phosphatase and N-acetyl-glucosaminidase activities (Table 4), which could be mediated by soil pH. We found that the enzyme assay protocol had an important effect on our potential enzyme activities. The enzyme assay protocol followed was the classical approach where conditions were optimized and optima pH for each enzyme selected (Burns et al. 2013). Optima pH for beta-glucosidase, acid phosphatase and N-acetyl-glucosaminidase activities was acidic (pH 5.5) while optima pH for leucyl aminopeptidase and dehydrogenase activities was basic (pH 7.8 and 7.5, respectively). These pH differences on assays are responsible for the marked variations between fields as the North field had acidic soils and the South field neutral to basic soils. Moreover, discrimination of the effect of pH and contamination was difficult in our experimental study as both effects correlated.

A tree species effect was found on enzyme activities when optima pH was naturally found in our soils. A possible explanation may be that when optima soil pH is reached then nutrient availability may influence enzymatic activities but when pH is far from optima other factors are not relevant for enzyme activities.

Beta-glucosidase activity is involved in the cellulose hydrolysis (Alef & Nannipieri 1995) and we found it to positively correlate to soil total N (but not to soil C content) as previous studies demonstrated (Eivazi & Tabatabai 1988; García-Gil et al. 2000). Pérez-De-Mora et al. (2006) reported that beta-glucosidase activity is less sensitive than other enzymes to trace element contamination which could explain the positive correlation to available Zn.

Acid phosphatase is involved in the mineralization of organic phosphate esters in acid soils (Frankenberger & Dick 1983; Pant & Warman 2000). This activity showed a high contrast between the North acidic field and the South neutral field. Soil acidification and contamination were highly correlated to acid phosphatase activity due to the nature of the enzyme. The possible acidification effect of stone pine in these soils may enhance the acid phosphatase activity, which is inversely related to soil pH (Staddon et al., 1998).

N-acetyl-glucosaminidase was positively correlated to soil N as it is one of the enzymes with a major role in N mineralization in soils. However, leucyl aminopeptidase activity, which is also involved in the N cycle through the degradation of proteins and peptides, did not present a correlation to soil N (Lin et al. 2017; Parham & Deng 2000).

Dehydrogenase was positively correlated with soil pH and microbial biomass C (r=0.341**) and N (r=0.500***), and negatively correlated with soluble HM concentrations, as suggested by Pérez-De-Mora et al. (2006). Dehydrogenase is an intracellular enzyme catalysing oxidoreduction reactions of organic compounds and occurs only on living cells and is affected by trace elements contamination (Chaperon & Sauvé 2007), which explains its higher activity in the less contaminated South field.

5 Conclusion

Nineteen years after the implementation of a phytoremediation plan to amend the Aznalcóllar mine-spill, a marked trace element contamination effect still exists along the Guadiamar Green Corridor. Despite the phytostabilisation long-term effect of the studied tree species was weak in terms of soil pH and contamination stabilisation, a marked tree species footprint was found in terms of soil total C and N contents as well as on microbial biomass and enzymatic activities performance.

Tree afforestation was found to be positive for the increase of soil fertility and microbial biomass on trace element contaminated soils. The studied tree species were found to affect differently the soil chemistry and microbial communities. White poplar and stone pine were the tree species with the greatest effects on soil. Soils under white poplar presented less acidification and more N content, while soils under stone pine were more acidified and presented the highest C:N ratio. Regarding microbial biomass stone pine was found to reduce the biomass growth. Regarding enzyme activities, tree species had different effects depending on the specific enzyme; however soil acidification and contamination were the main factors affecting them.

In conclusion, our study demonstrates the importance of planning properly the post-closure reclamation according to the nature of the mining activity and the local conditions and properties of the mine location. When phytostabilisation technology is selected, the effects of tree species should be taken into account to improve reclamation success and develop a self-sustaining ecosystem.

Acknowledgement

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Benefits and Necessity of Communicating Biodiversity in School Education. A Practical Example of Communication Science.

S Walter *Technical University Bergakademie Freiberg, Germany*

Abstract

The protection and conservation of biological diversity are crucial for mankind. Therefore, the introduction of the term biodiversity was linked to the goal of communicating the impact of possible losses to the public. However, there currently still exists a lack of knowledge and interest in the topic and science as interviews with pupils aged 15 to 16 in Saxony, Germany show. Hence, the project SOCIAL NATURE has been developed. The aim is to enhance environmental education in the field of biodiversity by linking it to a topic that is perceived as more interesting by this age group: digital and social media. Pupils learn how to deal best with digital and social media by creating content for different channels while at the same time researching biological and diversity facts for those pieces on their own. Due to using the communication method of storytelling, a large group of the population is reached and thus also informed about biodiversity. This paper illustrates the scientific background of the project SOCIAL NATURE, describes its design and the practical implementation as well as initial findings from its realisation.

Keywords: *biodiversity, environmental education, school, communication*

1 Introduction

Nature and the environment are the basis of human life (Possitt & Zander 2017). Their protection and thus the conservation of biological diversity are crucial and one of the main challenges for mankind (Krombaß 2007; Assmann et al. 2014; Steffen et al. 2015).

This is one of the reasons why the loss of biodiversity has become a focus of media and public interest in recent years (Gerl, Almer & Gerl 2018), but the term biodiversity and the related long-term effects are not widely known among the majority of citizens (Holzner in Splechtna 2010). According to Splechtna (2010), one reason given for the imbalance between necessity and knowledge with regard to biodiversity is the perspective; in his opinion, a purely scientific one is insufficient to convey the topic of biodiversity to the general public (Splechtna 2010). In addition, Haber (2004) states that the experts (subconsciously) wrongly assume that "the society is entirely made up of a human potential that is rationally and emotionally mobilizable for nature"(Haber 2004: 37). Consequently, it must also be the task of scientists to provide the population with knowledge on the topics of biodiversity and environmental protection in an appropriate manner.

2 Methodology

Originating from the English term Biological Diversity(Splechtna 2010), biologists in the field of nature conservation and entomologists for biological diversity (Assmann et al. 2014) used the abbreviation Biodiversity (Purvis & Hector 2000; Tilman 2000) since 1986 (Splechtna 2010; Assmann et al. 2014). The introduction of the term was linked to the goal of "communicating the global losses of biological diversity to the public and simultaneously establishing biodiversity research in the scientific landscape"(Splechtna 2010: 232) (Takracs 1996; Eser 2003).

Splechtna (2010) points out that since 1992, with the signing of the Convention of Biological Diversity (CBD) at the Earth Summit in Rio de Janeiro, political representatives have adopted biodiversity as an important goal (Splechtna 2010). Through this conference of the United Nations, biodiversity became a subject of public interest for the first time (Krombaß 2017). In the CBD, the preservation of biodiversity is presented as an essential task for the entire mankind and the value in "ecological, genetic, social, economic, scientific, educational, cultural, recreational and aesthetic values […] and its components"(UN 1992: 1) is outlined (Krombaß 2017). In addition to the scientific fields of biology and ecology, the term biodiversity is therefore also used in the sociopolitical context (Assmann et al. 2014).

In everyday parlance, the term biodiversity is synonymous with diversity of species (Splechtna 2010); the diversity of species is in any case a key indicator of biodiversity (Haber 2004). However, a restriction to the diversity and protection of species is misleading and incorrect in relation to the core idea of the CBD (Haber 2004). It explains that

> *"'Biological diversity' means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems"(UN 1992: 3).*

Consequently, biodiversity covers three levels: "genetic variability within species" (Assmann et al. 2014: 153), taxa, i.e. genera and subspecies (short: diversity of species), and diversity of biocoenoses and their ecosystems as well as the processes taking place therein (Wittig & Niekisch 2014; Assmann et al. 2014). The founder of Conservation Biology, Soulé, shortens this and identifies biodiversity as life in all its dimensions, manifestations and richness (Takacs 1996), in other words, biodiversity refers to the entire diversity of living nature (Splechtna 2010). However, these statements are not an exact definition, so Beierkuhnlein (2001) thinks that they do not support implementation (Beierkuhnlein 2001; Haber 2004). However, in any case it has become evident that the term biodiversity is an elusive and difficult-to-handle subject, partly because the term's broad definition and complexity made it difficult "to define definitive goals and to develop suitable metrics with which the achievement of the goals can be verified"(Splechtna 2010: 232).

This paper adopts the definition according to the CBD as being correct: "Biodiversity encompasses the entire diversity of life on earth, from genetic diversity and biodiversity to the diversity of ecosystems" (Krombaß 2017: 6 according to the UN 1992, Gaston 1996, Wilson 1997). The main products and services available on earth depend on this diversity and variability of ecosystems, species and genes (AAAS 1989). Biological resources nourish, clothe, heal through medicine and provide spiritual nurture for humanity (AAAS 1989). However, more and more animal and plant species as well as populations are being extinct without being replaced by new ones on a similar scale (Haber 2004). This documented loss is largely a direct or indirect consequence of human activity and poses a serious threat to humanity (Haber 2004; AAAS 1989).

An important factor of influence is the homogenisation of surfaces caused by humans (Haber 2004). In addition to agricultural and forestry use, projects in the energy and raw materials sector inevitably imply changes in nature and the environment. Critics cite negative consequences such as soil degradation, emissions of toxic substances, release of acidic mining water, noise pollution or tailings (Federal Environment Agency 2014). These effects exist, but cannot be generalised and applied to the entire industry and every mining site, especially during and after recultivation.

On the positive side, it should be noted that due to the specific conditions in many mining sites, unique ecosystems have emerged which, with their special flora and fauna, offer extraordinary opportunities for species protection (Wittig & Niekisch 2014; Wasserbach 2008). Knowledge of these characteristic environments, which are unique habitats for a large number of species, some of which are endangered, and biodiversity in general is scarce in the population: Neither the term biodiversity(Menzel & Bögeholz 2006) nor sustainability/sustainable development(Bolsho & Michelsen 2002) are generally known (Krombaß 2017). Biodiversity is understood, if at all, as "the number of species in a certain area."(Krombaß 2017: 10) In addition, "knowledge of species and forms is limited"(Krombaß 2017: 10 according to Jäkel 2005, Lindemann-Matthies 2002, Scherf & Bienengräber 1988), which means that there is a strong need for action in communicating these topics (Krombaß 2017). Scientists point out that education can make a decisive contribution to "making the public aware about the value of diversity and the measures necessary for its conservation"(Krombaß 2017: 8 according to UN 1992). This is based, among other things, on the assumption that the measures necessary for biodiversity cannot be borne and managed exclusively by government organisations, but by each individual citizen (BfN 1997). Consequently, especially pupils should be introduced to the associated problem areas in their role as the future generation of decision-makers, enabling them to develop "their own views on environmental and development policy"(Krombaß 2017: 9 according to BMU 1997) and "be prepared for environmentally responsible decisions and actions"(Krombaß 2017: 4).

On the one hand, it is scientifically confirmed that there is a positive "connection between experiencing nature directly and affirming it in the early phase of life and the willingness to commit oneself to nature and environmental protection in later life"(Gerl, Almer & Gerl 2018: 95 according to Eigner & Schmuck 1998); on the other hand, biodiversity is a field that deals with real challenges and recognises, critically questions and discusses "the various scientific and political value convictions"(Krombaß 2017: 9).

However, educators bemoan the fact that children and young adults hardly realize their immediate surroundings, that they do not encounter nature directly and thus increasingly alienate themselves from it (Gerl, Almer & Gerl 2018). Consequently, researchers call for consistent and interdisciplinary communication of biodiversity and sustainability in school education (de Haan & Harenberg 1999; Menzel & Bögeholz 2006; van Weelie & Wals 2002). It is essential to emphasise the pupils' own role in dealing with natural resources, the environment and biodiversity (Krombass 2017). Krombass (2017) supports this approach by pointing out that biodiversity "is ascribed only an ideal value, but its economic, ecological, scientific and aesthetic value is not recognized"(Krombaß 2017: 11). Therefore, near-nature places such as forests, meadows, waters "play an important role in the action-oriented teaching of knowledge about biodiversity and ecological relationships"(Krombaß 2017: 12).

During the past 15 years, many projects have been based on this approach, such as Lebensraum Bach, Tag der Artenvielfalt, etc. (Guggenberger n.d.; GEO n.d.; Krombaß 2017; Gerl, Almer & Gerl 2018); in addition, non-school institutions such as zoos or natural history museums were modernised and now provide "educational content with realistic application possibilities"(Krombaß 2017: 11) This exemplary list points to the broad spectrum of possibilities in communicating the topic of biodiversity in school-based education. Gross (2017) calls for "natural history education to begin in kindergartens and then continue at schools and universities up to adult education"(Gross & Behme 2017: 3), whereby each individual measure can make a contribution to improving the level of knowledge (Röser & Behme 2015).

3 Data

A variety of projects with and for different target groups are being created at two-year intervals as part of the Quarry Life Award of HeidelbergCement AG (HeidelbergCement n.d.a). Since 2011, more than 380 projects in 25 countries have been selected for realisation in four competitions and have been financially supported (HeidelbergCement n.d.a). During the 2017/2018 selection period, the project SOCIAL NATURE was supported among the six selected initiatives in Germany (HeidelbergCement n.d.). SOCIAL NATURE counteracts the lack of knowledge and interest of young people in the areas of biodiversity and the raw materials and energy sector (SOCIAL NATURE 2018 February 13).

In February 2018, a survey of pupils aged 15 to 16 at a grammar school in Saxony revealed that 68 percent of the young people rated their knowledge in the fields of raw materials and energy as rather low or low, and that the level of interest in these areas is also rather low or low for 68 percent. In the survey, students were also asked about their interest in social and digital media: more than 81 percent of those surveyed wanted their knowledge in this area to increase (see figure 1, adapted from SOCIAL NATURE 2018 February 19).

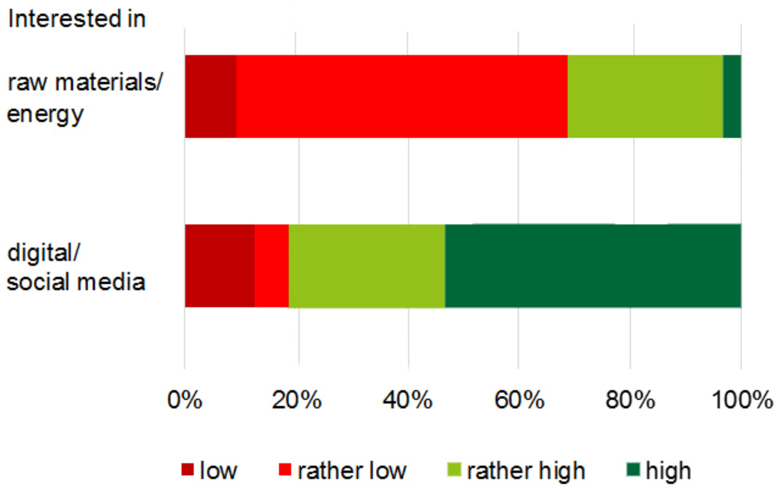

Figure 1 Interest in raw materials/energy and digital/social media (own figure adapted from SOCIAL NATURE 2018 February 19)

Digital media such as blogs, wikis, facebook, twitter, instagram have established as an "integral part of social life"(Fieseler, Hoffmann & Meckel 2010: 23 according to Meckel 2008). In this age group, the use of social media on average exceeds 172 minutes per day (DAK Gesundheit 2018: 8), the self-evaluation of the respondents and the identified interest gap between the subject areas raw materials/energy and digital/social media were used to design the project SOCIAL NATURE.

The adolescents followed the life of a bird with the help of personalized social media storytelling. Each piece was written for social media by the students using the view of a bird, the whitethroat. The work was carried out on the basis of their own research, on-site observations and expert interviews in an informative and entertaining way, whereby the existing knowledge gaps were reduced for specific target groups. The participants were deeply sensitised and motivated especially by the research in the mining site, because they committed themselves jointly and empathised with the bird. They were trained in the two areas of environment/biodiversity and digital/social media, resulting in increased educational value (SOCIAL NATURE 2018a; SOCIAL NATURE 2018 February 13).

Figure 2 Logo of the project SOCIAL NATURE (SOCIAL NATURE 2018a)

Throughout the project phase from January to September 2018, the pupils were trained once a week during their science lessons (two hours a week) by the project manager and external speakers (SOCIAL NATURE 2018a).

The project work started with an introduction to the topic "Raw materials in everyday life - and in the future?", in which the teenagers were objectively informed about mining, consumption and necessity of raw materials based on well-founded data. In addition, the participants conducted their own literature research for various tasks. The teachers were present during all the lessons, lectures and workshops in order to improve their knowledge as well, so that they can act as mediators in other classes in the future (SOCIAL NATURE 2018 March 29; SOCIAL NATURE 2018a).

Because the personal experience of nature must be preferred to other possibilities such as the mediation by means of modern technology, the pupils and their teachers were given a guided tour by experts outside the school: the nearby mining site. As a result, they were able to expand their knowledge of both the extent of production and the recultivation of mining sites individually and sustainably based on their interest in the subject (SOCIAL NATURE 2018 April 4). This form of excursion corresponds to the "calls for interdisciplinarity, everyday life, action orientation and integration of affectivity"(Krombaß 2017: 11).

Figure 3 Participants of the project SOCIAL NATURE in the quarry of HeidelbergCement AG (SOCIAL NATURE 2018 April 4)

In the subsequent lesson, a speaker of the prevention project "Social Web macht Schule"(queo GmbH n.d) from Dresden gave a workshop on social media (SOCIAL NATURE 2018 May 1). As the diversity of social media channels has increased (Breuer & Behme 2016), general, cross-channel topics such as copyright, intellectual property and data protection were discussed age-appropriate with a focus on several key questions: What do the terms mean? Which pictures, films etc. can be used under which conditions? What can be posted on the internet and in which way? What are the laws? What information does Facebook have about each individual user? What does Facebook want and do with it? What can I do to protect my privacy? (SOCIAL NATURE 2018 May 1) Obviously, the information was not limited to the use of new media or the project channels, information was also provided on profound and sometimes highly complex problems which were adapted to the target group and discussed with the participants.

In order to document the results of the SOCIAL NATURE project, address a larger user base and ensure the maximum possible transparency, information about the process was provided via several online channels. These included a project website(SOCIAL NATURE 2018a), a presence on Facebook(SOCIAL NATURE 2018) and a Youtube channel(SOCIAL NATURE 2018b). Part of these pieces of content were created by the pupils, enabling them to gain additional practical experience in dealing with social media alongside the theoretical basics.

Evaluation of the project will be completed in September 2018. The participating students will be asked about their growth of knowledge and interests as well as changes of attitude with the help of a questionnaire and group interviews. Furthermore, the experts involved in the project such as biologists, speakers and teachers will be interviewed about their impressions and desired changes.

4 Results

Compatibility with nature is largely taken into account in the operations of the raw materials sector; once the respective deposits have been exhausted, the areas are usually returned to nature by restoration or redesign (Wasserbacher 2008). The landscape-changing activities of humans created new habitats that were populated by animals and plants which did not previously exist there (Wittig & Niekisch 2014). According to German and European studies, "the raw materials industry makes a significant contribution to the conservation and promotion of biodiversity through its extraction activities."(Wasserbacher 2008: 143) Areas with unique conditions are created, without which certain species would no longer exist (Wasserbacher 2008). Mining sites are therefore important complementary areas for nature conservation (Wasserbacher 2008).

According to Splechtna (2010), knowledge of this interrelationship and biodiversity in general can "only be permanently preserved if it becomes a matter of concern to people"(Splechtna 2010: 233) Therefore, it is necessary to inform the public and especially to tackle school education. Thus, projects are needed that appeal to different age groups and target groups. The project SOCIAL NATURE meets these demands and shows that a comprehensive approach, as demanded by Splechtna (2010), is necessary and "includes economic, socio-political and cultural dimensions and enables inter- and transdisciplinary cooperation."(Splechtna 2010: 232) Furthermore, biodiversity should be strengthened and treated more consistently, also in the media (Gross & Behme 2017).

5 Conclusion

Biodiversity is not a fundamentally complex subject area if it is illustrated by specific examples and communicated in a way that is appropriate to the target group and compatible with the masses (Hey & Obermayr 2008). The aim of the SOCIAL NATURE project was not to influence the opinion of the participants or the consumers of the information published on the internet in a particular sense, but to provide them with knowledge on biodiversity, particularly in connection with mining sites, enabling them to shape their own opinions and argue them where necessary. With the whitethroat as a testimonial, the project SOCIAL NATURE aroused interest and sympathy among a broad group of the population through social media storytelling and by addressing stakeholders personally, thereby creating and strengthening awareness of biodiversity and the ecological value of mining areas. SOCIAL NATURE shows that it is possible from an economic, ecological and social point of view to provide participants with motivating and sustainable training in the fields of environment/raw materials and social media.

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Preliminary Results of the Rehabilitation Experiment Conducted on Waste Rock Dump in Gobi Region of Mongolia

G Gundensambuu *Ovoot Tolgoi mine, Environmental department of Southgobi sands LLC, Mongolia*

Abstract

As of 2016, there are a total of 295 mine licenses issued across the Mongolia. Of these, 91 are coal mines primarily operating in the Gobi region. Strategically important deposits in the region such as Tavantolgoi and NariinSukhait mines extract approximately 35.1 mill tons of coking coal annually and 70% of them are exported to abroad. Due to a large scale of the mine exploration, the restoration and rehabilitation with aim for reducing impacts of the mine operations is considered as a main mitigation activity. Despite the rehabilitations are being carried out in accordance with the national standard in the Gobi region, the area rehabilitated is cracked or degraded in 2 years due to soil quality, precipitations, and other environmental factors. Soil of this local area is eager to degrade from wind, water damage because of its high content of salt, low organic content and acidic property.

One of main issues in rehabilitation of mining in this region is lack of fertile soil resource and land disturbance caused by rain water following technical reclamation such as sloping. Let's take reclamation of Ovoot Tolgoi mine, South Gobi Sands LLC as an example. The Ovoot Tolgoi mine extracts 24-million-ton coal and removing 75 million m^3 waste rock since 2008. Technical and biological rehabilitation of 140.7 ha land disturbed by mine operation, 9.5 ha land of waste rock dump was conducted since 2009.

We are conducting rehabilitation according to the Mongolian standard however, after 1-2 years cracks destruction was created at rehabilitated area of stockpile due to precipitation. Furthermore, topsoil plant seeds are removed by flood, rain water and negative impact on rehabilitation result is being observed. To solve this issue, we have started experimental and research work of shaping rehabilitation area same as shape of natural hill, tuft by studying local hill, tufts' structure, shape by biomimicry method – imitation of shape, structure of nature.

Keywords: Rehabilitation of stockpile at open mine in Gobi region, biomimicry

1 Introduction

The Ovoot Tolgoi waste rock dump has height of 25 meter with slope of 34-36 degree. This is same as falling angle of rocks forming waste dump. Due to its steep slopes, the waste dump partially exposes to sunlight resulting unfavorable conditions for plant growth, as well as it violates safety requirement humans and vehicle movements. Thus, there is a critical need to decrease the slopes the ground level. Between 2010-2016, we conducted rehabilitation as modifying slopes of 10.1 hectare waste dump to 13-18 angle of slopes. However, negative impacts were still present as causing cracks and fertile soil and plant seeds were removed primarily owing to heavy rain. We noticed these issues raised due to not having proper control system and drainage channel.

The main purpose of our research work and experiment is to conduct the rehabilitation process successfully and for this reason we should take the most efficient method based on studying local nature structure, hill formation, their shape and size, soil property and elements as emulating (biomimicry) the nature, it's how the nature solves those problems naturally by itself.

Rehabilitation of Ovoot Tolgoi mine

In framework of environmental protection policy, we aim to not only rehabilitate disturbed land during mine excavation and other mine activities but also conduct rehabilitation works which is to provide ecosystem balance, to preserve nature's original structure according geological structure, soil property, local weather condition and relevant Mongolian legislation requirements in a complex way.

Figure 1 Rehabilitation work conducted at Sunset pit

Soil characteristics

Table 1 4 types of soil are spread over Ovoot Tolgoi mine license area

№	Soil name	Main soil	Occurrence
1	Brown grayish soil	Has plenty of muddy rock accumulation	Flank, side of hills
2	Steppe like desert light brown soil	Muddy, strong acidic property	Along the line of ravine
3	Desert light brown soil	Brown grey soil with muddy small gravel like rocks	Steppe, flank of small hills
4	Desert like steppe land, brown soil	Light muddy like components, has high carbonate content	Along shore of dried out water, well points

Organic substance content of soil is below 1.0%, low alkaline, alkalinity is different at every soil layer depending on concentration of calcium, magnum cations.

Researchers think that soil moisture highly affected to stabilize Gobi soil. Due to soil moisture carbonate, bi-carbonate accumulates at top part of the soil and muddy layer containing salt forms out. High content of salt and organic substance, alkalinity of soil affects soil to be easily degraded by wind, water also easily spread by wind and water. These are main factors affecting certain area to be damaged.

Top soil storage

We strip and store top soil of the Ovoot Togloi mine according to MNS5916:2008 and Feasibility study and DEIA report. If not to use top soil during operation, it is stored at designated area as stockpile and in order to protect it from wind, water and being covered by salt we have shaped top and side of stockpile and planted brushy plants. As of now 566,022м3 top soil is being stored at the Ovoot Tolgoi mine and if we conduct rehabilitation according to methodology approved by order A-138, 2015 of Minister of Environment, Green Development, Tourism this top soil is not enough. The Experiment we conduct reduces the usage of top soil by 40%.

From 2015-2016, we have been cooperating with QMC group on mine closure plan of the Ovoot Tolgoi project and volume of top soil usage enclosed in the plan.

Figure 2 Top soil stockpile of Ovoot tolgoi mine

Technical rehabilitation

The Ovoot Tolgoi waste rock dump has height of 25 meter with average slope of 34°-36° degree angle (Figure 3). Slope of stockpile is being shaped by Dozer D10. Technical reclamation is being conducted as shown in Figure 4.

Figure 3 Top soil stockpile of Ovoot tolgoi mine

Figure 4 Top soil stockpile of Ovoot tolgoi mine

Biological rehabilitation

Covering the technical reclamation area by top soil is fundamental to biological rehabilitation. Thickness of top soil is up to 0.35-0.45m. Even though we plan to cover with 0.20-00.30m thickness, top soil coverage is different at places due to vehicle conditions, dozer operator’s ability. In this experimental research top soil is covered as if it is poured and we observed that top soil usage is less.

Figure 5 Top soil stockpile of Ovoot Tolgoi mine

In biological rehabilitation inclination is made by dozer, soil of top soil covered area is shaped and local seeds are planted manually.

Figure 6 Top soil stockpile of Ovoot Tolgoi mine

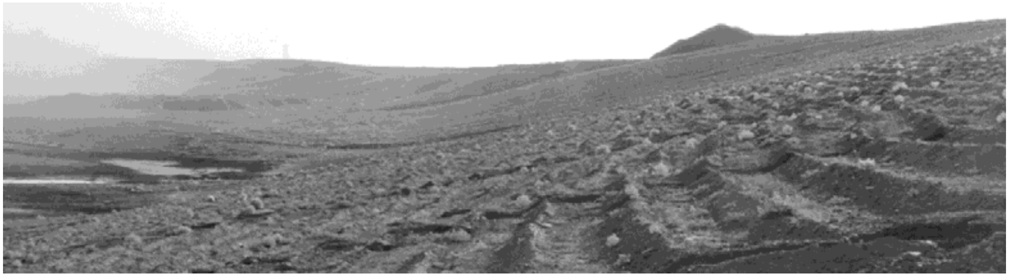

Figure 7 Top soil stockpile of Ovoot Tolgoi mine

Main policy of biological reclamation of our company is to plant local monocyclic and perennial plant seeds. Also rehabilitate disturbed land to its original shape and condition.

2 Experimental and research of Ovoot Tolgoi rehabilitation

The area where mining is operating has a dry weather condition, brushy small plants, ecologically fragile structure, many small and high hills, mountains with different shapes and long wide valleys. Mine waste dump is outspreaded as hills naturally finding its order (Figure 8).

We have started the research work for stockpile rehabilitation based on proven, tested in many countries methodology which is biomimicry or emulating the nature.

Natural hills do not degrade and contain soil damage, crack due to heavy rain and we observed that evolution of hills has managed to form surface to handle water flow. Also plants are mainly grown in ravines of hills and top of the hills are bold. Consequently, we have conducted experiment on stockpile by biomimicry or emulating natural state.

Figure 8 Hills near stockpile

To conduct experimental work of waste dump rehabilitation similar to natural state. With this goal, following activities are planned.

- Calculate size of area degraded by heavy rain and flooding at rehabilitated area.
- Determine the size, shape, and structure of the hills near mining zone
- Conduct experimental research by shaping rehabilitated area based on studying size, shape, structure of hills.
- Find design of hill that cannot be degraded by heavy rain or flood based on result of research.
- Compare cost of the rehabilitation work conducted in previous years with experimental rehabilitation and evaluate efficiency.
- Involve local environmental protection agency and communities via supplying them with plant seeds to increase biological rehabilitation

3 Methodology

- Calculate soil crack on rehabilitation area and estimate the percentage of the area affected by crack.
- Determine size and shape of hills in certain area
- Compare number of brushy plants and inclination angle between rehabilitated area and hills
- Conduct plantation by local seeds at different sections by shaping waste rocks after covering with top soil based on observation of hill's size, shape.

4 Results

In 2012, we randomly selected 60 x 60 m area (e.g. 3,600 m^2) and calculated their soil crack size. Rehabilitation on this waste rock dump was conducted by planting Saxaul seeds and total 66 pcs of Saxaul are characterized at an area of 3,600 m^2. In total, 17 cracks were recorded in the area.

Table 2 Crack depth and thickness of selected area

	Crack depth (cm)	Crack tickness (cm)
Big	130	117
Average	20.3	41.6
Small	2	8

Table 3 Total crack size of selected area 3600м2 /average/

	One crack	Total /17/
Crack size (m^3)	5.6	96.8
Total cracked area size (m^2)	33.3	566.4
Total cracked area (%)		**15.7%**

15.7% of total area is degraded by flood of heavy rain calculated by average number of soil crack at rehabilitated area. We have compared some specifications of rehabilitated area with hill specification. Details can be found in Table 4.

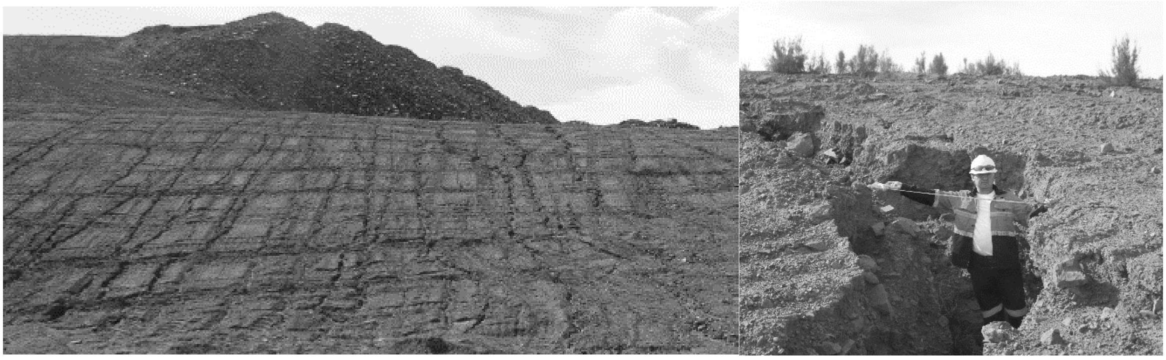

Figure 9 Cracks occurred due to flood of heavy rain at rehabilitated area

Table 4 Comparison of rehabilitated area in 2012 and natural hill

	Rehabilitated area	Natural hill
Inclination angle	16°	big 13°, small 7°
Size of total area	2 ha	6,288 m² – 0,6 ha
Size of total area	210 saxaul (other plants not counted)	197 species of bushes (Xanthoxylon spp, Caragana spp)
Distance between plants	uneven	2-3 meters
Number of plant in 1m²	0.0105	0.031
The size of degraded area due to flooding	15.7% of 3,600m² area	none

We conducted experiment through re-shaping the waste rock imitating natural hill and covered with top soil and planted saxaul seed. 240 tn dump truck transported waste rock 10 times and with help of loader top soil was covered after that watered to make surface harder and planted saxaul seed (Figure 10). Saxaul seeds are planted in ravines with 1.5-2.5 cm in depth and watered once. We prepared area for saxaul to grow naturally and in result they have grown (Figure 11).

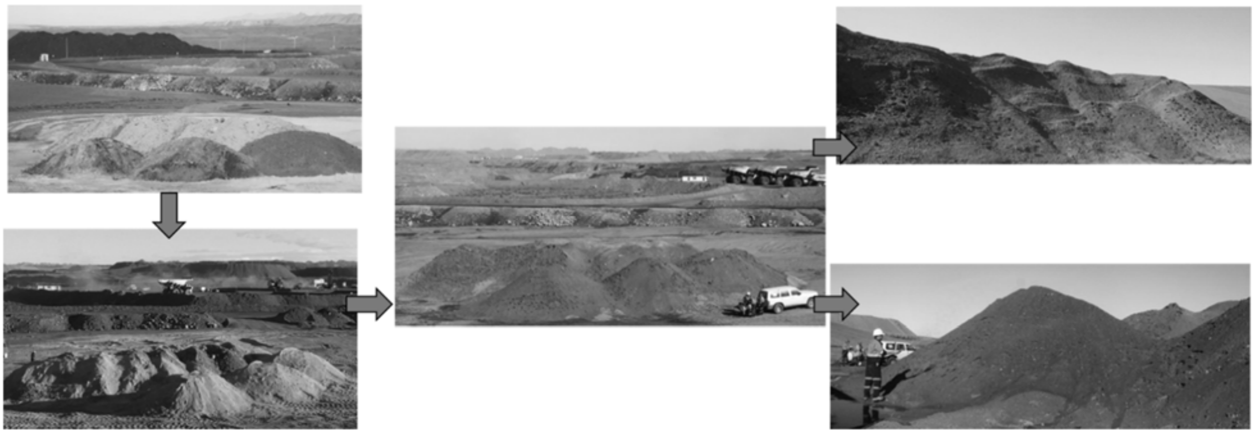

Figure 10 Rehabilitation of waste dump imitating natural hill

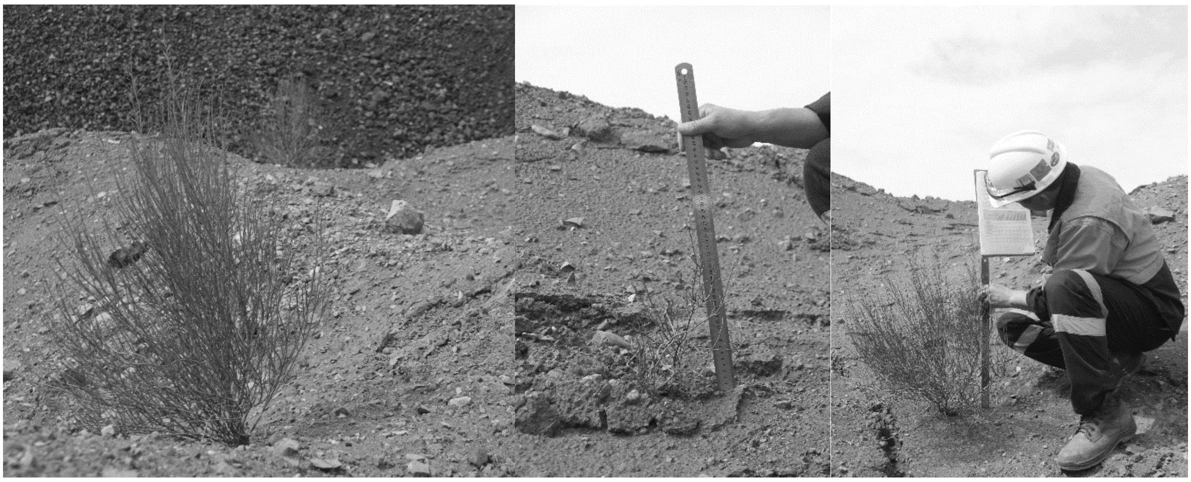

Figure 11 Saxaul grown at stockpile

5 Conclusion

- Although the waste rock dump is rehabilitated in accordance with national standard in Gobi region, the soil cracks tend be observed every year due to flood of heavy rain, which eventually influences success of the reclamation work.
- Our experimental area was not large enough and so that the size of area for experiment needs to be enlarged up to 1 ha.
- The rehabilitation cost of the experiment per area was less (by 8%) than the cost of previous years. Make a detailed expense report with comparison sheet.
- Saxaul seeds were removed during watering and heavy rain due to sparse and loose stockpile soil. So, it is suggested to plant them in pre-prepared cartridges and in trenches and channels.
- Further to create design of ideal rehabilitation shape of pile by determining water absorb coefficient, up and down, inclination shape and surface water flow of soil
- Also we conclude that if the result of the experiment is successful the green workplace will be created at local area, and biological rehabilitation can be conducted by members of Local Nature Protecting Community.

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Work of Mine Closure and its Influence on the Environment

J Melgarejo *Compañía de Minas Buenaventura SAA, Perú*

M Greco *Hatch Asociados SA, Perú*

P Quesada *Amphos 21 Perú Consulting SAC, Perú*

Abstract

Compañía de Minas Buenaventura S.A.A. is the holder of Esperanza 2001 Mine, located in the department of Huancavelica (Perú). Final closure activities have been developed in the mine components as they finish their life cycle. Ten adits had effluents with significant flows (between 0.8 and 43.7 L/s approximately). Consolidation of rock mass has been achieved applying cement grouting and, faults and cracks with water seepage from down the mine were sealed with polyurethane resin grouting. Therefore, using grouting helped to achieve the target of 0 L./s in effluents from down the mine. Likewise, the most part of waste rock facilities were relocated into a single main place, the Huayllacruz Waste Rock Facility, which is now encapsulated and in conditions under control basically. This unification helped in the environmental reclamation of the setting with soil quality effects as well as with surface (runoff) water quality effects which is intended to quantify in this study. The objective of geochemical, hydrochemical and water quality analyses developed was to support the identification of post-closure effects on soils, surface water and groundwater in the study area, as well as to validate the effectiveness of the closure activities performed and eventual identify critical conditions that would need additional closure activities. Geochemical characterization in the study area let determine that the waste rock from the waste rock dumps remaining in situ is predominantly PAG (potentially acid generating) and natural soil in the zone of old removed waste rock dumps are also PAG. However, in the in-situ remaining components, consequences would be limited to runoff surface flows, because covers would be left and restrict contact. The water quality evaluation indicated that the closure measures performed in different mine components in the study area have positively impacted receiving bodies and in terms of time evolution showed that previously Environmental Water Quality Standards exceedances occurred in control locations of receiving bodies regarding pH, cadmium, copper, iron, and zinc, which are not detected currently after carrying out closure measures

Keywords: *mine closure, influence on environment*

1 Introduction and objectives

Compañía de Minas Buenaventura S.A.A. is the holder of Esperanza 2001 Mine, located in the district of Lircay, province of Angaraes, department of Huancavelica.

Final closure activities have been developed in the mine components as they finish their life cycle in coLMPiance with the management instruments of the said mine.

Currently, all components are closed. Ten adits had effluents with significant flows (between 0.8 and 43.7 L/s approximately). Plugs were constructed for these adits as stated preliminarily in the closure plan, without using cement and polyurethane resin grouting.

Consolidation of rock mass has been achieved applying cement grouting and, faults and cracks with water seepage from down the mine were sealed with polyurethane resin grouting. Therefore, using grouting helped to achieve the target of 0 L./s in effluents from down the mine.

Likewise, all waste rock facilities were relocated into a single main place, the Huayllacruz Waste Rock Facility, which is now encapsulated and in conditions under control basically. This unification helped in the environmental reclamation of the setting with soil quality effects as well as with surface (runoff) water quality effects which is intended to quantify in this study.

1.1 Closure activities

The closure activities carried out by CMB are summarized below:

- Adit plugging of the study area with existing effluents from old underground workings applying cement and polyurethane resin grouting.
- Relocation of waste material from small dumps and remediation of these zones through disposal of organic material.
- Disposal of waste rock removed to a centralized single dump (Huayllacruz), covered with geomembrane,clay and organic soil.
- Remediation in situ of other small dumps (like Nancy Luz).

1.2 Context Study

The following activities were carried out to develop this work:

- Geochemical and hydrochemical studies (along with AMPHOS 21).
  - Post-closure geochemical characterization of the study area.
  - Post-closure hydrochemical characterization and water quality analysis of the study area.

As reference standards for water quality, the following environmental regulations applicable in Peru were used:

- Maximum Permissible Limits (LMP) for mining effluents, regulated through DS-010-2010-MINAM.
- Environmental Quality Standards for water (ECA) of receiving bodies, category 3, which include water for animal consumption and agriculture, regulated through DS-004-2017-MINAM.

1.3 General objectives

The objective of the mine closure is the reclamation of the natural environment with appropriate water and soil quality. The objective of geochemical, hydrochemical and water quality analyses was to support the identification of post-closure effects on soils, surface water and groundwater in the study area, as well as to validate the effectiveness of the closure activities performed and eventual critical conditions that would need additional closure activities.

2 Activities

2.1 Waterproofing and/or consolidation of the rock mass with polyurethane resin

2.1.1 Stages

Ground consolidation was carried out considering the following stages:

- *Pregrouting*. This activity prevented water seepage in the work fronts and allowed prestabilization of the rock mass preventing cost overruns related to excavation due to existing groundwater. Application of resin provided quick and profitable solution with minimum environmental consequences.
- *Waterproofing*. Water seepage through cracks and joints in the underground structures results in significant reduction of the structure cohesion and implies the need to keep an ongoing pumping

system. If water seepage has fines content, differential settlements will occur, which will, in turn, result in new cracks and filtered flow increase. Aqua-reactive resin has proved to be an appropriate product to provide solution to this type of problems. This is an essential tool to perform waterproofing treatment because of its reaction nature at water contact, expansiveness and stability over time.

- *Ground Consolidation*. If the ground has a reduced mechanical strength, the resin grouting will improve its physical properties, like compressive and tensile strength, internal friction angle, etc. A resin treatment adequately designed by expert technicians and applied in a controlled way with the injection equipment appropriate to each situation, can provide sandstone consistency to the flowing area or make the saturated gravel behave as a solid conglomerate.
- *Soil Improvement*. Effective action to improve the soil bearing capacity for special construction.

2.1.2 Product used

The process was carried out considering the following products:

- *MasterRoc MP 358 GS/MP 358 SC.*
- *MasterRoc MP 367 Foam.*
- *MasterRoc MP 3551K (One-component).*
- *MasterRoc MP 355.*

They are two-component and one-component resins, without solvents, designed especially for water fast detection and rock mass stabilization.

2.1.3 Resin grouting process

Detailed phases of the resin grouting process are presented in Figure 1.

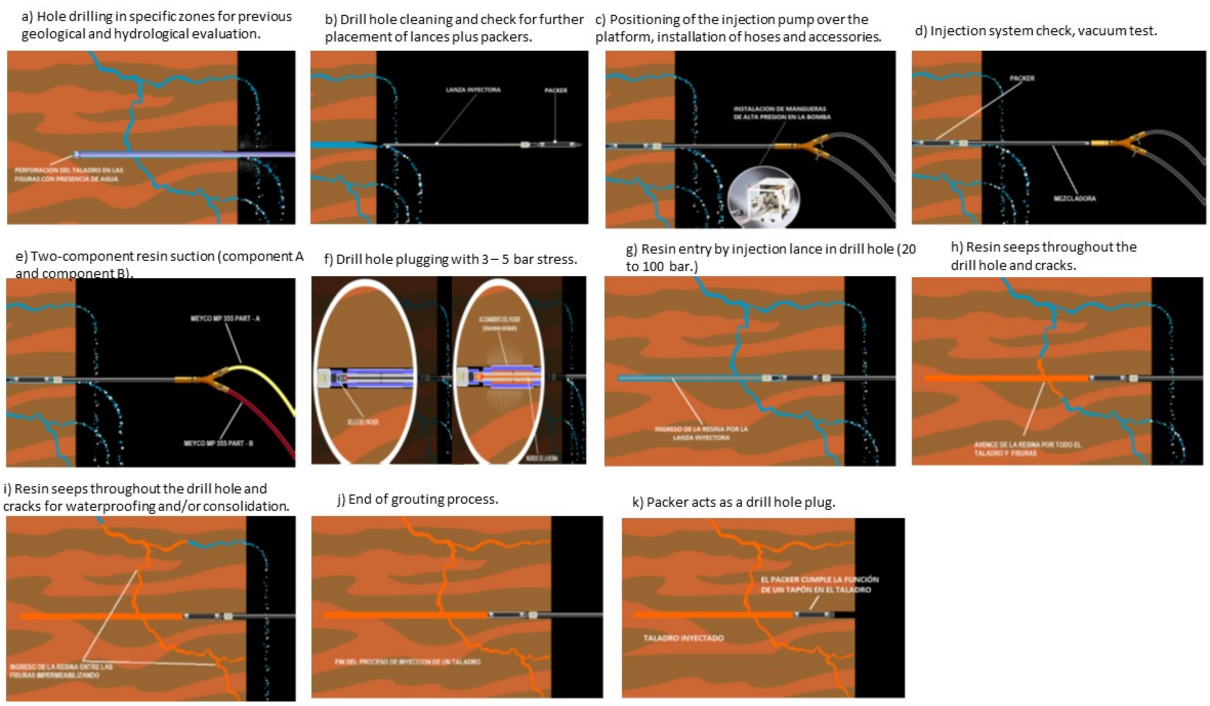


Figure 1 Detailed phases of the resin grouting process

2.2 Geochemical characterization - activities

The geochemical characterization of the materials targeted in the study area (December 2017), to develop the hydrochemical conceptual model that relates existing material to the resulting quality of surrounding surface water and groundwater. The sampling involved analysis of various types of saLMPes:

- *Waste rock dumped in the various existing reclaimed dumps (Huayllacruz and Nancy Luz).*
- *Waste rock identified in areas of old removed dumps and, therefore, not completely cleaned.*
- *Soil used to cover existing and reclaimed dumps (Huayllacruz and Nancy Luz).*
- *Existing soil in reclaimed areas of old dumps.*
- *Natural mineralization or rock outcrops identified in the area that might have leachate with negative impacts on water.*

2.3 Hydrochemical characterization - activities

The hydrochemical characterization was carried out based on the laboratory tests to samples collected in the sampling campaign of December 2017. A further comprehensive analysis was carried out on the water quality data, including also the historical data, thus a space and time distribution could be established for parameters exceeding water quality standards applicable in Peru (ECA and LMP).

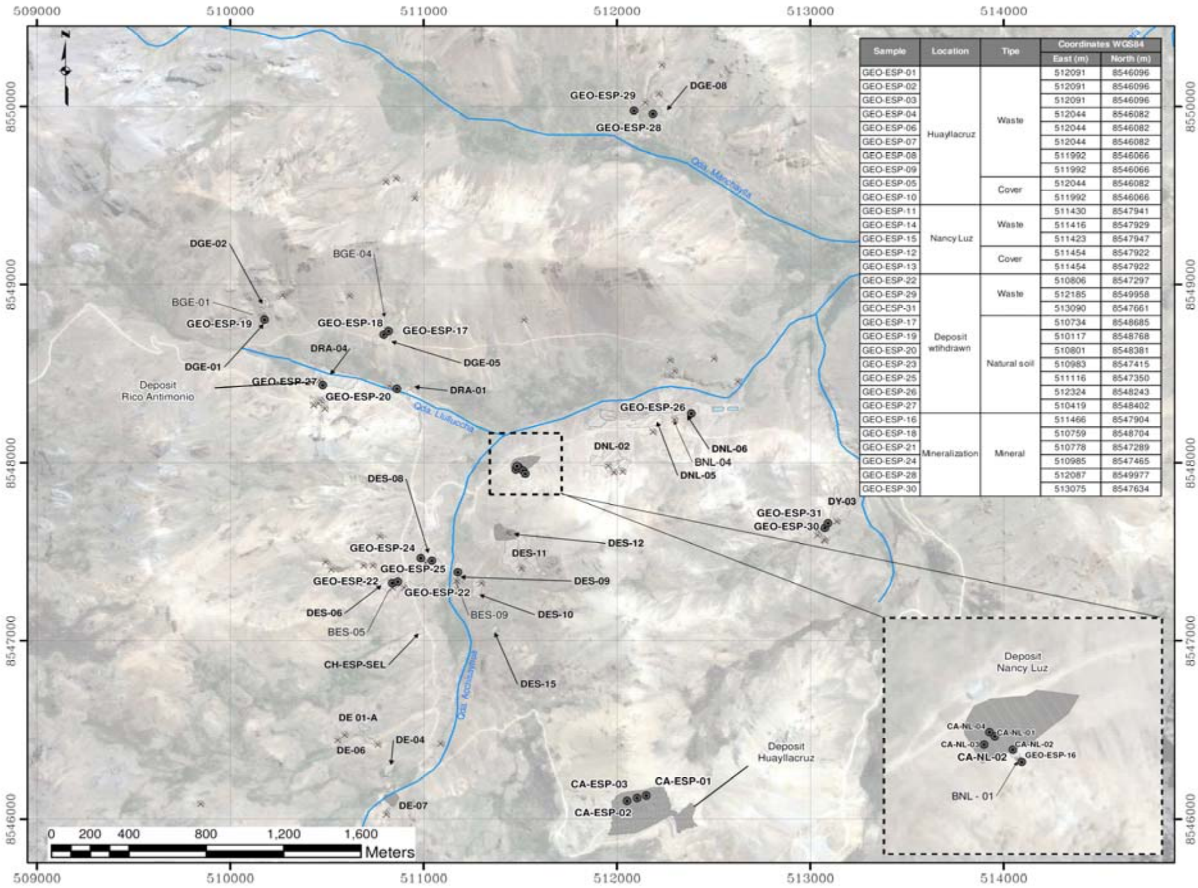
3 Field Investigation and Methodology

3.1 Geochemical Sampling Plan

After reviewing the geochemical background, the need for a complementary sampling was identified to improve the characterization of the mine components existing in the study area as well as soil characterization in the removed dumps and other materials of interest (like rock outcrops and/or mineralization in the proximity of identified adits). Based on this, a sampling campaign in the study area was performed in December 2017. The sample space distribution is shown in Figure 2.

During the first sampling campaign 31 samples were collected. A set of static and mineralogical tests were carried out, which involved:

- Acid Base Accounting (ABA) by Lawrence method.
- Waste Rock Analysis (WRA) by four acid digestion method.
- Seven-stage sequential extraction procedure by B. Dold method.
- Short-term Synthetic Precipitation Leaching Procedure (SPLP) by EPA Method 200.8.
- Mineralogy by X-Ray Diffraction Analysis and polished section.



Sample	Location	Tipe	Coordinates WGS84	
			East (m)	North (m)
GEO-ESP-01	Huayllacruz	Waste	512091	8546096
GEO-ESP-02			512091	8546096
GEO-ESP-03			512091	8546096
GEO-ESP-04			512044	8546082
GEO-ESP-06			512044	8546082
GEO-ESP-07			512044	8546082
GEO-ESP-08			511992	8546066
GEO-ESP-09			511992	8546066
GEO-ESP-05		Cover	512044	8546082
GEO-ESP-10			511992	8546066
GEO-ESP-11	Nancy Luz	Waste	511430	8547941
GEO-ESP-14			511416	8547929
GEO-ESP-15			511423	8547947
GEO-ESP-12		Cover	511454	8547922
GEO-ESP-13			511454	8547922
GEO-ESP-22	Deposit wtihdrawn	Waste	510806	8547297
GEO-ESP-29			512185	8549958
GEO-ESP-31			513090	8547661
GEO-ESP-17		Natural soil	510734	8548685
GEO-ESP-19			510117	8548768
GEO-ESP-20			510801	8548381
GEO-ESP-23			510983	8547415
GEO-ESP-25			511116	8547350
GEO-ESP-26			512324	8548243
GEO-ESP-27			510419	8548402
GEO-ESP-16	Mineralization	Mineral	511466	8547904
GEO-ESP-18			510759	8548704
GEO-ESP-21			510778	8547289
GEO-ESP-24			510985	8547465
GEO-ESP-28			512087	8549977
GEO-ESP-30			513075	8547634

Figure 2 Hidrochemical sample distribution

3.2 Results of geochemical characterization

3.2.1 Mineralogy

Potential metal ore sources could be identified:

- Considering the sample acid neutralization potential, carbonate content, especially calcite and dolomite, was evaluated. However, their concentration was minor or none in most samples analyzed. Iron carbonates were identified like ankerite (Ca(Mg,Fe)(CO3)2), but they do not have neutralization potential.
- Hight sulfide contents were identified, with incidence on acid drainage generation and metal leaching (especially pyrite, chalcopyrite, galena, and sphalerite). Presence of jarosite and alunite should also be highlighted.

3.2.2 Acid Base Accounting (ABA), paste pH, and NAG pH

Results of the ABA test, paste pH, and NAG pH (Table 1), allowed evaluation of main parameters involved in the sample acid generation potential. In general, high contents of total sulfur were identified in most samples (>0.1%), even in some from natural soil of old removed dump areas. Relation between sulfide sulfur and total sulfur showed an acceptable correspondence for the sample set, thus, significant values of acid potential were estimated regarding sulfide (PA= Sulfide x 31.25).

Values reported for the neutralization potential (NP) were low or even zero, which is consistent with the absence or limited presence of calcite. In addition, correlation between the NP measured (chemical rating) and that established from the inorganic carbon (NP = C x 83.33), did not show any clear relationship. The inorganic carbon NP exceeds significantly the NP measured, so it can reflect the mineral dissolving in metallic carbonates (ankerite). Regarding paste pH, the recorded values were within the neutral to slightly acidic range in most samples (between 7 and 4). However, the NAG pH that results in total oxidation of the sample, has more acidic values, around 2.

Table 1 ABA Test Results

Sample	Location	Tipe	S total	S sulfide	PA	PN	PN/PA	PNN	C inorg.	PN-TIC	pH paste	pH NAG	DAR criteria		
			%	%	kg $CaCO_3$/t	kg $CaCO_3$/t			%	kg $CaCO_3$/t			N°1 (PNN)	N°2 (S %)	N°3 (pH NAG)
GEO-ESP-01	Huayllacruz	Waste	4.70	3.70	115.6	21.21	0.183	-94.42	0.197	16.428	7.46	2.12	**PAG**	**PAG**	**PAG**
GEO-ESP-02			2.10	1.10	34.4	0.00	0.000	-34.38	0.044	3.669	4.88	2.54	**PAG**	**PAG**	**PAG**
GEO-ESP-03			3.80	2.60	81.3	14.83	0.183	-66.42	0.350	29.186	7.42	2.38	**PAG**	**PAG**	**PAG**
GEO-ESP-04			4.00	3.00	93.8	16.42	0.175	-77.33	0.216	18.012	7.24	2.19	**PAG**	**PAG**	**PAG**
GEO-ESP-06			3.60	2.50	78.1	11.77	0.151	-66.36	0.182	15.177	6.52	2.25	**PAG**	**PAG**	**PAG**
GEO-ESP-07			1.60	0.78	24.4	6.14	0.252	-18.24	0.119	9.923	6.95	2.96	**UNCERTAIN**	**PAG**	**PAG**
GEO-ESP-08			3.00	1.90	59.4	8.71	0.147	-50.67	0.180	15.010	6.68	2.43	**PAG**	**PAG**	**PAG**
GEO-ESP-09			3.50	2.40	75.0	8.22	0.110	-66.78	0.156	13.009	6.85	2.33	**PAG**	**PAG**	**PAG**
GEO-ESP-05		Cover	0.93	0.20	6.3	0.00	0.000	-6.25	0.041	3.419	4.46	3.14	**UNCERTAIN**	**PAG**	**PAG**
GEO-ESP-10			1.30	0.51	15.9	0.00	0.000	-15.94	0.118	9.840	4.29	2.55	**UNCERTAIN**	**PAG**	**PAG**
GEO-ESP-11	Nancy Luz	Waste	0.94	0.49	15.3	0.00	0.000	-15.31	0.058	4.837	4.18	2.40	**UNCERTAIN**	**PAG**	**PAG**
GEO-ESP-14			4.20	2.60	81.3	0.00	0.000	-81.25	0.060	5.003	5.27	2.28	**PAG**	**PAG**	**PAG**
GEO-ESP-15			2.90	1.40	43.8	0.00	0.000	-43.75	0.051	4.253	3.96	2.50	**PAG**	**PAG**	**PAG**
GEO-ESP-12		Cover	0.10	0.01	0.3	0.00	0.000	-0.31	0.046	3.836	5.44		**UNCERTAIN**	**PAG**	
GEO-ESP-13			0.09	0.02	0.6	0.00	0.000	-0.63	0.054	4.503	5.78		**UNCERTAIN**	**PAG**	
GEO-ESP-22	Removed deposit	Waste	0.94	0.21	6.6	0.00	0.000	-6.56	0.135	11.257	3.89	2.98	**UNCERTAIN**	**PAG**	**PAG**
GEO-ESP-29			0.47	0.29	9.1	19.12	2.110	10.06	< 0.010	0.834	4.44	3.88	**UNCERTAIN**	**PAG**	**PAG**
GEO-ESP-31			0.68	0.57	17.8	19.61	1.101	1.80	< 0.010	0.834	4.16	2.61	**UNCERTAIN**	**PAG**	**PAG**
GEO-ESP-23		Cover	0.36	0.22	6.9	0.00	0.000	-6.88	0.099	8.255	4.31		**UNCERTAIN**	**PAG**	
GEO-ESP-25			0.52	0.37	11.6	0.00	0.000	-11.56	0.301	25.100	4.05		**UNCERTAIN**	**PAG**	
GEO-ESP-26			0.12	0.01	0.3	0.00	0.000	-0.31	0.080	6.671	4.73		**UNCERTAIN**	**PAG**	
GEO-ESP-27			0.04	0.01	0.3	0.00	0.000	-0.31	0.063	5.253	4.47		**UNCERTAIN**	**NAG**	
GEO-ESP-17			0.11	0.01	0.3	0.00	0.000	-0.31	0.136	11.341	4.46		**UNCERTAIN**	**PAG**	
GEO-ESP-19			0.07	0.01	0.3	4.91	15.712	4.60	0.288	24.016	6.02		**UNCERTAIN**	**NAG**	
GEO-ESP-20			0.14	0.01	0.3	0.00	0.000	-0.31	0.091	7.588	3.90		**UNCERTAIN**	**PAG**	
GEO-ESP-16	Mineralization	Mineral	0.55	0.48	15.0	0.00	0.000	-15.00	0.009	0.750	4.14	2.45	**UNCERTAIN**	**PAG**	**PAG**
GEO-ESP-18			0.70	0.61	19.1	5.15	0.270	-13.91	0.022	1.835	6.10	2.93	**UNCERTAIN**	**PAG**	**PAG**
GEO-ESP-21			2.00	1.80	56.3	0.13	0.002	-56.12	0.029	2.418	4.05	2.42	**PAG**	**PAG**	**PAG**
GEO-ESP-24			0.02	0.01	0.3	13.73	43.936	13.42	0.268	22.348	8.02	9.20	**UNCERTAIN**	**NAG**	**NAG**
GEO-ESP-28			4.70	4.60	143.8	96.90	0.674	-46.85	0.849	70.794	7.72	2.29	**PAG**	**PAG**	**PAG**
GEO-ESP-30			< 0.01	< 0.01	0.3	28.48	91.144	28.17	0.064	5.367	7.62	7.48	**UNCERTAIN**	**NAG**	**NAG**

Finally, acid generation potential of samples studied was classified as potentially acid generating (PAG) and non-acid generating (NAG). The following “Sulfide S” criteria (SME, 2011) were used: > 0.1%: PAG; < 0.1%: NAG); and “NAG pH” (AMIRA, 2002): < 4.5: PAG; > 4.5: NAG.

The classification allows stating that the sample set is mostly PAG, even some natural soil samples from removed dumps are. Two natural soil samples would be rated as NAG related to dumps removed from the Desmonte Rico Antimonio dump area (GEO-ESP-19 and GEO-ESP-27), and 02 samples from rock outcrops of the section (GEO-ESP-24 and GEO-ESP-30) in the surroundings of dumps DES-08 and DY-03.

3.2.3 Waste Rock Analysis (WRA) and sequential extractions

Total contents of the main elements reported were analyzed in the total rock analysis for the different samples evaluated of the study area, to set the elements that stand out in the chemistry. For this, as a reference framework, they were compared to the average estimated abundance of these elements in the continental crust (Price, 1997), also called clarke, as presented in Table 2. Results show that for many elements concentrations are clearly higher than the average value in the Earth’s crust (shaded in gray color), which is consistent with a study area linked to an ore deposit.

Table 2 WRA Results compared to the average abundance in the continental crust

Element			Al	As	Ba	Cd	Ca	Cu	Fe	K	Mn	Mo	Pb	Si	Zn
Unit			%	ppm	ppm	ppm	%	ppm	%	%	ppm	ppm	ppm	%	ppm
Average abundance in continentan crust			8.23	1.8	425	3	4.15	60	5.63	2.1	950	1.2	14	28.2	70
Abundancia en muestra	GEO-ESP-01		7.05	157	2753	16.0	1.74	271	4.64	3.2	1363	16.3	1322	25.5	3107
	GEO-ESP-02		7.31	203	4046	8.3	1.12	139	3.67	3.0	336	10.7	2062	28.1	1872
	GEO-ESP-03		6.13	219	2124	38.2	2.11	233	3.90	2.9	831	11.7	3086	30.3	8417
	GEO-ESP-04		6.14	340	2993	19.5	1.57	167	4.15	2.7	887	10.1	1640	28.8	4440
	GEO-ESP-05	D. Huayllacruz	8.67	72	798	2.2	0.45	30	4.20	1.0	96	0.9	136	28.4	603
	GEO-ESP-06		7.21	230	3253	12.4	1.51	133	4.39	2.9	746	5.6	2150	27.1	2820
	GEO-ESP-07		7.79	203	1909	11.2	2.30	145	4.76	2.8	797	7.4	1210	27.1	3042
	GEO-ESP-08		6.76	231	3592	13.9	1.65	176	4.55	2.9	690	7.8	1458	25.4	3118
	GEO-ESP-09		6.64	223	2288	14.7	1.63	162	4.27	3.0	750	17.2	1707	28.7	3225
	GEO-ESP-10		6.53	130	3051	6.0	0.81	77	4.35	2.7	401	10.4	925	29.9	1424
	GEO-ESP-11		7.67	36	919	1.4	0.31	95	3.36	3.2	206	9.5	98	29.2	174
	GEO-ESP-14	D. Nancy Luz	5.37	324	3867	54.3	0.69	432	3.29	2.9	364	16.0	6644	30.9	11454
	GEO-ESP-15		6.59	278	3074	45.5	0.79	323	3.01	3.3	177	9.0	7279	30.3	11349
	GEO-ESP-22		7.97	156	2184	9.8	0.70	104	4.26	3.1	746	3.5	1655	28.8	2265
	GEO-ESP-29	Removed deposit	5.46	83	1149	<0.25	0.14	14	3.35	2.4	172	1.9	62	27.8	36
	GEO-ESP-31		8.84	21	738	<0.25	2.06	32	3.85	2.8	116	3.1	14	27.5	82
	GEO-ESP-16		6.78	6	847	<0.25	0.10	16	1.45	5.6	181	1.3	67	32.3	245
	GEO-ESP-18		7.47	16	563	<0.25	3.13	32	4.66	1.6	1147	2.2	23	28.8	102
	GEO-ESP-21	Mineralization	7.67	304	741	2.2	0.65	51	4.41	2.6	769	<0.25	18	28.6	147
	GEO-ESP-24		8.02	6	664	<0.25	4.35	39	4.81	2.4	597	6.0	38	27.8	162
	GEO-ESP-28		8.05	51	359	1.0	2.43	22	3.65	1.8	816	9.3	14	29.7	62
	GEO-ESP-30		8.70	4	862	<0.25	4.26	48	4.87	2.7	719	19.2	14	26.5	119

The following contents prevail:

- Arsenic, cadmium, lead, and zinc, in concentrations higher than clarke in ranges from 01 to 02 orders of magnitude, which is consistent with the sulfide mineralogy described for the samples, involving pyrite ((Fe,As)S2), galena (PbS), and sphalerite ((Zn, Cd)S)).
- Calcium, is generally below clarke, which is consistent with the null or minimum presence of calcite (CaCO3) present as trace or not higher than 3% in the mineralogical analysis.

The sequential extraction tests allowed determining the mineral origin for different elements of interest. Regarding this, the following was proved:

- Arsenic, cadmium, copper, iron, lead, and zinc are predominantly associated to sulfides.
- Manganese is associated to carbonates and iron oxides, which indicates that this element is everywhere in all the materials of the study area.

3.2.4 Short term Synthetic Precipitation Leaching Procedure (SPLP)

Leachates obtained during the slightly acidified water interaction test that simulates rainwater with materials under study, were analyzed. Results of this test are similar to those expected by surface water interaction (runoff) with the materials. For representativeness and analysis, leachate concentrations for most relevant elements are presented subject to sample sulfur content (Figure 3), since due to absence of carbonates, this descriptor alone only indicates fairly accurate acid generating and metal leaching rates of a given material.

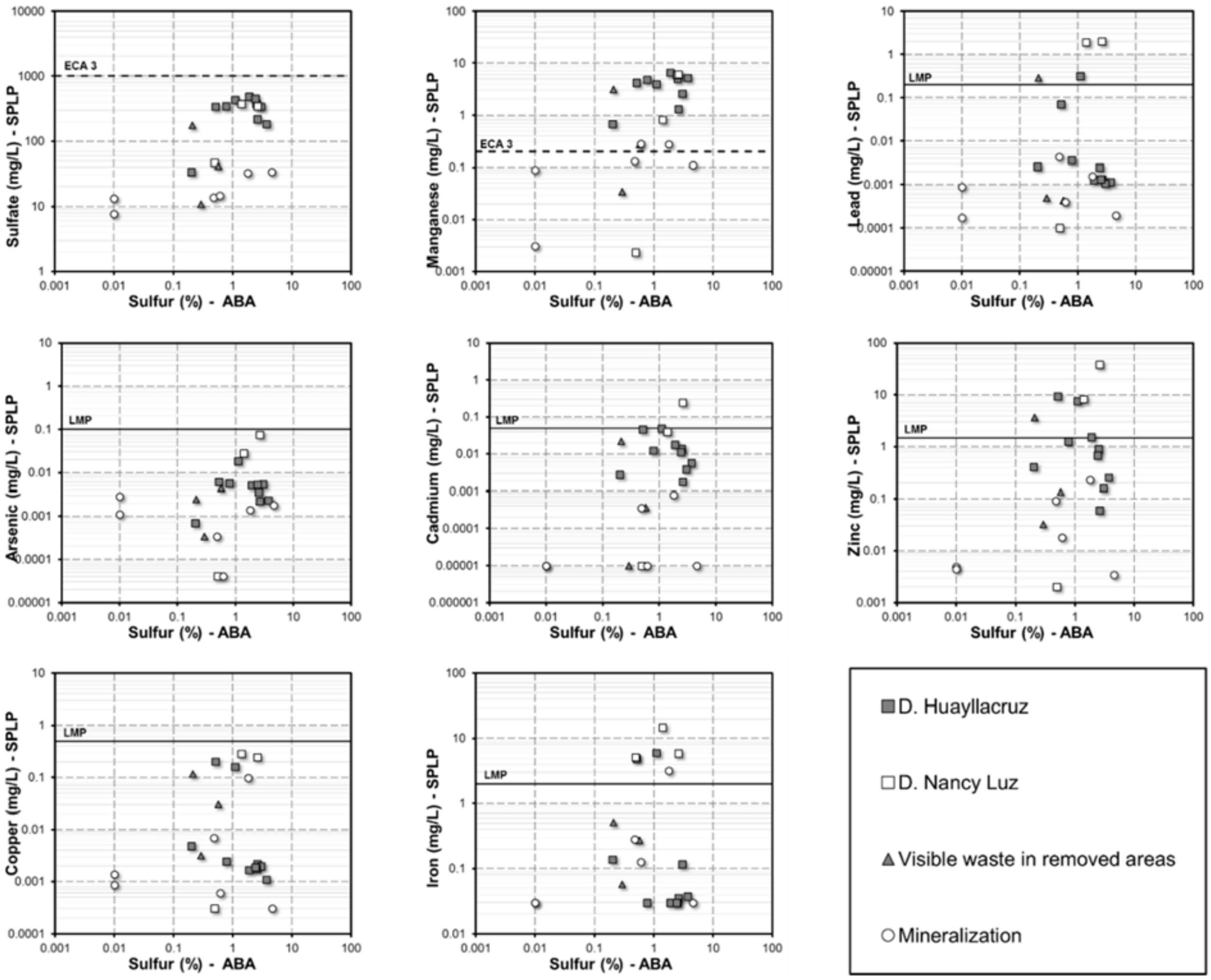
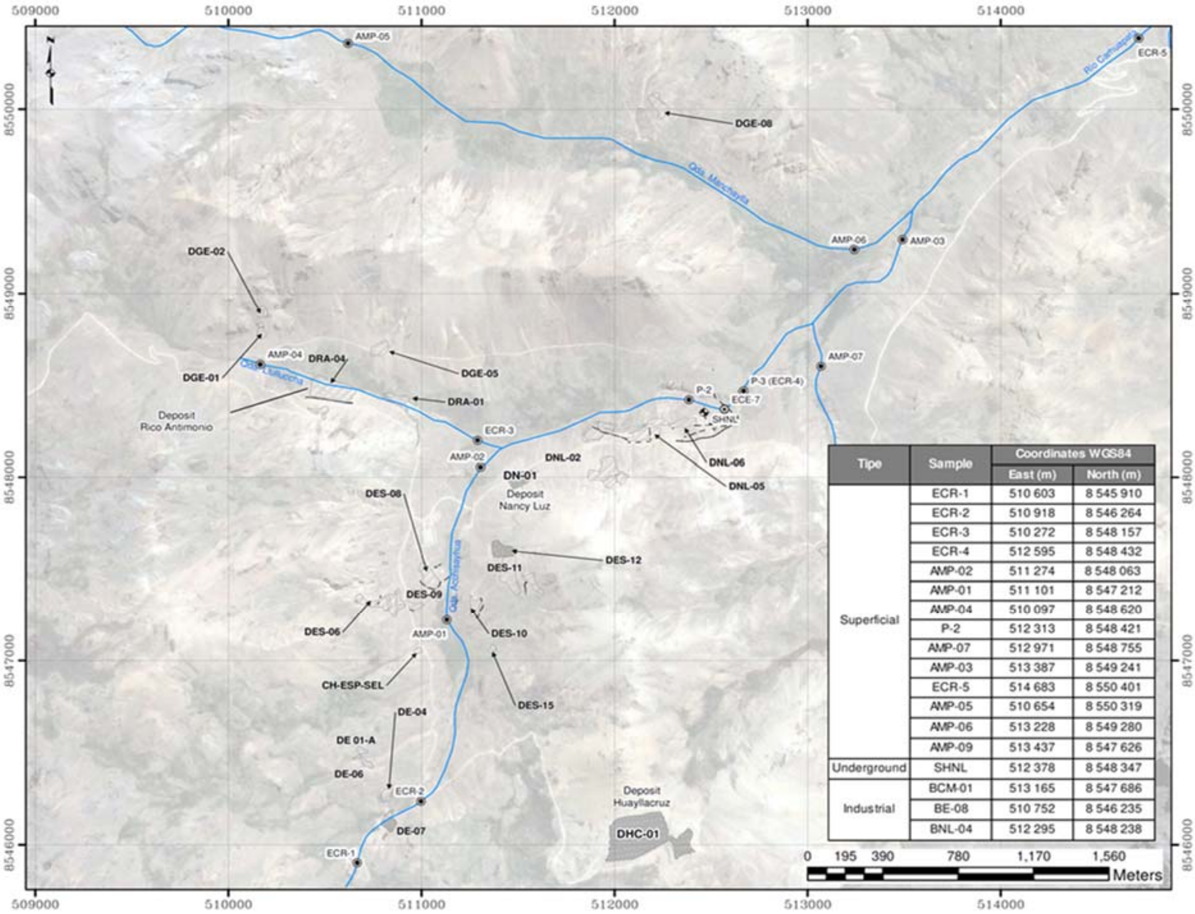


Figure 3 SPLP leachate results for SO4, Mn, As, Cd, Cu, Fe, Pb, and Zn.

Results showed that:

- There is a good relationship between the sulfide sulfur content and the leachate rate of various metals; no leachate was above the quality standards below a sulfide sulfur content of 0.1%.
- The following elements exceeded the compliant quality standards:
  - Manganese, above the ECA 3 (0.2 mg/L), for all the evaluated zones.
  - Cadmium, above the LMP, established in 0.05 mg/L, only in one sample from the Nancy Luz dump though.
  - Iron, above the LMP compliance value, established in 2 mg/L, for samples from the in-situ remaining dumps and mineralization or rock outcrops.
  - Iron, above the LMP compliance value, established in 0.2 mg/L, for samples from the in-situ remaining dumps and existing waste still in the removed dumps.

- o Zinc, above the LMP compliance value, established in 1.5 mg/L, for samples from the in-situ remaining dumps and existing waste still in the removed dumps.



Tipe	Sample	Coordinates WGS84	
		East (m)	North (m)
Superficial	ECR-1	510 603	8 545 910
	ECR-2	510 918	8 546 264
	ECR-3	510 272	8 548 157
	ECR-4	512 595	8 548 432
	AMP-02	511 274	8 548 063
	AMP-01	511 101	8 547 212
	AMP-04	510 097	8 548 620
	P-2	512 313	8 548 421
	AMP-07	512 971	8 548 755
	AMP-03	513 387	8 549 241
	ECR-5	514 683	8 550 401
	AMP-05	510 654	8 550 319
	AMP-06	513 228	8 549 280
	AMP-09	513 437	8 547 626
Underground	SHNL	512 378	8 548 347
Industrial	BCM-01	513 165	8 547 686
	BE-08	510 752	8 546 235
	BNL-04	512 295	8 548 238

Figure 4 Location and description of water sampling stations

3.2.5 Hydrochemical Sampling Plan

The sampling program was designed taking the following criteria into account:

- Extension of the study area/area of interest.
- Hydrographic network distribution.
- Location of components subject to study (removed dump zones and existing/current dumps that are left closed in situ).
- Location of sampling points considering the existing monitoring network, as well as including some stations.

Figure 4 shows the location and description of the considered sampling stations.

4 Results

4.1 Results of closure activities

Removal of all acid water sources and zone reclamation were achieved with the closure activities (Table 3).

Table 3 Acid water sources achieves with closure activities

N°	Adit	Q – Pre-Closure Activities (lts/sec.)	Q – Post-Closure Activities (lts/sec.)
01	Germana Nv. 650.	2.40	0.00
02	Española.	2.40	0.00
03	Nancy Luz Nv. 560.	35.0	0.00
04	Esperanza Nv. 595.	43.7	0.00
05	Tecllorcco.	1.90	0.00
06	Esperanza Nv. 590.	35.0	0.00
07	Esperanza Nv. 700.	5.30	0.00
08	Esperanza Nv. 650.	31.3	0.00
09	Nancy Luz Nv. 610.	0.80	0.00
10	Rico Antimonio Nv. 610.	35.0	0.00

Surrounding communities are content with the works carried out.

4.2 Results of Hydrochemical Characterization

4.2.1 Hydrogen Potential (pH)

- The groundwater sample pH was recorded at 6.57, which is within the neutral range.
- Regarding the industrial waste water, the pH was recorded within the slightly acidic to neutral range (between 6.22 and 7.17).
- The surface water recorded pH values within the acidic to slightly alkaline range (between 6.03 and 8.12). Except for location AMP-07, which recorded a pH of 4.87, clearly acidic. This indicates that removed waste dumps upstream may influence somehow, since the effluent of the close adit that discharges in stream BCM-01 has neutral pH.

4.2.2 Electrical Conductivity (EC)

- The groundwater sample EC recorded a value of 1359 µS/cm, which indicates high mineralization waters.
- Regarding industrial waste water, CE records are 1529 to 3210 µS/cm. These records correspond also to very mineralized waters.
- On the other hand, surface water evaluated recorded conductivity values generally between 70 and 370 µS/cm, typical of low mineralization. In cases with clear interaction of industrial waste water discharges, CE records increase in the control points located downstream.

4.2.3 Total Alkalinity

- It was evident that consistent with reported value records, in the slightly acidic range, the dominant anion is the bicarbonate in all the samples evaluated capable of providing alkalinity.
- Almost all the surface water samples evaluated had low alkalinity (below 75 mg/L CaCO3).

4.2.4 Main Components

The next step in the water hydrochemical characterization was the classification based on their main components, according to its hydrochemical facie. For the groundwater description in the study are subject to this classification, data obtained for main cations (Ca2+, Mg2+, Na+) and main anions (SO42-, Cl-, HCO3-) were considered in Piper ternary diagrams. This helped to assign the following characterization of hydrochemical facies to the study waters:

- *Surface Water*: Up to three types of water were identified in the monitoring locations:
  - Calcium bicarbonate: Prevalence of these ions in the high section of streams Acchisayhua (ECR-1), Llulluccha (AMP-04), and Manchaylla (AMP-05) was observed.
  - Sulfate calcium bicarbonate: Prevalence of these ions in the control location ECR2, situated downstream ECR-1 was observed. Thus, it can be said that ECR-1 water gained some mineralization, maybe due to the influence of the still existing waste dump DE-07.
  - Calcium sulfate: In general, this facie was observed in lower sections of streams Acchisayhua (AMP-02), Llulluccha (ECR-3), Yuraccmachay (AMP-09 and AMP-07), Carhuapata river (ECR-5), and areas of influence (ECR-4, P-2, AMP-03).
- *Industrial Waste Water*: Based on water main components, effluents BE-08, BNL-04, and BCM-01, have calcium sulfate facie, because they have sulfate input resulting from the sulfide oxidation in the ore deposit.
- *Groundwater*: SHNL location had sulfate calcium bicarbonate facie.

4.3 Results of Quality Water Characterization

Water quality in water bodies was evaluated regarding:

- Space distribution. This evaluation was performed along the flow directions of rivers and streams of interest in the study area, related to existing mine passives, closed waste rock dumps in situ and reclaimed zones (removed waste rock dumps).
- Time distribution. This evaluation was carried out on control points in the study area with quality historic record (2011-2015).

4.3.1 Space Evaluation

The control point quality was evaluated relative to its location in rivers and streams and to existing and non-existing components:

- In stream Acchisayhua (Figure 5), sulfate, aluminum, manganese, lead, and zinc concentrations from location ECR-1 to AMP-02 increased. This indicates effects related to seepage from adit BE-08, closed areas that had waste rock dumps, and existing waste rock dumps like DE-07 and DES-12. In the confluence of streams Llulluccha and Acchisayhua, and further confluence with stream Yaraccmachay and Manchaylla, in that sequence, generally no increases are observed along the body water course related to mixing processes.
- Regarding stream Llulluccha (Figure), sulfate, aluminum, manganese, lead, and zinc concentrations increase from location AMP-04 to ECR-3. A decreased pH from 7.64 to 7.25 is also observed. It is clear the influence of the area where the removed dumps DR-04 and DR-01 where located (waste rock dumps Rico en Antimonio). Increased concentrations were also observed downstream old components in stream Manchaylla and stream Yaramacchay.

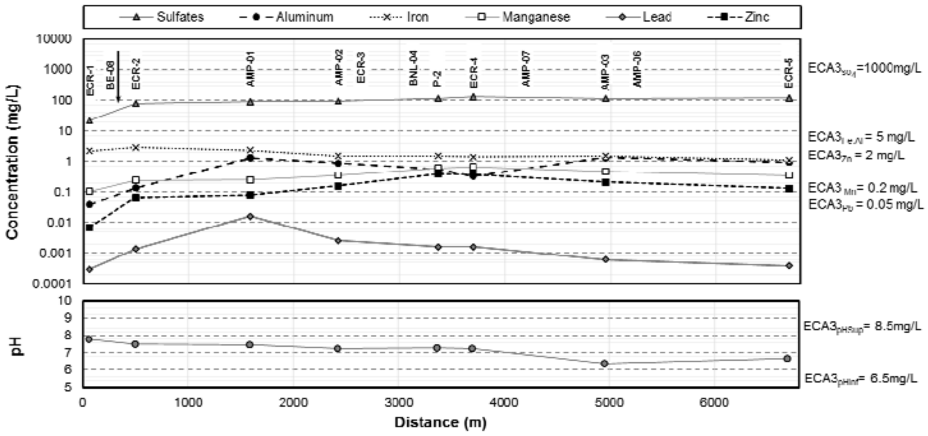


Figure 5 Evolution of Stream Acchisayhua and Stream Carhuapata quality subject to distance

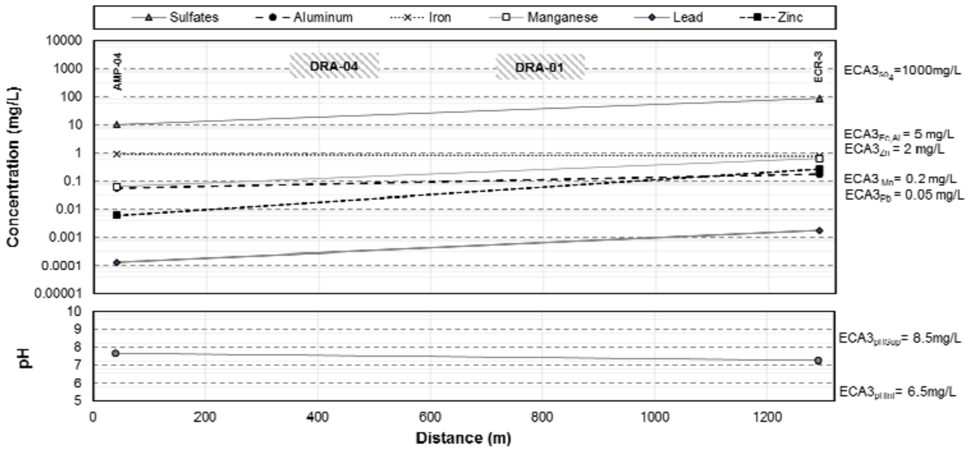


Figure 6 Evolution of Stream Llulluccha quality subject to distance

4.3.2 Time evaluation

The comparative analysis of the historic data allowed determining potential temporary variations in some parameters related to water quality control points before and after the closure measures. Evolution over time of those parameters were estimated in receiving water bodies based on available information in the study for adequacy to ECA and LMP (Geoservice, 2012), relative to the most recent campaign (Dec-17, Amphos 21).

The analysis results are shown in Figure for the elements of greater interest.

- The pH, historically (2011-2014) has been within the range permitted by the ECA 3, between 6.5 and 8.5, with specific exceptions. This is also observed in the saLMPing campaign of December 2017.
- Cadmium, had some specific ECA 3 exceedances, regulated in 0.01 mg/L, in control points ECR-3 (stream Llulluccha), ECR-4 (stream Acchisayhua), and ECR-5 (Carhuapata river downstream all components). However, no exceedance was observed regarding that standard in the campaign performed, and even some records were below the detection limit.
- Copper had a similar behavior to cadmium, with exceedances in the same mentioned locations, but concentrations exceeded ECA in up to 01 order of magnitude, although currently they are down below.

- Iron, had some specific ECA 3 exceedances, regulated in 5 mg/L, specifically in control points ECR-3 (stream Llulluccha), and ECR-5 (Carhuapata river downstream all components). In December 2017 no exceedance was observed.
- For manganese, all control points exceeded ECA 3, regulated in 0.2 mg/L. Exceedances in receiving bodies were very high in the historic record even before the reclamation works.
- Lead and zinc basically did not exceed the coLMPiance standards of ECA 3 (0.05 and 2 mg/L, respectively), except for location ECR-3. However, currently those exceedances are not identified, and concentrations are much lower.

Closure measures carried out in the study area in general have allowed concentration decrease of different parameters of interest in the receiving body.

5 Conclusions

5.1 Conclusions of Direct Closure Activities

Closure activities let determine that:

- With the application of the mix method (Application of cement and polyurethane resin), good results were obtained during closure of Esperanza Mine, reducing effluents from down the mine to 0 lts/sec.
- It is a fact that resin grouting is used basically to solve seepage problems in waterproofing systems. However, and as mentioned in this article, resins have a wide range of properties that allow its use in different injection works that provide efficient solutions to other problems that frequently come up in the field of civil engineering, public works, roads, mining, etc.
- To know the properties of the resin used and how they are going to spread by the rock cracks, in the soil interstices or in the backfill of the structure to repair is the essential basis to carry out good injection treatments at reasonable costs.
- Bentonite cement is a particular material, since it acts as a thixotropic fluid during many hours, before setting, and later it becomes a very waterproof solid, with high resistance as required within wide margins (0.5 to 100 kg/cm^2).
- With cement grouting waterproofing and improvement of the rock mass structure have been achieved, reducing up to 40% existing water seepage; the other 60% was controlled with polyurethane resin grouting, preventing failure of the concrete structure built by excessive seepage.

5.2 Conclusion of Geochemical Characterization

Geochemical characterization of the 31 saLMPes collected during the first saLMPing campaign in the study area let determine that:

- The material acid neutralization potential is very low (zero or limited carbonate presence).
- The waste rock from the waste rock dumps remaining in situ is predominantly PAG (potentially acid generating) due to the high sulfide sulfur content.
- SaLMPes both of still existing waste rock and natural soil in the zone of old removed waste rock dumps are PAG.
- Part of the soil material used to cover the in-situ waste rock dumps is PAG.
- Existing mineralizations or rock outcrops characterized with available saLMPes are also PAG, which could have effects on waters of the study area.

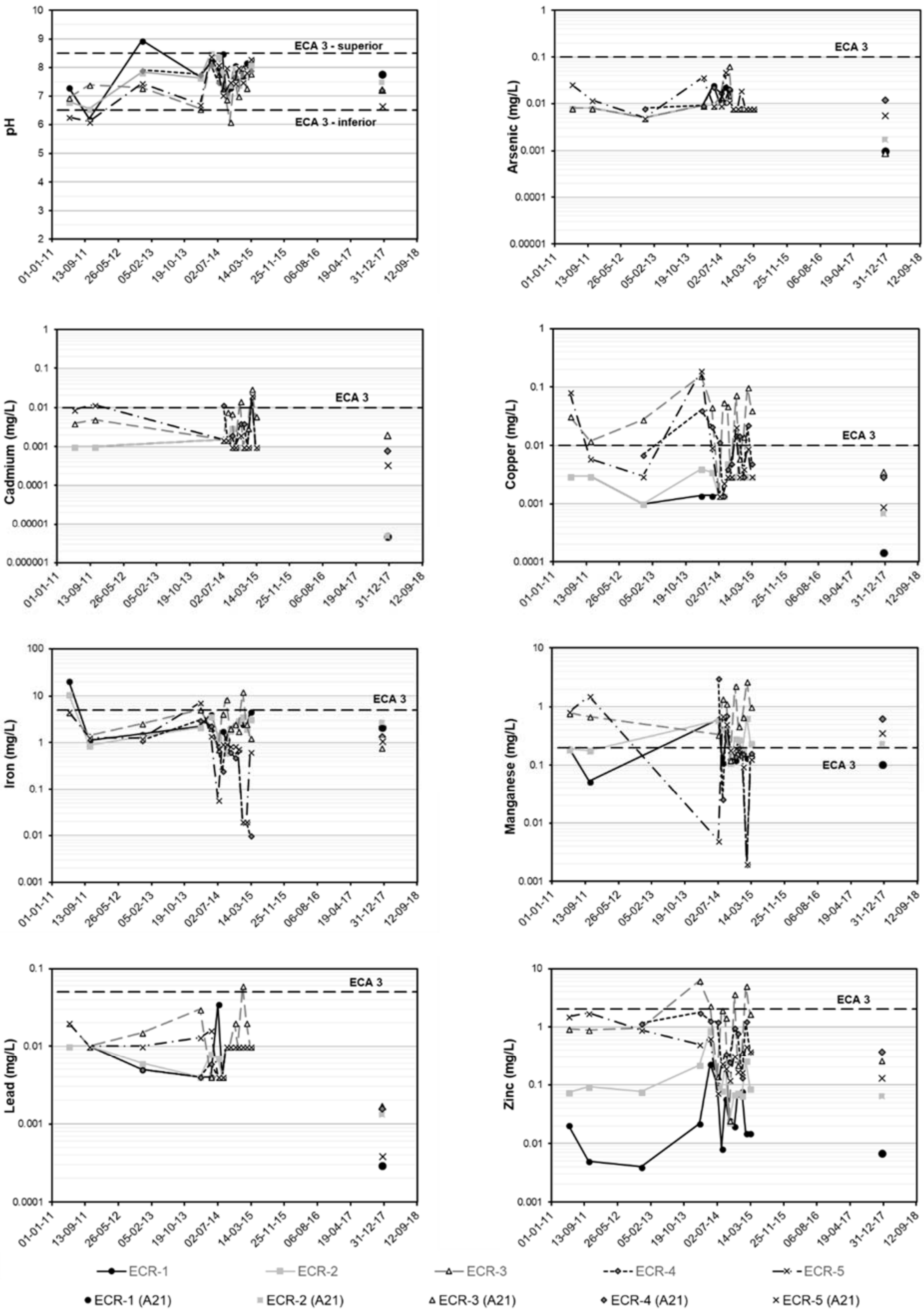


Figure 7 Historic Record for pH, As, Cd, Cu, Fe, Mn, Pb, and Zn in control locations

- The mineralogical analysis determined presence of:
  - Sulfides: pyrite, marcasite, pyrrothite, sphalerite, galena
  - Sulfates: Alunite and jarosite.
  - Very low carbonates.
- The total rock analysis shows very high contents of various elements regarding clarke which is consistent with the ore deposit surroundings.
- The sequential extraction tests allowed determining the mineral origin for different elements of interest. Regarding this, the following was proved:
  - Arsenic, cadmium, copper, iron, lead, and zinc are predominantly associated to sulfides.
  - Manganese is associated to carbonates and iron oxides, which indicates that this element is everywhere in all the materials of the study area.
- The short-term leaching test (SPLP) estimated leachate that exceeds quality standards for sulfide sulfur content above 0.1%. However, in the in-situ remaining components (Huayllacruz and Nancy Luz waste rock dump), consequences would be limited to runoff surface flows, because covers would be left and restrict contact.

5.3 Conclusion of Hydrochemical Characterization

The hydrochemical characterization of the water locations sampled provided the chemistry associated to water bodies in the study area, and to effluents related to still existing and non-existing components of Esperanza mine. The main conclusions were:

- In regard to hydrochemical characterization:
  - The water pH in the study area was recorded within the range near the neutral value (6 – 8).
  - The electrical conductivity indicated presence of waters with average and high mineralization, and some influence on receiving water bodies was identified downstream the old removed waste rock dumps and in-situ waste rock dumps.
  - The study waters had three different types of facies.
  - Surface water in high stream zones had calcium bicarbonate facie.
  - Surface water in low stream zones (influenced by existing components) had calcium sulfate facie.
  - Waste water had calcium sulfate facies because it is contact water.
- Quality analysis, in terms of space distribution, let estimate exceedances compared to environmental standards regulated in Peru (LMP and ECA 3) in study area waters for pH, iron sulfate, and manganese. It was identified that:
  - Higher concentrations were recorded in BE-08 and BNL-04, that are related to seepage from adit zones.
  - In streams and rivers, waters only exceeded ECA 3 for manganese. In that sense, influence of in-situ waste rock dumps and removed waste rock dump zones with presence of waste rock in surface water bodies is evident, which iLMPies a concentration slight increase.
- The quality analysis in terms of time evolution showed that previously ECA 3 exceedances occurred in control locations of receiving bodies regarding pH, cadmium, copper, iron, and zinc, which are not detected currently after carrying out closure measures.

- The evaluation indicated that the closure measures performed in different mine components in the study area have positively impacted receiving bodies.

6 Recommendations

6.1 Recommendations of Direct Closure Activities

Activities of cement and polyurethane resin grouting is recommended for construction process of sealing plugs.

Use of doses proposed and experimented on field related to cement grouting is recommended.

Use of established methods for cement and polyurethane resin grouting respectively is recommended.

6.2 Recommendations of Geochemical Characterization

A complementary study of the removed tailings areas is recommended to prove that rocks and soils naturally exposed in the zone are PAG.

6.3 Recommendations of Hydrochemical Characterization

Effects on waters regarding various parameters are still present if compared to concentrations upstream and downstream the components, especially manganese. Therefore, the following should be done:

- Check if all waste was completely removed from the following zones:
    - Old waste rock dumps of stream Llulluccha.
    - Old waste rock dumps of the stream right border in the passive zones of Yuracmachay.
- Update interpretations with a comprehensive analysis involving contact waters further identified, as well as geochemical soil samples of natural surroundings.

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Forest Reclamation in the Lusatian Lignite District A Wounded Landscape Heading for New Horizons

D Knoche *Forschungsinstitut für Bergbaufolgelandschaften e.V. (FIB), Germany*

J Schlenstedt *Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH (LMBV),Germany*

Abstract

In the Lusatian Lignite District up to now 550 square kilometres are restored and released from mining supervision. Thereof 310 km2 woodland underlie a regular post-mining forest management. Timber stands growing up, play a key role to minimise the environmental impact of surface mining, e.g. by reducing leaching from acid-forming sulfurous spoil banks. Beyond a simple revegetation by accident, systematic forest reclamation aims at good performing stockings for a sustainable after-use. It relates to the transfer of quite infertile, mostly sandy and sorption-poor stripped land into productive woodland and goes ahead with the re-establishment of essential ecosystem functions.

Thereby, native common/sessile oak (Quercus petraea, Quercus robur), Scots pine (Pinus sylvestris) and common birch (Betula pendula) are opening the way to the suspected climax forest at most sites. Because of the small-scale substrate heterogeneity and against remaining prognostic uncertainties, risk-spreading mixed stands are always reasonable, with a well-balanced ratio of commercial trees (50-75 % proportion of plants per each stand), ancillary trees (25-50 %) and especially biodiversity increasing species (<25 %). Natural seeding of gap-filling pioneers is welcome, insofar as they do not counteract the silvicultural ideal. In contrast, all non-naturalised, invasive and poorly site-adapted trees or bushes are refused.

Overall the ecological demands of such plantings meet the long-term habitat conditions. After overcoming some initial growth limiting factors, like the lack of plant-available nitrogen and soil humus, there is a quite promising ecosystem development: Already within 25 to 30 years both biological parameters and timber yield are comparable to the surrounding forest landscape.

Keywords: *afforestation, raw soil, cultivation, growing stock, forest growth, silviculture, sustainability, climate change*

1 The landscape in transition

Germany is still and by far the leading lignite producer worldwide. From its 170 million tons mined in 2016, one third falls upon the *Lusatian Lignite District* (DEBRIV 2018). Despite far-reaching structural changes, coal energy industry remains the economic lifeline of the region. Overall, one hundred years of large-scale opencast mining have turned the landscape *upside down*, from a fragmented, pre-industrial rural area in a large-scale technogenic living space (Katzur & Böcker 2010, Krümmelbein et al. 2013, Drebenstedt & Kuyumcu 2014, figure 1).

Actually, the removed surface comprises 900 square kilometres which takes half of the nationwide area claimed by lignite mining. Up to now 550 km^2 are restored and released from mining supervision. Thereof 31,000 hectares woodland are under regular post-mining management (Statsitik der Kohlenwirtschaft e.V. 2018) - although unexpected geotechnical instabilities cause some local use restrictions. Further 4,000 hectares of young plantations belong to the working zone, still needing care for a proper establishment, like fertilisation, weeding and mixture regulation.

Below the line, afforestation plays a key role to minimise the environmental footprint of mining. Up growing timber stands are of paramount importance for revitalisation, due to their multiple ecological functions, goods and public services (Knoche 2001, Schwarzer 2014).

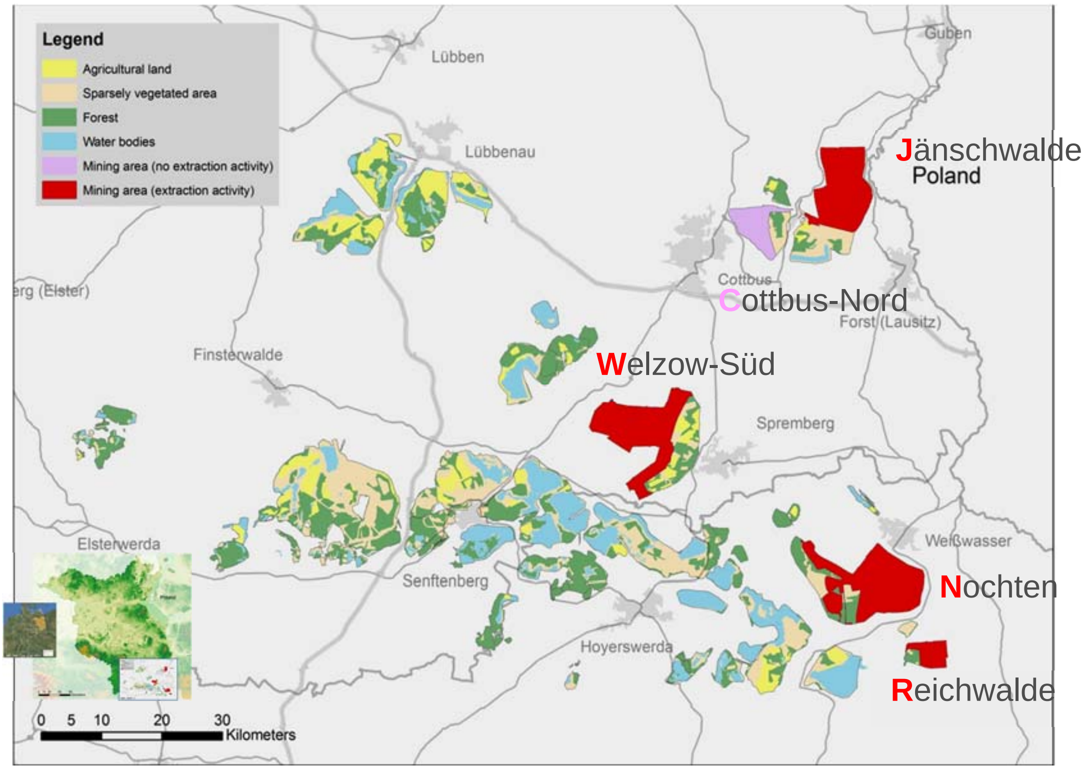

Figure 1 The Lusatian Lignite District with its widespread reclamation sites and the four open-cast mines in operation: Welzow-Süd, Jänschwalde, Nochten and Reichwalde (coloured red)

Table 1 A brief landscape characterization: Geomorphology - regional climate - soil cover & forest vegetation

Main landscape / Natural region	- Lusatian Lowland (55 to 200 m a.s.l.) - in transition of the Northeast German Lowland and Saxonian Hill and Mountainous Country, located between the rivers Schwarze Elster, Spree and Neiße - landscape-formative: sediments of the Lusatian glacial period / Saale II and Saale III (304,000 to 127,000 yr AC), covering lignite and pyrite bearing Tertiary strata of the Upper and Middle Miocene (23 to 2.580 mio. yr ago)
Regional climate	- sub-continental temperate lowland climate, summer-dry - mean annual temperature: 8.0 to 8.5 °C - average precipitation: 550 to 650 mm yr^{-1}, with half of rainfall in the vegetation period from April to September - climatic water balance during the growth period < -150 mm
Site conditions	- Quaternary glacial and fluvial sands, dune sands, gravel and loam with a low to medium yield potential - forming sandy brown earths, sandy podzols, hydromorphic soils
Potential natural vegetation	- Scots pine-sessile/common oak forests - pure, mono-structured Scots pine plantations with common birch - mixed oak-lime-beech forests with other valuable broadleaved trees - alder-ash swamp forests - actually, 80 % of woodland are stocked with Scots pine, naturally it covers less than 40 %

2 Regulatory requirements for forest reclamation …

The Lusatian Lignite District is the largest artificial landscape in Europe. And still there are 32,000 ha under management of the mining companies LEAG / active mining and LMBV / rehabilitation of former state-owned mining areas. Major target of reclamation is to compensate the environmental impact, in particular, by establishing multifunctional post-mining landscapes and ecosystems compliant to regional planning (Federal Mining Act, BBergG 1980, Lignite and Land Recultivation Act, RegBkPlG 2002). In the framework of operation plans, post-mining land use distribution gets fixed for each management unit, up to the single woodlot, field or residual lake (figure 2). Furthermore, it is obligate that the rehabilitation starts at the very beginning of the active mining. Dumps and back filled inner dumps shall be recultivated as fast as possible.

By this, the Federal Mining Act (has replaced the really confusing mass of state mining regulations with a single unified, albeit not definitive, public regulatory regime. Thereby, other regulations of the general legislation that stand opposed to the extraction of raw materials should be applied only to the extent that any deleterious impact on exploration and extraction can be kept to a minimum. The mining regulations are overriding to speed up and simplify the complex planning process. But they have to integrate the diverse public interest parties, so called *agents of concern*. However, concerning requirements of reclamation in detail the demands of the general legal provisions are relevant, i.e. soil protection, waste legislation, nature conservation, water protection, forest and other environmental regulations (von Bismarck et al. 2014).

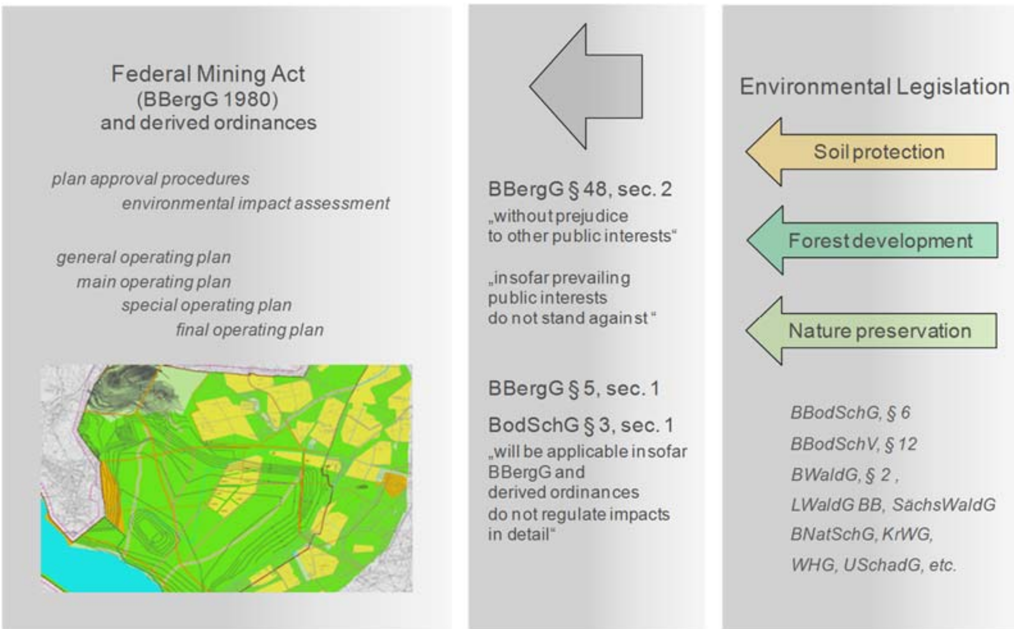

Figure 2 Environmental legislation defines reclamation standards within the binding operation plans according to the Federal Mining Act (BBergG 1980)

From a formal point of view, forest reclamation means to restore woodland which is - in narrow interpretation - just a surface stocked with woody species (planting), according to forest legislation (Federal Forest Act, BWaldG 1975).

In the case of active mining additional technical implementation rules set by the regional forest approval authorities are concretising this fundamental obligation. Some quality criteria for proper plantings and their final acceptance as wood or commercial timberland are: cultivable soil material with a plant-friendly topsoil target pH_{KCl} of 5.0 to 6.5 - use of site-adapted forest tree species, as possible from regional provenances - plant failures less than 10 % of the initial stem number - no single gaps larger than 1,000 square metres. The success of afforestation is defined by tree species-specific minimum plant numbers per hectare which have to be achieved in the early sapling stage, i.e. time of canopy closure, first tending: Scots pine / 8,000 pcs., sessile and common oak / 6,000 pcs., other species / 2,500 to 4,000 pcs. per 10,000 square metres.

Even more, before any forests are cleared in advance of the mining operation, there must be equal area compensation on the dump side. This link between loss of forests and restoration ensures a proper and near-time reclamation, minimizing the ecological time-lag.

... and commitment going above regulations

However, the claim and self-image of the responsible mining companies exceed the legal requirements described before. Their stated goal is to establish useful and stable, near-nature mixed forests, following the ecological orientation of reclamation (Bradshaw 1983, Hüttl & Bradshaw 2000, Schlenstedt et al. 2014). Climax forests should develop, already in the first forest generation and without the interim stage of temporal greening or soil-preparing pioneer wood (Haubold-Rosar & Knoche 2010). New woodlands have to meet the increasing demands on forests, right from the very beginning - concerning productivity, protection of natural resources and including recreational claims of the population. Moreover, the implied ecological sustainability leads to low-input and low-risk systems - in terms of biological self-regulation a basic condition for a long-term profitable forest management. However, besides re-vegetation, restoring fully integer ecosystems is a process taking several decades (Jordan et al. 1987).

3 Raw soils require special measures

Creating a new-born post-mining landscape does not mean the imitation of the former situation. It notably targets at ground with its own, very specific landscape features, soils, habitats, ecological potentials and cropping properties. In this context, afforestation of raw soils is more difficult as compared to the replanting on natural, soundly managed fertile land. Especially, the exceptional soil chemical properties are challenging (Drebenstedt 2001).

- Juvenile mine substrates are structure-poor geological substrates, free of humus. Ecosystem development starts at point zero: At the beginning, microbiological activity and nutrient turnover are negligible.
- Notably, nitrogen, phosphorus and sometimes potassium are plant growth limiting, even for quite unassuming pioneer tree species (Heinsdorf 1996).
- As consequence the ecosystem nutrient cycle establishes in delay, having a retarding effect on initial soil and forest stand development (Katzur 1998, Knoche et al. 2000, Knoche et al. 2002).

Therefore, a growth-supporting and soil life stimulating mineral NP(K)-fertilisation just before planting is essential. In addition there are up to three needs-based top-dressings spread over the first decade. The tree species-specific fertilisation sequence does not only enhance survival rate and stimulate early plant development but also accelerates the desired humus-forming soil processes (Schlenstedt et al. 2014). Already in the sapling stage, ecosystem nutrient turnover by crown leaching, litterfall and humus mineralisation is similar to comparable forest stands growing on undisturbed soils. This corresponds to the establishment of self-sustaining natural element cycles (Knoche et al. 2000). From then on, fertilisation gets unnecessary, and ecologically tolerable wood exploitation is quite comparable to surrounding woodland (Köhler et al. 2016). Finally, the young timber stands show a well-balanced nutrient supply, even under a nowadays moderate atmospheric deposition (Stähr et al. 2000).

For the most part, sandy to loamy Tertiary sediments are containing high amounts of iron sulphide (pyrite) and dispersed lignite. Because of strong acidification (pH_{KCl} <2.5) by pyrite oxidation and intensive clay mineral weathering, these substrates remain free of vegetation - sometimes even for decades (Pietsch 1996). But the acidification potential varies considerably, and it is necessary to calculate the lime requirement exactly for each mapped substrate unit. The field-proven acid-base-balance (Illner & Katzur 1964, Katzur 1998) does not only refer to the hydrolytic acidity. It also accounts the acidification from complete pyrite weathering and the substrate-specific buffer capacity, in order to maintain a crop-friendly pH level of the major rooting zone. Long-term planting trials confirm that optimal forest growth can be achieved at pH_{KCl} >5.0

and within an effective depth of lime incorporation from 0.6 to 1.0 m (Knoche & Haubold-Rosar 2004). In the case of very sulphurous and fine textured substrates the cultivable soil layer can require up to 50 Mg CaO ha^{1}.

Against higher environmental standards, nowadays heaps and dumps are covered with a minimum of one meter acid-free, quite fertile Quaternary overburden - wherever available, technologically possible and economically feasible. With pH_{KCl}-values from 4.5 (decalcified) to 7.5 (calcareous) the base saturation of the unweathered fine-grained soil usually reaches 60 % and hence is optimal for most common forest trees. However, extraction, transport and dumping of overburden material with large mining equipment cause a considerable small-scale heterogeneity of the land cover, making the optimal choice of tree species and latter stand management rather demanding.

The covering of the ameliorated substrate with forest soil from the deforested future part of the mine foster the biological rehabilitation and helps to establish the nutrient cycles. Especially most earthworms and terrestrial isopods depend on active measures to reach the sites again (Landeck 2017). Both species groups are important for the soil development. Also the seeds of typical forest plants are transported to the new sites. Measures have proven successful in which the humus bearing topsoil was removed to 20 cm on the donor site and applied with a thickness of 3 to 5 cm on the rehabilitation site (Schlenstedt et al. 2014). The seed and the earthworms with the highest survival chances on the new site collected in the upper 20 cm.

4 Decades-long experience and scientific support

In the Lusatian Lignite District we can look back on over hundred years of forest reclamation and profound empirical knowledge. The first systematic growing stocks date back in the late 1960s, based on a scientific soil evaluation and classification (Lorenz et al. 1968, Schwabe 1970). In short, they favoured robust, less nutrient and water demanding pioneer trees, like Scots pine (*Pinus sylvestris*), European larch (*Larix decidua*), common birch (*Betula pendula*), red oak (*Quercus rubra*), black/red and grey/white alder (*Alnus glutinosa*, *Alnus incana*) or European aspen (*Populus tremula*). Although survival rate and initial growth are sufficient, they clearly undervalue the site-related growth potential. In addition, short-lived and low-quality softwood trees, like aspen, alder or birch, are aging early, thus calling for a stand conversion already in immature pole forests.

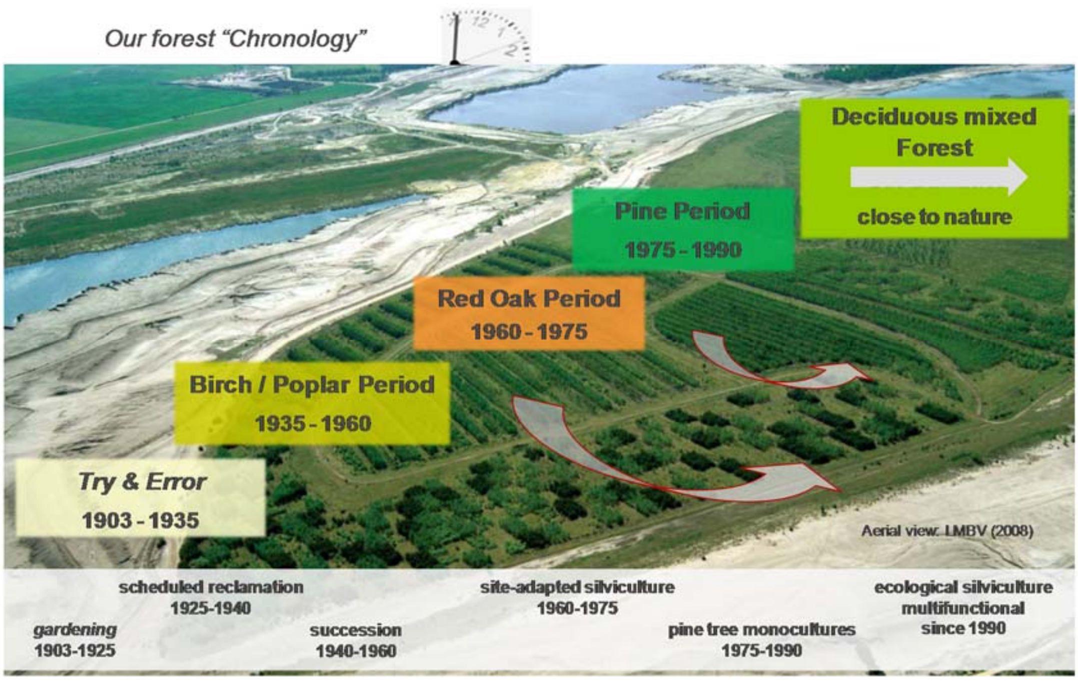

Figure 3 Milestones of forest reclamation in the Lusatian Lignite District - 115 years: A treasure of experience

As we know now, even on moderately cohesive and shallow ameliorated substrates, competitive stockings of more demanding deciduous hardwood trees can be established with good success - notably, native sessile or common oak (*Quercus petrea*, *Quercus robur*), small-leaved lime (*Tilia cordata*) and hornbeam (*Carpinus betulus*). Against the initial growth depression, as mentioned above, many stands exceed the yield level of nearby forests on well-developed soils from nutrient poor ice-age formed sediments (Katzur et al. 2000). Hence modern forest reclamation takes up consequently the common trend towards a near-natural forest management, with a high portion of ecologically beneficial broad-leafed trees. Whereas in the surrounding area structure-poor and quite instable pine monocultures still cover 80 percentage of the woodland, it are only 40 % in present-day mine site afforestation.

5 Leading to best practice target growing stocks

Based on long-term trials, multifactorial growth analysis and forest modeling considering the different mine sites, soils and mature forests, a consistent scheme for the selection of proper trees is derived (table 2): The designated target stocks are representing tree species combinations as they appear most likely by free succession in the terminal stage of ecosystem development. The specific ecological demands are in good agreement with the soil and long-term habitat conditions (Knoche 2001, Haubold-Rosar & Knoche 2010).

- Thereby, nutrient poor substrates, like Quaternary gravel, gravel sand or coarse sand, are left to undemanding Scots pine, common birch and European aspen as dominant tree species with a broad ecological amplitude.
- Already on weakly cohesive loamy sands, having a low to medium alkali content and pHKCl values above 4.0, sessile and common oak become competitive.
- Moreover, valuable substrates with a growth optimum topsoil pHKCl range from 5.0 to 6.5 and higher, broadleaved trees are recommended, in the combination with small-leaved lime, European beech (Fagus sylvatica), plane and sycamore maple (Acer platanoides, Acer pseudoplatanus) or common ash (Fraxinus excelsior).

However, in the Lusatian Lignite District only less than 15 % are high-yielding sites. Approximately three-quarter of plantings are stocking on heterogeneous, water sorption and nutrient poor mixed soils. All the more, the formation of mixed stands is reasonable from the ecological point of view. In doing so, the silvicultural scope is growing with an increasing nutrient supply and water storage capacity of the parent soil material:

- For example, in pine stands growing on pure fine sands only drought tolerant and nutrient undemanding common birch or aspen are sounding partners - as temporary or permanent mixture.
- On the other hand, Scots pine can be integrated in oak stands, stocking on weakly cohesive substrates which corresponds to the near-natural forest vegetation of the region.
- Suitable ancillary native tree species on high-yielding loamy soils are small-leaved lime, hornbeam, plane and sycamore maple, field and mountain elm (Ulmus minor, Ulmus glabra).
- Notably, in areas with higher annual precipitation and some interflow or backwater European beech and common ash come into question as mixed tree species.
- Furthermore, rare provenances worthy of conservation (Acer campestre, wild fruit woods, Salix spec., Sorbus aucuparia, Picea abies, Abies alba) and autochtonous bushes (Rosa canina, Prunus spinosa, Crataegus monogyna, etc.) should be considered.
- Added in small groups, they contribute to biodiversity and serve landscape aesthetics, especially along stand edges, forest roads and in transition to the open land.
- The natural seeding of gap-filling pioneer trees like common birch, European aspen, goat willow (Salix caprea) or mountain ash (Sorbus aucuparia) is welcome, insofar they do not counteract the higher-level development goal towards the terminal forest type.

- Consequently, non-native trees and bushes - how they are still frequently used in gardening or small-scale landscaping - are refused.
- Exceptions are the well site-adapted North American red oak and nitrogen-fixing black locust (Robinia pseudoacacia). Fast growing, they are structuring large plantings. Another application is the small-sized cultivation of dry, acidic or erosion-prone soils.

Table 2: Target growing stocks in the Lusatian Lignite District - groundwater level >2 m below soil surface, according to Knoche (2001) and Schlenstedt et al. (2014), modified outline

Dumped substrate	Nutritional value	Soil moisture class	Target growing stock / forest-forming tree species combination
calcareous loam and silt (partly with gravel or lignite)	rich	moist to moderately dry	(1) common oak + small-leaved lime, (2) valuable broadleaved trees (plane and sycamore maple, common ash) + common oak + small-leaved lime / hornbeam; (3) valuable broadleaved trees / common oak + European beech
		dry	(1) sessile oak + European beech; (2) sessile / common oak + small-leaved lime / hornbeam; (3) sessile oak + Scots pine
loam / loamy sand / silt / calcareous loamy sand with lignite	strong	moist to moderately dry	(1) sessile / common oak + small-leaved lime / hornbeam; (2) common oak + broadleaved trees; (3) European beech + broadleaved trees
		dry	(1) sessile oak + small-leaved lime; (2) sessile oak + Scots pine / common birch
loam / loamy sand / lignite containing loam, loamy sand or silt / calcareous sand with lignite	medium	moist to moderately dry	(1) sessile / common oak +small-leaved lime / hornbeam; (2) sessile oak + European beech; (3) sessile oak + sycamore maple
		dry	(1) sessile oak / red oak + Scots pine; (2) sessile oak + common birch / European aspen
loamy sand / loamy sand and sand with lignite and gravel / pure sand (medium and fine textured)	low	moist to moderately dry	(1) sessile / common oak + Scots pine / common birch / European aspen; (2) Scots pine + common birch / black and grey alder
		dry	(1) sessile oak / red oak+ Scots pine / birch; (2) common oak + birch; (3) Scots pine + common birch / European aspen
coarse sand / sand with lignite or gravel / gravel	poor	moist to moderately dry	(1) Scots pine + common birch / European aspen; (2) Scots pine + black and grey alder
		dry	(1) pure Scots pine; (2) pure common birch; (3) Scots pine + common birch

(+) = in combination with, (/) = optional

The establishment of mixed stands is no end in itself: Selecting trees should always consider the special site conditions, growth potential and competitive relationships. As a general rule, the growth dominant and forest-forming tree species take 50 to 75 % of the total plant number, ancillary fillers or complementary and economically important understory 30 to 50 %. At least some additional, particularly ecological valuable intermediate trees cover between 10 and 20 %. In any case, only regional and proofed propagation material is suitable. Due to the challenging site conditions, damage free one-year-old seedlings (pine tree) to two/three-year-old nursery transplants (hardwoods) with a tight shoot/root ratio are preferred. As turned out, the survival rate of such plantings is comparable to common afforestation of woodland or deforested fallow land (80 to 95 %), although the initial shoot growth may be lower in favour of early root development. Therefore, the spacing, tree assortments and quality of plant material orientates at general forest guidelines. This also applies for the proportions and forms of admixtures. For example, the average plant number is usually between 5,000 to 10,000 stems per hectare (Schlenstedt et al. 2014). For the practitioners of silviculture, it is recommended the low-stress admixture in small groups or double rows.

Figure 4 Young afforestation with sessile oak, small-leaved lime and Scots pine on an ameliorated acid sulphate loamy sand, photo: D. Knoche, FIB e.V.

The creation of forest edges around the afforested fields with typical local shrubs and trees, like hazelnut, blackthorn, wild cherry, white beam and different kinds of roses establish very fast worthy conditions for birds, insects and small mammals. By this other species benefit from this structure and enhance the biodiversity of a specific site (Schlenstedt et al. 2014). But these structures attract also rabbits, hares, roe and deer. Survival of the forest edges depends therefore on dense and regularly controlled forest fences in the first years. The range of these hedges ideally with an herbaceous fringe in direction to the open agricultural used neighborhood should be minimum 5 meters up to 30 meters.

Below the line, after 20 to 30 years forests on the mine sites show a growth performance and biological-ecological diversity which is comparable to the surrounding countryside (Hüttl & Weber 2001). However, the soil chemical properties remain rather different from non-mined natural soils in the long-term, especially concerning acid-sulphurous and lignite containing Tertiary substrates and non-ameliorated, still very acid and saline subsoil layers (Knoche 2001, Schaaf & Hüttl 2006).

6 Enhancing biodiversity by establishing forests

Beside typical buyers of rehabilitated mine sites, like farmers, hunters and touristic developers, natural conservation organisations, both public and private, take over responsibility of post-mining sites. In total more than 11,000 hectares of post-mining land of different rehabilitation stages are owned by them (Schlenstedt 2017). Open, sparely vegetated areas and depressions filled with shallow water are in the focus, as these structures became rare in the intensely used landscapes surrounding the mines (Köck 2000). But future forest areas are the most important part of their ownership (figure 5).

Figure 5 Multifunctional post-mining landscape Meuro: afforestation with Scots pine, sessile oak and common birch, biotope-mosaics (semi-natural succession, open land) and a solar power plant in the background, photo: P. Radke, LMBV mbH

Reforestation by guided succession and planting with a reduced density of plants open space to natural processes. Thereby, early stages on raw soils with shrubs and the Lusatian pioneer trees Scots pine and common birch remain as worthy patchwork of habitats for otherwise endangered species (Lorenz & Landeck 2017). But also overstocked hardwood timber stands in the age beyond 60 years have a great relevance for biodiversity, e.g. saproxylic beetles, due to the high portion of deadwood (Landeck et al. 2006). The very special site conditions and different biogenesis compared to forests on undisturbed soils result in manifold varieties of the typical species composition. Overall, the whole aspect of insects, benthic organisms, amphibian, reptilian and birds find refuge in the unfragmented woodland and establish populations with astonishing numbers (Landeck et al. 2017).

7 Adaption to climate change

However, the Lusatian mining area is an ecologically sensitive region with amplified responses to climate change impact (Linke et al. 2010). Across all climate scenarios (Wettreg, Cosmo-CLM, Remo) the annual average temperature will increase by 2.0 to 3.0 degrees Celsius by the end of this century, compared to climate normal period 1971-2000 (Knoche et al. 2012). In addition, the growth-limiting water availability in the vegetation season will further decrease. Long rainless and hot early summer periods occur more frequently calling for modifications in the cultivation planning.

- The silvicultural scope on mine sites decreases under plant-growth complicating environmental conditions. That applies in particular for the predominant water sorption and nutrient poor sandy soils, having already now few stocking options.
- Notably, water demanding valuable hardwoods, like common ash or plane and sycamore maple, will come under pressure which restricts their already limited suitability for mine site afforestation.
- Tree-ring based growth simulations indicate, that both sessile and common oak benefit from a further warming, if the plant available water storage capacity exceeds 100 mm per one meter soil depth (Knoche & Ertle 2014).
- It is foreseeable that more drought tolerant Scots pine suffers from high summer temperatures with daily peaks of 40 oC in the shade. The boreal tree species grows already at the southwest border of its natural distribution range.

One promising way forward are mixed forests with a high genetic diversity, but also using drought and heat tolerant genotypes. Another approach pays more attention at spontaneous succession and natural selection processes, especially on very low-yielding and heterogeneous sites. Even though that means an extensification of forest management, it is no turning away from a multifunctional forestry including timber production (Abresch et al. 2000, Schlenstedt et al. 2014, Prach 2015).

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Biodiversity - Species and Habitats in Post-Mining Landscapes of the Lusatian and Central German Mining District

C Hildmann *Research Institute for Post-Mining Landscapes (FIB), Germany*

J Schlenstedt *Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH (LMBV), Germany*

Abstract

Although lignite mining turns entire landscapes upside down, mining landscapes continuously develop into new habitats. As part of a study commissioned by the LMBV, we compiled the current state of knowledge on biodiversity in the mining landscape of the Lusatian and Central German districts.

The sediments brought to the surface by mining typically feature very special site conditions – they are poor in nutrients, raw soils, sometimes featuring closely inter-fingered moist and very dry patches, together with their relative lack of disturbance. On the longer term, these site conditions remain where the pressure of utilization is low and nature conservation is given room as it is the case in several large nature conservation projects of the Lusatian and Central German post-mining landscapes. Initially, pioneer societies are developing here, for which only niches exist in the surrounding "normal" landscape without mining. With progressing succession, the landscape inherently changes. However, despite increasing forest shares, still open special sites are to be found for a prolonged time, for example in habitats located on tertiary sediments.

The biodiversity that we identified under these conditions is amazingly high. We collected data from available reports, publications and a variety of other sources, such as information from volunteer mapping experts. Compiled results are available for a number of species groups from both flora and fauna, featuring with mammals, birds, dragonflies, beetles, grasshoppers and many more. We find that many of the species groups are represented by a surprisingly high proportion of species in the post-mining landscape: the diversity of habitats also documented here has an advantageous effect for the species diversity. For example, we identified 1,300 plant species, 145 breeding bird species, 457 spider species and 44 grasshopper species in post-mining landscapes of the Lusatian and Central German district. Many of these species have become very rare in the "normal" landscape and are red-listed therefore. Despite the overall small area (0.37% of Germany's land area), a considerable proportion of the species inventory could be found in post-mining landscapes, about 31% of plant species or 52% of locust species. Nevertheless, there are registration deficits for some species group.

Therefore, and against all adverse environmental effects of opencast mining, studied post-mining landscapes developed as important habitats for many animal and plant species who are in need of protection.

Keywords: *biodiversity, habitats in post mining landscapes*

1 Introduction and objective

Opencast lignite mining causes a complete transformation of the landscape, where the pre-mining landscape get completely extinguished. At the same time, a completely new landscape is being created after mining – the post-mining landscape.

LMBV is the company responsible for geotechnical protection and design of extensive open-cast mining in the Lausitzer and Central German mining districts. After the political change in East Germany in 1989, the demand for lignite declined drastically. As a result, open pits of ~475 km² in the Lusatian and ~290 km² in the Central German mining districts were abandoned.

However, these large areas did not become inanimate deserts, but rather the very reverse. Soon after dumping of overburden, settlement commenced, and special site conditions granted suitable habitats for species, which nowadays are rare in the surrounding normal landscape.

For this reason, and since the ongoing frequent geotechnical safety interventions on partial areas, an up-to-date knowledge of the species and habitats in the post-mining landscape is of great interest. While a number of studies were conducted in the 1990s, the current state of development remained elusive. With our study, we close this gap of knowledge, and we give advice regarding the current restoration practice.

We summarize a comprehensive study by Landeck et al. (2017) on the occurrence of a total of 29 species groups and 25 biotope types and habitats. We focus on areas of so-called remediation mining, a strategy aiming to ensure geotechnical safety and subsequent use of the land. This study was conducted under the leadership of Research Institute for Post-Mining Landscapes in Finsterwalde (FIB) and Anhalt University of Applied Sciences in Bernburg, and with contributions of Institute of Inland Fisheries in Potsdam, Beak Consultants GmbH in Freiberg, Heinz-Sielmann-Foundation and BUND Foundation Wildnis Goitzsche.

2 Special features of lignite mining in eastern Germany

Lignite mining in Lusatia around the cities Hoyerswerda, Lauchhammer, Senftenberg, Cottbus, and Weißwasser, and in the Central German area with the urban centres Zeitz, Weissenfels, Borna, Leipzig, and Halle-Bitterfeld has been promoted on industrial scale for more than 200 years. As a result, and including ongoing exploitation of by legislation approved lignite reserves, a total of ~1,800 km² of land will have been claimed by opencast mining in Lusatia and the Central German territory. The region was facing a production peak between 1950 and 1990, when land consumption was on correspondingly the highest level. If lignite was still very close to the surface at the beginning of industrial use, nowadays up to 120 m of overburden need to be removed before target layer mining.

Commencing in the 1920s, vast masses of overburden were mostly spoiled using conveyor bridges and large spreaders. This resulted in mixed substrate systems containing material of Pleistocene origin, pyrite-bearing tertiary sands, and clays with different carbon contents. As educts of soil formation, these melanges lead to compartmentalized changing properties on the surface of the dumps. Adversely for the affected landscapes, during the time of the former GDR recultivation of mine dumps did not keep pace with exploitation of new areas. Consequentially, an excess of non-recultivated dumps arose. Over the years, this recultivation deficit summed up to tens of thousands of hectares, and nature had up to 40 years to develop undisturbedly.

In the course of the political changes after the decay of the Warsaw Pact in the early 1990s, perception of the value of dedication of land to nature conservation changed. As a result, various nature conservation associations (e.g. BUND foundation “Wildnis Goitzsche”, Heinz-Sielmann-foundation, NABU foundation) – mainly serving process protection and permitting undisturbed development – have taken over responsibility for to-protect-areas. These areas are of particular importance for the variety of species and habitats present today.

3 Methodology

In order to compile habitats, species occurring and the natural development (succession), we compiled, systematised and evaluated documents available from the LMBV for the Central German and Lusatian mining districts. We found these documentations to be heterogeneous regarding their quality of processing, the observation period, and spatial referencing. In total, we evaluated and harmonized expert contributions on species protection, mapping documents from protected areas, procedures for intervention regulations and landscape plans from > 100 documentations per mining district. In some areas we performed repeated vegetation mappings, aiming to tie these to previous mappings of the past twenty years.

However, still the resulting picture of habitats and species groups was patchy. Therefore, we decided to tap other information source, such as mappings by species scientists (ornithologists, beetle specialists, etc.), surveys of state institutions, scientific work and databases in both the Central German and Lusatian mining districts. This resulted in very extensive databases for 29 different species groups. More than 100 experts provided data, or participated in the evaluation. Thus, we got enabled to draw a comprehensive and detailed picture of biodiversity of the mining landscapes under examination.

4 Site characteristics

Prior to a targeted agricultural or forestry land re-use, the dumped sediments of the surface, which are the educt of soil formation, have the following characteristics:

1. They are predominantly nutrient-poor sediments.
2. They are raw soils without humus and plant remains.
3. They neither feature soil organisms nor seed banks of plants.
4. They can contain small-scale, heterogeneous sequences of weakly to strongly sulphuric acid substrates.
5. They show pronounced gradients in the water balance – very dry areas alternate with moist to wet areas.
6. Dry areas tend to heat up strongly, thus having a challenging micro climate.

In addition, there are the following noteworthy factors and potentials of abandoned pits a landscape ecology level:

1. They are extensive, undivided and relatively undisturbed by human activities.
2. They have a high variety of locations and niches.
3. They are highly dynamic from a geomorphological, and even from a biological perspective.

Lignite opencast mining leads, due to massive large-scale intervention in the landscape, to a complete destruction of the original land surface. This applies to the historically grown land uses, to the established food web and relationship networks of plants and animals, and even to all underlying natural processes in the landscapes. Lignite mining in Europe and especially in Germany happens in intensely used cultural landscapes. Therefore, the resulting successive mining landscapes offer nature new space and opportunities in the form of unique structures, habitats and areas without intensive and regular use. However, even intentionally recultivated open-pit areas can contain valuable habitats, and therefore contribute to the high biodiversity of the mining landscape.

5 Dynamics of development

Exhausted open-cast mines and dumps can either develop into post-mining landscapes largely uninfluenced by man or be prepared for a desired subsequential use through targeted recultivation measures. A completely uncontrolled development will hardly be possible in European mining areas, as European environmental laws and mostly also national mining laws oppose that. In Germany, open-cast mines are subject to the Federal Mining Act, which requires the elimination of hazards for the general public and public protective goods such as water, meaning that the entrepreneur obliged under mining law is responsible. In Lusatia, the Pleistocene-derived, homogeneous, frequently round and therefore geotechnically unstable sands also require extensive securing work in future areas of nature conservation.

Targeted recultivation considers ground and surface water, near-surface substrate, the (future) vegetation, the development of the areas through paths and equipment for firefighting, and nature conservation and recreation aspects. These measures steer development, but still leave room for natural developments to a certain extent.

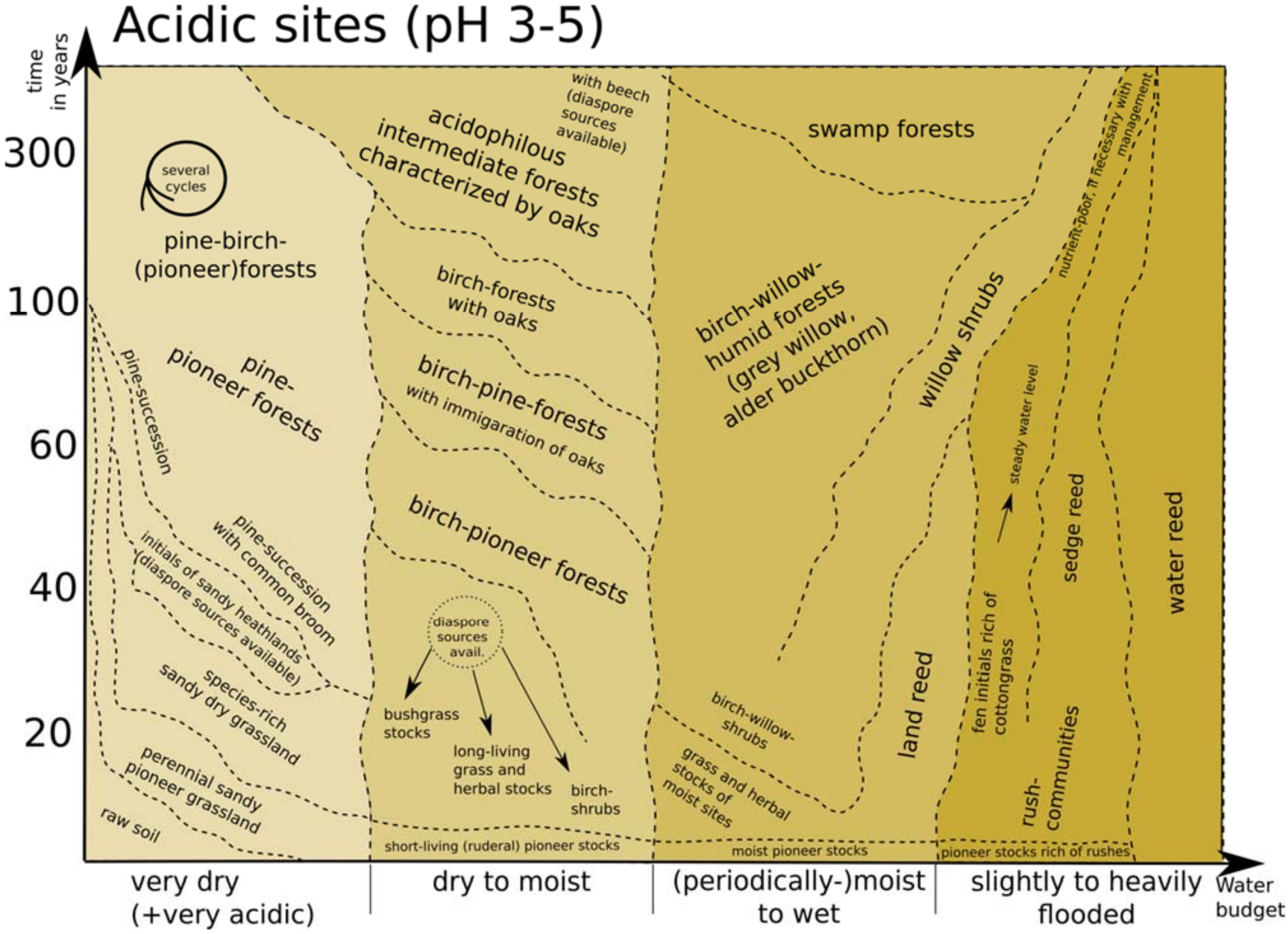

Figure 1 **Possible succession sequences in East German post-mining landscapes on acid soils depending on the age of the area and the water balance. Source: Landeck et al. 2017 (modified).**

These natural development sequences and the time periods required for them are to be shown using acid sites as an example. Figure 1 shows the natural succession for acid locations with different moisture levels, which usually lead to different forest types. It can be seen that on dry to fresh sites there is a varied succession sequence, while on the very dry acidic soils, after de-acidification of the upper soil and a certain degree of soil development, stable pioneer pine forests develop quickly. These pioneer forests can last for very long periods. On extreme locations, which are very warm, dry and acidic, raw soils can survive for decades. The same applies to wet to over stowed locations. Such stable habitats for animal species that have become rare in the cultural landscapes are formed over a long period of time.

As the example of acid locations shows, the dynamics of succession are determined by a few location factors. In addition to the dependence on the water balance (dry to wet), these are soil chemical properties (acid content, presence or absence of nutrients or phytotoxic substances) and the thermal situation of the site.

In line with these factors, the succession of vegetation also progresses in a differentiated manner and has an impact on biotope diversity. According to previous studies, biotope types of open habitats that are not established in extreme locations have declined sharply over the last 15 years. The reason for this is that almost all sites in the post-mining landscapes are forestable. Open land biotopes, such as dry sand grasslands and grass and herbal stocks can therefore only be secured in post-mining landscapes by regular maintenance measures. Only the highly undesirable bushgrass (Calamagrostis epigeijos) can develop stable grasslands over several decades without management.

In conclusion, it can be stated that in the post-mining landscapes of both mining districts the dynamics leads to changed habitat compositions. At the waters reeds and above all (pre)forests on the terrestrial areas will continue to increase in the coming years. In contrast, raw soil areas and raw soil mosaics will only be found in extreme locations in the long term.

We note that, despite a shift towards more developed types of vegetation, only a minor decline in floristic species diversity happened so far. Most of the species identified in the first mappings twenty years ago could be found in subsequent mappings in the Central German region. The proportion of species that have disappeared is contrasted by newly found species. The changes in the proportions of biotope areas lead to an increase or decrease in species characteristic of the respective biotope type.

With the succession of vegetation, soils undergo further devolpment. The enrichment of biogenic carbon and biologically bound nutrients in the form of roots, humus, litter and soil organisms also promotes the development of nutrient cycles in the soil.

Compared to the succession of many plant species, immigration of animal groups important for soil development, such as earthworms or woodlice, is rather very slow and delayed (Dunger, W. & Voigtländer, K. 2009). These animals migrate at a low propagation speed and are dependent on human help. Spreading can take place through active measures such as the intentional displacement of forest soil, the creation of stump and deadwood walls or the planting of trees with bales of soil. Indirectly, the animals reach the recultivation areas by transporting them or their eggs with the material and equipment used.

6 Diversity of biotope and vegetation types

Three fundamentally different types of vegetation in succession of post mining landscapes can be distinguished:

1. Pure aquatic habitats. These can be divided into a) on the water surface and b) subaquatic, then graded by depth.
2. Water-bound terrestrial habitats. These include a) springs and slope water outlets, b) water reeds on the banks of the lakes, c) land reeds as accompanying biotopes to springs and slope water outlets as well as wet to moist locations, d) sedges in the sedimentation zones of the lakes, e) initial stages of fens and swamps as very rare biotope types and finally f) wet meadows, particularly rich in orchids, very valuable.
3. Terrestrial habitats. In addition to the water areas, these determine the character of the post-mining landscapes. These include a) inland salt deposits, as rare forms on dumps of saline coal seams and ash dumps of lignite-fired power plants, b) vegetation-free and low vegetation raw soils, c) erosion edges, gullies, steep walls, steep slopes, d) sandy pioneer plots on dry sites far from groundwater water, e) dry sand grasslands as the typical picture of early succession, especially on Lusatian dumps, f) dwarf shrub heaths with Calluna, g) calcareous grassland initials exclusively in the Central German area, h) grassland and herbal plots, which also occupy a large area due to recultivation, i) bushgrass plots, with *Calamagrostis epigejos* as dominant and most widespread species in the post-mining landscapes, j) biotope mosaics from diverse vegetation and habitat structures, k) bush stages of native species are also widespread, l) bush stages of alien species, which were often planted as part of earlier recultivation measures, m) pioneer forests of mesotrophic to rich locations, n) pioneer forests on extreme sites, such as superficially de-acidified tertiary soil material, sites with high coal content (coal contents >10 – 40% coal), very steep sites and heaps with a high clay content, o) pioneer forests of varyingly wet to wet sites under the influence of groundwater, p) intermediary forests, i.e. forests aged between 60 – 100 years, q) forests of indigenous tree species, and finally r) Forests of alien tree species.

From the results of our study, we draw the following conclusions:

1. A large number of vegetation types has formed as a result of the one and the same massive disturbance, i.e. the extraction of lignite in open-cast mines. Variability of vegetation types reflects the different geological and natural conditions in which the intervention took place.

2. At the same time, we find that – despite different species composition in individual cases and despite different dominant geological sediments – the overall vegetation structure in the Central German and Lusatian mining districts is very similar.
3. Numerous post-mining vegetation associations, such as the different types of forests, grass and herbal plots, and bushgrass stands are also present in the non-mining landscape.
4. However, certain vegetation types that have become very rare in the "normal" landscape, or do not occur there at all, such as pioneer forests on strongly coal-bearing material, use the unique chance that post-mining landscapes offer to them.

It is the mix of habitats, sometimes in very confined spaces, that has an impact on the species, their frequency and developments in post-mining landscapes (fig. 2).

Figure 2 Examples of post-mining landscapes located in the Lusatian mining district (photos: Hildmann).

7 Examples of biodiversity

The studies forming our compilation on habitats and species cover a total area of around 1,300 km², equalling to ~2.7 percent of the area of the German Federal States of Brandenburg and Saxonia. We excluded active mining areas and their future mining reaches from our study. The processing area corresponds to 0.37% of Germany's land area. The ratio of species found in post-mining landscapes to the total number of species of the respective species group in Germany provides astonishing results (table 1). For example, 4,165 different vascular plants are known in Germany. Of these, 1,300 species, or 31%, were found in the post-mining landscapes. Out of 105 mammal species native to Germany, 51 species inhabit post-mining landscapes, and of 5 out of 13 indigenous reptiles resp. 15 out of 22 indigenous amphibian species have been sighted there. 145 bird species, i.e. almost every second breeding species in Germany, breed in post-mining landscapes. But, first of all, post-mining landscapes are very important habitats for weaving spiders, grasshoppers, cicadas, ground beetles, butterflies and wild bees.

Post-mining landscapes are also important habitats for species bound to aquatic life, such as water bugs. Of 69 species occurring in Germany, 43 now live in the post-mining landscapes of Lusatia and Central Germany. For some groups of species, it should also be taken into account that the intensity of detection and the level of knowledge about their occurrence in the post-mining landscape is incomplete, e.g. for water beetles, mayflies or cicadas. Here, the shares determined tend to represent underestimates.

Species of animals that are problematic either because of their comprehensive conservation status in the cultivated landscapes, such as the sand lizard (Lacerta agilis), or because of their way of life such as the wolf (Lupus lupus) and the beaver (Castor fiber), have found a much less conflicting habitat in post-mining landscapes.

Immigration into post-mining landscapes depends on the different strategies of the species. The flora in particular is clearly related to the species in the direct open-cast mining surroundings.

The sand lizard is one of the characteristic species of post-mining landscapes, although it is rather rare outside of these. It benefits from the warmer locations and makes particular use of the open areas bordering bushes. Immigration takes place along linear structures such as strips of woodland or stump hedges. With the progressive succession in the opencast mines, a long-term decline in the population density of sand lizards is to be expected.

Figure 3 The wood cricket (left) spreads slowly in the post-mining landscapes, because it is a flightless species. Contrary, the Italian locust (right), a formerly endangered species, is widely distributed in the Lusatian mining district (photos: Hildmann).

A total of 44 species of grasshoppers could be detected in the study area, most of them heat-loving species. Species such as the sand hopper (Sphingonotus caerulans) are pioneer species that are able fly over longer distances, even across forest areas. It preferably inhabits raw soils and sandy habitats with little vegetation, so that the post-mining landscape is of great importance for the species. However, with the progressive development of vegetation, sand hopper counts are already decreasing again in places. In the Lusatian region, the Italian locust (Calliptamus italicus) was also able to spread (fig. 3). Previously close to extinction in Brandenburg, it made the leap from the Lieberoser Heide (a former military training ground) into the post-mining landscapes. Today it is a common species on pioneer grass and herbal stocks, and on dry grasslands. The colonization by the wood cricket (Nemobius sylvestris), a flightless species, proceeded completely differently. It could only immigrate from the mining pit margins when suitable forest sites had developed there (fig. 3). Elsewhere, as on the isolated Schipkau high dump, it has apparently arrived as a stowaway.

The numbers prove the very high importance of post-mining landscapes for biodiversity and species protection in Germany. The structural diversity, large surface area and relative lack of disturbance in the former opencast mines are the reasons for this success. On the other hand, they also indicate a problem, because these factors were lost on most of the cultural landscape.

Table 1 **Number of species of selected groups in the post-mining landscapes. PML: post-mining landscape, PMLtot: total, PMLCG: Central German mining district, PMLLR: Lusatian mining district, PMLboth: number of species in both mining districts, following columns: number of species in Brandenburg (BB), Saxony (SN), Saxony-Anhalt (ST) and Germany (D). †: not enough data for further differentiation, n.a.: not available. Source: Landeck et al. 2017, modified.**

Species group	PML_{tot}	PML_{CG}	PML_{LR}	PML_{both}	BB	SN	ST	D
vascular plants	1,300	1,063	961	724	1,961	2,812	2,293	4,165
mosses	182	131	122	71	507	727	754	1,159
lichens	118	62	104	48	543	951	676	~ 1,700
macrofungi	556	296	381	121	n.a.	4,551	3,232	6,162
stoneworts	19	16	15	12	28	22	19	36
mammals	51	32	45	26	n.a.	78	81	105
reptiles	5	5	5	5	8	7	7	13
amphibians	15	13	12	12	15	18	18	22
breeding bird species	145	135	133	123	219	215	225	328
freshwater fishes, cyclostomes	33	n.a.	n.a.	n.a.	61	59	50	106
earthworms	12	10	11	9	n.a.	n.a.	21	47
woodlouses	7	7	2	2	n.a.	n.a.	28	48
spiders	457	341	405	289	615	630	649	992
harvesters	15	9	9	3	26	27	32	52
mantises	1	1	1	1	1	1	1	1
earwigs	5	4	5	4	n.a.	7	5	9
grasshoppers	44	38	42	36	65	58	62	85
dragonflies, damselflies	55	53	54	52	66	70	71	81
antlions	3	3	3	3	4	4	3	6
cicadas	209	179	136	106	378	427	443	635
water bugs	43	5	43	5	n.a.	n.a.	55	69
seed bugs	184	n.a.	184	-	n.a.	n.a.	582	798
ground beetles	274	220	236	152	340	369	414	583
aquatic beetles	121	†	†	†	237	233	267	344
wood living beetles	264	22	256	16	917	930	887	1,371
butterflies	79	65	74	60	118	114	130	189
Zygaenidae moths	10	8	8	6	13	15	15	27
other moths	655	422	632	399	898	957	957	1,235
caddisflies	49	n.a.	49	-	165	n.a.	204	315
Aculeata	670	359	633	322	817	n.a.	860	1,238
hoverflies	97	45	77	25	n.a.	n.a.	322	463

8 Conclusions and recommendations

- Post-mining landscapes offer a unique opportunity to secure important structures for nature conservation and biodiversity. They are thus an unexpected partial substitute for lost habitats of cultural landscapes.
- In post-mining landscapes, large areas should be created without economical use, or intensive human disturbance.
- Competent organisations should be encouraged and supported to acquire and maintain such land in the long term.
- The recultivation of areas should always allow room for natural developments.
- The different plans in the active mining companies should take into account raw soil areas, succession areas and areas for temporary water accumulations in their planning at an early stage, and design them accordingly.
- Post-mining landscapes should not be unnecessarily cleared up. This means the preservation of small-scale structures, the retention of non-polluting mining residues, or the permitting of geotechnically unproblematic changes on embankments and banks.
- Management plans and corresponding resources should be created at an early stage for the preservation of biotope types to be maintained, such as the colonisation-friendly open habitats. Wherever management is provided, a variety of methods should be applied to different types. A promising approach, for which there are first examples from post-mining landscapes, are "wild pastures", on which a small, adapted stock of large herbivores (e.g. robust cattle and/or horses) is kept all year round.
- Long-term monitoring on dedicated areas makes it possible to obtain data that are also relevant outside the mining areas.
- The post-mining landscapes are subject to numerous usage requirements (agriculture, forestry, tourism) and nature conservation claims. Therefore, these areas should be made accessible for people under certain rules, e.g. for nature experience.

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The Environment Condition Before and After Mining in Iron Sand Mining of Cilacap, Central Java, Indonesia

D Septriana *Tambang Tbk. Jakarta, Indonesia*

PT Aneka *Tambang Tbk. Jakarta, Indonesia*

Jl Letjen *Tambang Tbk. Jakarta, Indonesia*

L Selatan *Tambang Tbk. Jakarta, Indonesia*

Abstract

Every mining activity surely will have effects to the environment, this was also happened in Iron Sand Mining in Cilacap region which used Hydraulic Mining System. It takes maximum effort to recover the land use back into the previous function. But, in this site all environmental aspect after mining can be maintain below the threshold for soil, air and water quality. The use of the land before mining is dominated by agriculture, as well as in after mining, agricultural land for agriculture even broader because reclamation of land is used for rice fields and vegetables, crops and fruits, even the sand of the beach in mined out area wich used of certain agricultural technologies can give more value for land utilization. The land use after mining can be recover faster to its previous function for crops, and even more better for some area that never been used for crops before so it can be use for crops after reclamation. Apart from rice, also produce vegetables and fruits. And also supported by the community livelihoods, mostly as farmers. All of these increase the income of the people in Cilacap as increasing numbers of agricultural land and reclamation. Beside that, before the activities of mining begin, a source of livelihood mostly from agriculture and traditional animal husbandry. And because there are many large rivers and swamps in the area of Cilacap, and freshwater fisheries is plenty and also the maintenance of fish ponds in undisturbed mined out area which are cultivated by local people. This condition caused the increasing of flora and fauna enrichment. All of that resulted the condition of biologi, physic/chemist, social and economic aspect in ex-mining in Cilacap were better than before.

Keywords*: Iron Sand Mining, agiculture, reclamation, environment*

1 Introduction

Iron sand mining of Cilacap (ISMC) lies Cilacap regency, Province of Central Java, owned by PT Antam Tbk has been started since 1971 with extensive Mining Concession1547.849 ha and its products such as iron ore grades of concentrate (Fe) above 50%. In the years 1971 to 1978 mostly exported to Japan, but since 1978 until 2003 marketed in the country. ISMC is applied in open pit mining with a spray mine system (hydraulic mining) and re-fill. Environmental damage caused by mining activities, of course not be avoided, ranging from land clearing, and degradation of vegetation, degradation of soil, water, air and even the impact on the socio-economic lives of the surrounding community. What can be done is to minimize these impacts, the philosophy of land use is only temporary, and after mining is completed, the land will be returned in accordance with the functions and other functions. This certainly would be better if the return on the land function can add value from the previous land use.

Despite the efforts of environmental management and environmental monitoring has been conducted, and cultivated land damage is minimized, but the state of the post mining environment quality of ISMC would have a different from before mining. Impacts of mining activities is not all negative, but there is also a positive impact, such as increased economic community, the contribution of local revenue (PAD), local employment, improving regional infrastructure development, improving education and health, and may also include increased functionality land.

To be able to see a comparison of state environmental and public life before and after the completion of mining, there needs assessment on Life After the Iron Sand Mining in Cilacap.

1.1 Purpose of the Study

- Conducting studies and community differences in environmental conditions before and after mining.
- To evaluate the added value of land use after mining.

1.2 Scope

The scope of this study that the quality of soil, water, air, used of land, flora and fauna, and socio-economic communities.

2 Methodology

The methods are performed in this study are:

- Collect and recapitulate data
- Perform comparisons of data
- Evaluate data

2.1 Iron Sand Mining

ISMC already exists since 1971 with products such as iron sand concentrate grades of iron (Fe) above 50% are exported to Japan with a total export of 300,000 tons per year. However, export demand is reduced and since the year 1978-2003 only product marketed in the country to meet the needs of the cement plant raw materials. The location of ISMC is along the southern coast of Cilacap covers the entire width of 1000 m in Cilacap regency, Central Java. Area activities include DU. 110/Jateng area of 280 950 Ha, DU. 109/Central Java area of 562.33 Ha, DU. 207/Central Java area of 568.50 hectares, and DU. 209/Central Java area of 136.724 Ha.

In general, the status of landownership in the concession is owned by Antam Cilacap Army that covering 200 m from the beach landward of the form where cattle grazing pastures. While the remainder is owned by local residents that consists of rice fields, plantations, crops, and coconuts. The Mining is applied in open pit mining with a spray mine system (hydraulic mining). The mined lands was reclaimed and revegetation. The landfill reclamation is done by using the back filling system. Furthermore, the mined land which is the status of land owned by the villages and individuals returned to their owners and usually will be immediately planted by the owner with beans and after that make them become a rice fields. While the land army will be reforested by planting cash crops such as palm, acacia, and *nyamplung*.

2.2 Climate and Physiography Profile

2.2.1 Climate

Generally Cilacap district has a tropical climate with high rainfall ranges from 3187-5616 mm with rainy days ranges from 2-25 days/month. Monthly average temperature for this area is about 24.6 to 27.8°C and humidity ranged from 82-88%. While solar radiation ranged between 27-91%. Average wind speed was low, ranging between 2-9 knots. On the east monsoon, the wind was blowing from the southeast, while in the west monsoon, the wind blowing from the west (Cilacap Meteorological Agency, 1988).

2.2.2 Physiography

Topographic location of ISMC activities rests fully on the plains with an altitude of 0-15 m above the sea level. The eastern part of the site is limited by the Ijo river, the west is limited by the Serayu river, to the south is bounded by the Indonesian Ocean, and on the north side is residential land. The whole project ground work overgrown shrubbery, and even bald. The soil consists of loose sand that contains iron. After the completion of mining activities, the color of the soil/land form becomes irregular, appears puddles former excavations that have not organized well. But when the puddles after mining has been filled in and flattened out again and there are several locations that have been reclaimed rainfed lowland and upland agriculture, such as in the area of Glempang Pasir and Karangbenda.

2.3 The Differences of Environment Condition Before and After Mining

Table 1 Differences of land Quality Before and After Mining (Environment Auditing of Post-Closure Iron Mine Sand Cilacap, 2009)

No	Parameter	unit	Location			
			GP (MAB)	GP (PMA)	B (MAB)	B (PMA)
1	pH – H2O	-	6,6	7,1	5,8	6,4
	pH - KCl	-	6,1	7,0	4,9	5,8
2	C	%	0,3	0,04	0,04	0,04
	N	%	0,04	0,01	0,01	0,01
	C/N		8	6	6	6
3	P2O5 HCl 25%	mg/100 g	70	66	73	78
	P2O5 Olsen	Ppm	16	9	7	6
4	K2O HCl 25%	mg/100 g	14	27	14	29
5	Kation Basa Dapat Tukar					
	Ca	meq/100 g	2,63	3,81	1,83	1,91
	Mg	meq/100 g	0,62	3,24	2,01	3,92
	K	meq/100 g	0,07	0,14	0,07	0,26
	Na	meq/100 g	0,06	0,06	0,06	0,17
6	KTK NH4 Asetat – 1N	meq/100 g	3,38	7,25	4,04	6,26
	KTK NHCl	meq/100 g	5,67	4,57	0,69	0,9
7	Kejenuhan Basa (KB)	%	3,25	6,29	3,83	6,09
8	Logam-logam		60	>100	>100	>100
	Fe Total	%	5,65	4,37	3,59	4,61
	S Total	%	0,06	0,03	0,05	0,02
	Cu	ppm	1,39	1,73	1,45	1,91
	Zn	ppm	2,24	3,98	3,04	3,71
	Fe Dithiomit	ppm	6,329	6,210	6,685	6,619
	Al Dithiomit	ppm	220	115	105	92

GP (MAB): Glempang Pasir area before mining, GP (PMA): Glempang Pasir area after mining
B (MAB): Bunton area before mining, B (PMA): Bunton pasca area after mining

2.3.1 Type and Soil Quality

The soil physical condition in the area of Cilacap is textured sand-colored argillaceous dusky and sand composition has greater than 80%. This location is a garden soil population. Organic matter content in this area generally is very low. Differences in land quality before and after in the mines at two locations, Glempang Pasir and Bunton (Table 1).

In Table 1 can be seen that in general soil chemical conditions after mining is not much different than before mining, even for a few parameters is higher than the quality standard such as pH, HCl 25% P2O5, K2O HCl 25%, Ca, Mg, K, Na, NH4 Acetate CEC – 1N, Total Fe, Cu, and Zn. This is because soil fertility conditions before mining is quite low. After mining is completed soil quality is increasing as the soil is already being processed and the presence of organic fertilizer at the time of reclamation. Community owned land is returned to its owner and most used as agricultural land planted with rice, watermelon, beans, green beans and other food crops.

2.3.2 Water Quality

The main waterworks of Cilacap consists of rivers and sea. To determine the water quality around the mining area before and after can be seen in the following table 2. Table 2 shows that the river water quality during post mining better than before mining, such as lead (Pb) decreased to undetectable, Zn also decreased. This is expected because of the mine using a spray system and do not use materials containing heavy metals as well as effective environmental management programs to maintain the lost of fuel or oil in the mining area.

Table 2 The River Water Quality Before and After Mining (Study of Environment Evaluation in Iron Sand Mining Activities of Cilacap, 1990 and Iron Sand Mine Closure Plan Cilacap, 2005)

No	Parameter	Unit	R (BM)	R (AM)	Rr
1	pH	-	6,85	7,40	6 – 9
2	Pb	mg/l	0,11	udt	0,03
3	Zn	mg/l	0,15	0,01	0,05
4	N-NO_2	mg/l	udt	0,02	0,06
5	N-NO_3	mg/l	0,11	0,28	10

R (BM): River water quality before mining; R (AM): River water quality after mining, Udt: Undetectable; Rr: raw river water quality based on PP No.82/2001, category II

Table 3 Quality of sea water before and after mining (Study of Environment Evaluation iron sand mining activities in Cilacap, in 1990 and Iron Sand Mine Closure Plan Cilacap, 2005)

No	Parameter	Unit	S (BM)	S (AM)	Sqs
1	pH	-	7,42	7,60	6 – 9
2	Pb	mg/l	0,21	Udt	0,03
3	Zn	mg/l	0,05	0,01	0,05
4	N-NO_2	mg/l	Udt	Udt	0,06
5	N-NO_3	mg/l	0,23	Udt	10

S (BM): marine water quality before mining; S (AM): marine water quality after mining; Udt: undetectable; Sqs: sea water quality standard, KepMen LH No. 51/2004 for marine life

For the parameters of the N-NO_2 and N-NO_3 seen increased, this may be because the situation in post-mining land are also better than before mining conditions due to fertilization, thus affecting the state of N- NO_2 and NO_3-N of river water.

In Table 3 can be seen that the quality of sea water before and after mining is still below the quality standard is set so that it can be said that mining activity does not cause a negative impact on marine water quality around the mine.

2.3.3 Air Quality

Generally, the air in Cilacap is clean enough. Location of iron sand mining in the area located 50 m from the beach and surrounded by the bare land/fallow and agricultural lands. Iron sand mining in the area are carried out with a spray system of the mine, the mine system thus emit less gas and dust into the air, so the impact on air quality was relatively small. Activities of agriculture-based communities also do not produce gas and dust in large numbers. The main pollutants from mining activities are iron dust, mainly from ore transportation activities.

The air quality at the mine in the post-mined sites, tourist sites and settlements can be seen in Table 4 below it can be seen that the air quality after mining is still below the threshold established quality standards.

Table 4 Ambient Air Quality in the former mining, tourism and residential

Parameter	Unit	U1	U2	U3	U4	Eqs
Dust (TSP)	ug/m^3	150	70	60	50	230
Sulfur dioxide (SO_2)	ug/m^3	46	29	24	23	632
Nitrogen dioxide (NO_2)	ug/m^3	52	34	29	28	316
Carbon monoxide (CO)	ug/m^3	3.000	1.600	1.300	1.200	15.000
Oxidant (O_3)	ug/m^3	<10	<10	<10	<10	235

Source : Environment Auditing of Post-Closure Iron Mine Sand Cilacap, 2009

U1: mined location; U2: tourism sites; U3: settlements of Karangbenda village; U4: settlement og Glempang pasir Village; Eqs: environmental quality standards, Kep.Gubernur Jateng No.8/2001 ambient air quality standard

2.3.4 Land Use

In general, the pattern of use of agricultural land in Cilacap regency, which is dominated by extensive rice fields, 63.095 million ha (29.5% of districts), followed by an extensive moor 34.952 million (19.65% of the district). Land use of mined area in the region of Glempang Pasir, Karangbenda and Bunton is currently a garden mix consisting of annual plant:

- coconut, acacia, *jarak*
- Annual Plants: seeds, crops (peanuts, green beans, long beans, kale, *oyong,* cassava and watermelon)
- stretch of bare land that is fallow land that has not been used

Former mining land use by local communities for various activities such as green area (81.41 hectares), agriculture fields (202.58 hectares), horticulture fields (13.13 hectares), resident area (153.46 hectares). The

Figure 2 Morphology in the mine area

Figure 3 Morphology of sand beach is shaped like elongated parallel to the dike

Figure 4 Mined land use for the garden eggplant

Figure 5 Mined land uses for peanuts

use of land for agricultural activities gets the biggest portion since reclamation activities increase and expand the agriculture area, especially for rice cultivation, and land that used to not be exploited as agricultural land as land belonging to the army, have now reclaimed and can be used for agricultural activities. Even the lands along the shore of the structure in the form of mined sand, by using agriculture technology has now been sown vegetables such as onions, cabbage and water melon. This gives a very high added value for all land uses.

2.3.5 Flora and Fauna

Broadly speaking, the iron sand mining activities in the areas of Cilacap is in the built environment in the form of agricultural land and rice fields. Natural vegetation found only shrubs that inhabit coastal areas. Types of common plants found in gardens and yards are in the form of trees, like coconut *(Coccos nucifera),* cashew (*Anacardium ocidentale)*, mango *(Mangifera indica),* guava water *(Syzigum aquenum),* guava *(Psidium guajava)*, banana *(Musa paradisiaca),* jackfruit *(Arthrocarpus integra)* and there are also rain-fed rice / rice (Oryza sativa) with production of approximately 4-5 tons / ha. Agricultural land is generally planted with crops such as cassava species (Manihot esculenta), maize *(Zea mays),* soybean *(Glycine max),* mung bean *(Pheseolus radiatus),* cucumber *(Cucumis sativus),* watermelon *(Cucurbita mashata).* Regional shrubs include prickly pandanus *(Pandanus tectoris),* goat legs *(Ipomea Pressed caprae)* and various types of grass.

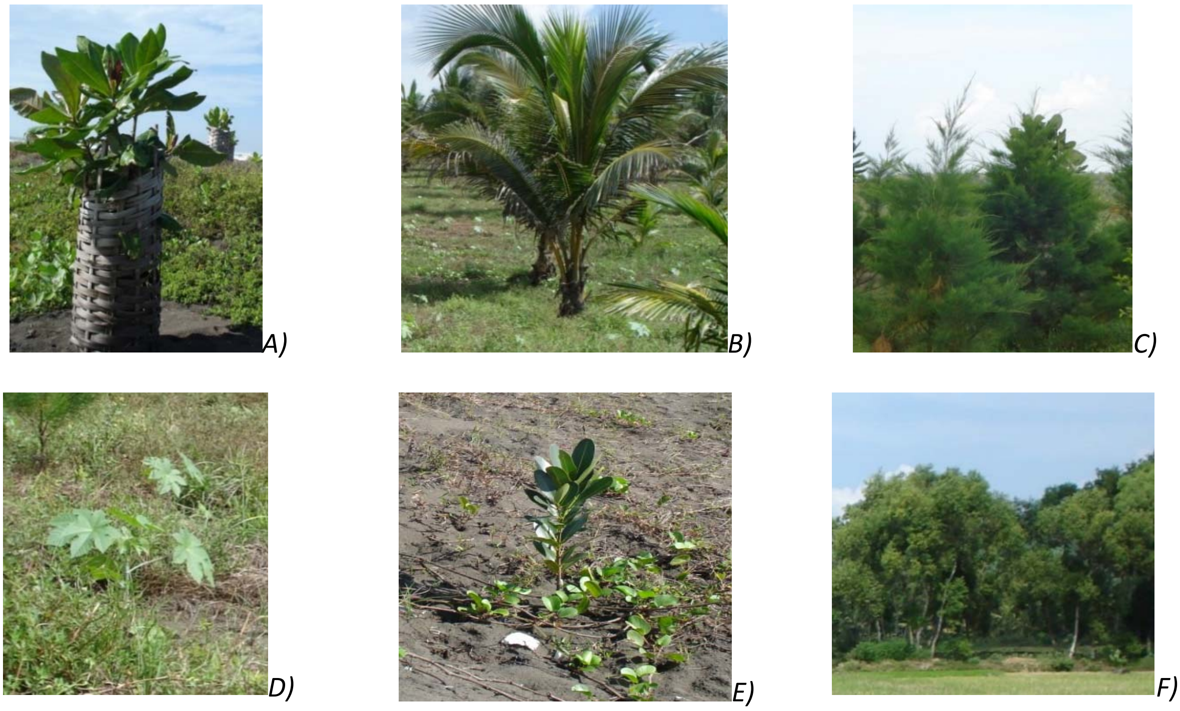

Figure 6 The plants is growing in the mined area, (A) Ketapang laut, (B) Kelapa, (C) Cemara laut, (D) Jarak, (E) Nyamplung, (F) Acacia

After completion of mining activities, mining areas have been appointed to the rice fields and farmland in accordance with the desires of the community. Post-iron sand mining land have been returned to rainfed lowland (45.81%) and farm/garden (15.40%). Level of rice production in post-mining land to reach 4 tons / ha and there is not much different from the productivity of rice prior to mining. Common types of crops planted in the garden is the type of crops, including cassava *(Manihot esculenta),* soybean *(Glycine max),* mung bean *(Phaseolus radiatus),* cucumber (*Cucumis sativus),* long beans and melons *(Cucurbita mashata).*

While these types of plants in land reclamation is a sea almond, coconut, sea pines, *jarak*, *Nyamplung* and acacia. *(ketapang laut, kelapa, cemara laut, jarak, nyamplung dan akasia.)* Wild animals that existed after mining is relatively the same post with the prior conditions, namely birds egrets *(Ardeola),* sparrow *(Passer montana)* and sparrow *(Lonchura).* Other animals are commonly found as live stock such as chickens, ducks, goats, buffaloes and cows. From above description shows that the impact of iron sand mining on terrestrial flora and fauna are relatively insignificant.

2.3.6 Social and community

2.3.6.1 Population

District is strongly influenced by mining activities in the area of Cilacap regency is Sub-district of Adipala. The number of residents in this area in 1983 was 59,707 inhabitants, and increased to 66,416 inhabitants in 1987. With the existence of the mining activities led to an increasing number of residents in the area, so that when the post of mine in the year 2008 the population reached 80,162 inhabitants.

2.3.6.2 Employment Opportunities

Before mining activities was begin, area most people in Cilacap have livelihoods as farmers (69.87%), other than that there is also as employers (5.02%), traders (4.89%), industrial workers (3.62%), construction workers (2.46%), and others (0.36%). At the time of mining activities still exist, most people turn to work at Antam's mining sector, after mining is completed they switch back to the agricultural sector. Livelihood of the people after mining as farmers (56.01%), services (11.87%), commerce (10.85%) and industry (6.61%).

(Auditing Post-Mine Closure and Iron Sand Cilacap, 2009). Termination of mining activities instead of work opportunities in the agricultural sector. Reclamation activities have been added or expanded agricultural land, because land that used to not be exploited as agricultural land, especially land owned by the Army, now the community can be utilized as agricultural land after going through the process of restoration. So that can be said that the reclamation and mine closure activities give benefit to the surrounding community.

2.3.6.3 Increased Public Economics

Before the activities of mining begin, a source of livelihood mostly from agriculture and animal husbandry. Apart from rice, also produce vegetables and fruits. And because there are many large rivers and swamps in the area of Cilacap, and freshwater fisheries is plenty and also the maintenance of fish ponds are cultivated by local people. The income per capita of Cilacap residents in 1986, Rp. 357, 925. and in the year 1988 increased to USD. 459,060. In that time, mining activity is still ongoing, and after mining is completed the community economy actually increased because the majority of land used for agricultural land reclamation, and even land as sand beach can be planted by vegetables and fruits with the use of certain agricultural technologies. Therefore it can be said that there is no economic dependence on society community after mining.

3 Conclusion

General condition of the soil chemistry after mining is not much different than before mining, even for a few parameters are higher than the original state such as pH, HCl 25%,% P_2O_5, 25 K_2O HCl, Ca, Mg, K, Na, NH_4 Acetate CEC - 1N, Total Fe, Cu, and Zn. This is because the conditions prior to mining of soil fertility is low enough. After mining is completed the quality of the soil increased as the soil has been processed and the presence of organic fertilizer at the time of reclamation.

River water quality during post mining better than before mining, such as lead (Pb) decreased to undetectable, Zn also decreased. This is expected because of the mine using a spray system and do not use materials containing heavy metals as well as effective environmental management programs to maintain the lost of fuel or oil in the mining area. For the parameters of the N-NO_2 and N-NO_3 seen increased, due to the situation in post-mining land is also better than before mining conditions due to fertilization. Both before and after mining there are no water quality parameters that exceed environmental quality standards.

Impact of mining activities on air quality was relatively small, so either before or after mining there are no air quality that exceeds environmental quality standards.

The use of the land before the mining sector is dominated by agriculture, as well as in after mining, agricultural land for rice and vegetable fields even broader because reclamation of land used for rice fields and vegetable crops and fruits, even the sand of the beach area mined with the use of certain agricultural technologies have been used for agriculture, this gives more value for land utilization.

The type of flora and fauna before and after mining is completed is not so different, this is because the return of land back to the primarily function, so the vegetation types are relatively similar.

Level of public economy at the mine take a rose, where per capita income residents of Cilacap Regency 1986 is Rp. 357,925. and in 1988 increased to Rp. 459,060. After the completion of mining activities, income of the people can still continue to rise as increasing numbers of agricultural land to former mined lands reclamation. And also supported by the community livelihoods, mostly as farmers.

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What Should Ecological Function of an Intertidal Zone Look Like at a Historic Mine Site at Closure?

BG Wernick *Golder Associates Ltd., Canada*

Abstract

The former Britannia Mine operated near Vancouver, Canada from 1904 to 1974, and at its peak was the largest copper mine in the British Commonwealth. During its 70 years of operation it generated more than 40 million tonnes of tailings which was used as fill along the Britannia Beach shoreline and was deposited in the adjacent marine environment of Howe Sound. Canadian mining practices no longer allow this form of mine waste management. The acid-generating tailings and upland former mine workings leached dissolved copper and zinc into Howe Sound until recently when the government began an extensive remediation program to intercept, collect and treat water-borne metals discharging to the environment. Monitoring of water quality and intertidal ecology over more than a decade is providing information confirming that environmental conditions are improving along a majority of the shoreline. The objective of initial remediation activities was to address severe, acutely lethal conditions that posed a mortality hazard to out-migrating juvenile salmon and this objective has been achieved. As site characterization continues and additional remediation is undertaken, realistic remediation goals need to be defined both in the context of significant modifications to the shoreline including filling and replacement of the natural shoreline with engineered surfaces (e.g., rip rap) and construction of a transportation corridor, and changing climate. "Resource conservation objectives" (RCOs) have been recommended to help direct remediation efforts. The RCOs consist of a description of important shoreline ecological functions and/or features as well as acceptable levels of those features that are based on: 1) the results of the monitoring program which provide an understanding of the ecological conditions of near-field and reference areas, including natural variability; 2) the broader mandate of environmental regulatory agencies to maintain and/or or restore a healthy productive ecosystem; and 3) the local community's desire for environmental improvement.

Keywords: *Britannia Mine, closure, ecological function, intertidal zone, recovery, restoration, resource conservation objectives*

1 Introduction

The former Britannia Mine (Figure 1), located 45 km north of Vancouver, adjacent to Howe Sound (ca. 49°37'30" N, 123°12'17"W), operated primarily as a copper and zinc mine from early 1904 to 1974 and at its peak, was the largest copper mine in the British Commonwealth. During its 70 years of life, the mine generated over 40 million tonnes of tailings, largely deposited onto the marine, subtidal slope of Howe Sound within 3 km of Britannia Beach. Mining operations also led to generation of acid rock drainage (ARD), which was historically released from two mine portals ("2200 Level" and "4100 Level") into Britannia Creek as well as other, non-point, sources of contaminated surface water (Wernick et al. 2010a). Soil contamination also resulted in elevated concentrations of metals in groundwater, which in the alluvial fan area of Britannia Creek discharge to Howe Sound's intertidal zone. The primary contaminants of concern have been identified as copper and zinc, and to a lesser extent, cadmium.

The presence of ARD from mining has been known since at least 1556 (BCAMDTF 1989) but when the Britannia Mine started operating in 1904 there was a poor understanding of the cause and environmental effects of ARD, and management methods and regulatory imperative (law, policy, and government will to prevent and control ARD) were not in place. In the late-1990s government and university scientists conducted a series of studies in Howe Sound in the vicinity of Britannia Beach due to growing concerns regarding the ongoing discharge of contaminants from the Mine. These studies showed effects to the intertidal community approximately 2 km to both the north and south of Britannia Creek, including the mortality of caged Chinook salmon (*Oncorhynchus tshawytscha*) smolts, absence of typical species such as *Fucus gardneri*, *Mytilus* sp., and gammarid amphipods, and dominance by a copper-tolerant filamentous green alga (Barry et a. 2000; Marsden & DeWreede 2000; Grout & Levings 2001; Levings et al. 2004). Partially in response to the findings of these studies, the government of the Province of British Columbia assumed responsibility for remediation of the Britannia Mine in June 2001 and in December 2001, University of British Columbia (Vancouver, Canada) engineers installed a concrete plug in the 2200 Level portal to divert flow back into the underground mine workings (Wernick et al. 2010a). Initially, this stored water was discharged untreated via an outfall at a depth of 26 m in Howe Sound directly offshore from the mouth of Britannia Creek (Figure 1). In 2005, a water treatment plan (WTP) began treating the contaminated mine water and discharging the effluent to Howe Sound via a new deep-water multiport diffuser at a depth of 50 m, 1 km south of Britannia Beach, and a groundwater management (GMS) system was commissioned in 2006 to intercept metal-contaminated groundwater in the southern portion of the Fan Area and pump the groundwater the WTP.

Strategies for the prediction and management of reactive mine wastes in modern mining operations is now common knowledge with extensive global guidance available “off the shelf” (INAP 2009) so that remediation programs such as at Britannia Mine should not be needed at modern mines. However, mining has been carried out for millennia and so there is no shortage of sites that will be in need of remediation. Sharing approaches, experiences and successful outcomes is therefore of broad environmental benefit. An environmental monitoring program was implemented in 2003 with the objectives of documenting changes in the environment resulting from the progressive reduction in metals loading to the Britannia Beach shoreline resulting from the improvements undertaken at the site, and supporting informed decision making regarding the scope, magnitude and timing of additional remedial activities as necessary. The purpose of this paper is to describe how information obtained through this environmental monitoring program could be used to define what the community structure of the Howe Sound intertidal zone should look like at closure.

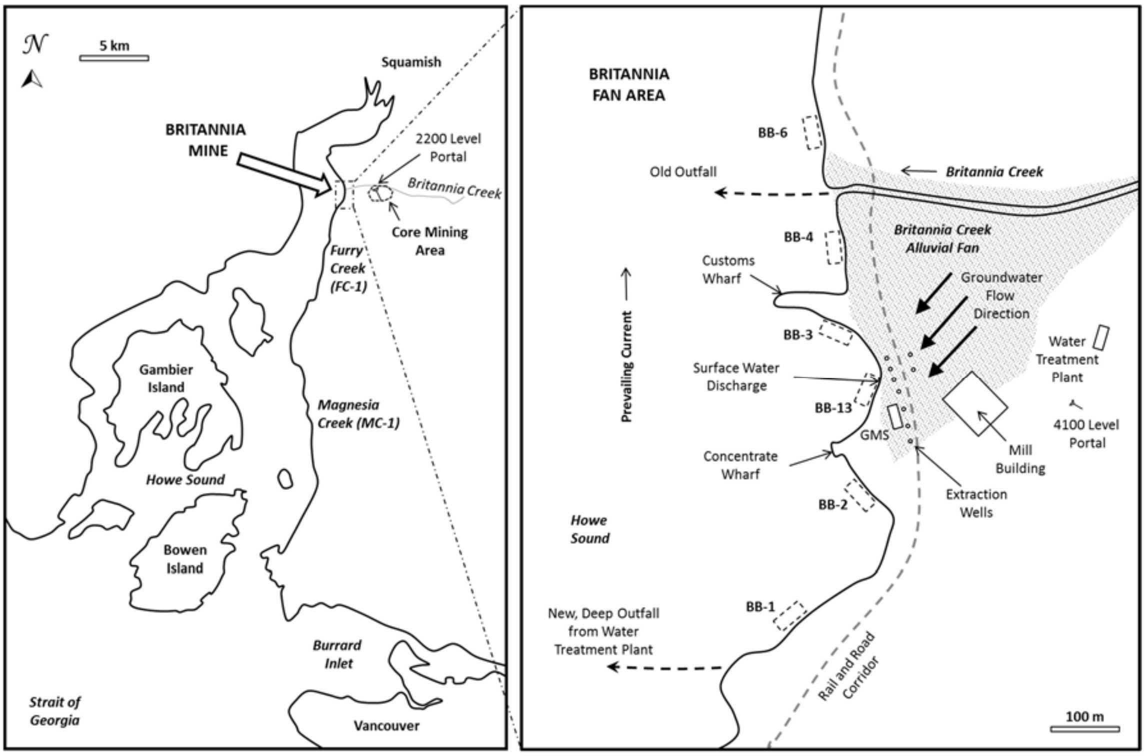

Figure 1 Location of the Britannia Mine along Howe Sound and location of shoreline reaches for marine water sampling and intertidal community assessment

2 Overview of the Ecological Monitoring Program

2.1 Physical Setting

Howe Sound is a deep (max. depth 200 m) fjord extending approximately 43 km between the delta of the Squamish River to the north and the Strait of Georgia to the south (Figure 1). The tidal amplitude is 3.2 m and currents in the top 10 m of the water column are predominantly seaward (south). The seaward flow of the Squamish River and southerly winds can result in a localized northward current in the surface layer of the water column adjacent to Britannia Beach (Thomson 1981). The top 5 to 10 m of water generally has a low-salinity relative to the open ocean and temperatures are cool (~10°C) due to the significant flow of the Squamish River and, to a lesser extent, smaller streams around Howe Sound.

The shoreline in the Britannia Beach area has been significantly modified from pre-industrial conditions. Filling of the shoreline commenced during operation of the mine through placement of waste rock and tailings in the Britannia alluvial fan area to reclaim land for construction of wharf structures, and further filling occurred in the mid-20th century as road and rail services linking Britannia Beach and communities further north with Vancouver were developed (O'Hara et al. 2010). The current shoreline consists of angular rip-rap material and historic pilings and crib walls from the historic wharves.

2.2 Methods

Throughout the monitoring program, several matrices have been sampled at varying intervals in response to the changing understanding of the Site and ongoing consultation (Wernick et al. 2010b). This paper focusses on intertidal community composition (as an indicator of ecological function) and the salinity regime (as an indicator of an abiotic variable that has an important role in governing intertidal community structure). Sampling locations were selected based on physical characteristics such as intertidal substrate (to reduce variability between sites) and to address multiple discharge points (e.g., groundwater and creek water) along Britannia Beach exposed and near-field locations. Exposed stations are located in an area that was, or still is, exposed to multiple sources of mine-contact water such as Britannia Creek, stormwater, contaminated groundwater, and tidal flushing of reactive tailings and waste rock along the shoreline. Near-field stations were exposed to Britannia Creek as well as relatively minor deposits of reactive material in the shoreline. The reference stations (Furry and Magnesia Creeks) are each proximal to a creek estuary for similarity of hydrological condition to the Britannia Beach area.

2.2.1 Salinity Regime

Salinity measurements were recorded with continuous data loggers. Seastar™ salinity data loggers (Star Oddi Marine Device Manufacturing, Iceland) were installed from 2005 to 2007 in the intertidal zone 2 cm above the substrate to provide continuous (every 15 minutes) measurement of in situ salinity. The data logger values were validated with spot salinity measurements collected with a field meter during other sampling activities To evaluate potential correlations with other measures of freshwater inputs, the aggregated salinity data were compared to precipitation data measured in Squamish (Environment Canada climate station 10476F0) and with Squamish River discharge (Canadian Hydrographic Service hydrometric station 08GA022).

2.2.2 Intertidal Community Structure

The community composition component involved an assessment of the diversity and coverage of algae and invertebrates, involving first three (2003-2005) and then five (2006-2013) transects oriented perpendicular to the shoreline, each with three 1 x 1 m quadrats (located at low, mid and high intertidal levels). Non-destructive survey methods were used to determine the percent cover of algal taxa and sessile invertebrates in each of the quadrats and presence of motile invertebrates was noted. Between 2004 and 2006 the intertidal community was characterized as noted above during each of three seasonal sampling events representative of differing freshwater inputs from the Squamish River (i.e., pre-freshet, post-freshet, and late summer). In 2008, the frequency was reduced to once per year in late summer or early fall as this is the time when the shoreline community typically reaches its peak growth. Mean % coverage was calculated from the coverage for individual quadrats placed at mid- and low-tide elevations for the stations and number of transects available for a given sampling event. Total richness was calculated as the total number of species observed at least once in a given area, not taking into consideration frequency of occurrence.

2.3 Results

2.3.1 Salinity Regime

Salinity changes at Britannia Beach reflected both rainfall and Squamish River discharge as illustrated for Britannia Beach location BB-4 (Figure 2). An increase in precipitation was typically followed by a relatively rapid decrease in daily average intertidal water salinity; this was particularly notable in November 2006 when decreased salinity followed an antecedent period of particularly heavy rainfall in the area. Overlying the response to precipitation was an overall salinity pattern related to river discharge, which was typically delayed following precipitation events, and during freshet (snowmelt in the broader watershed) river flow corresponded with a longer-term decrease in salinity readings through June/July.

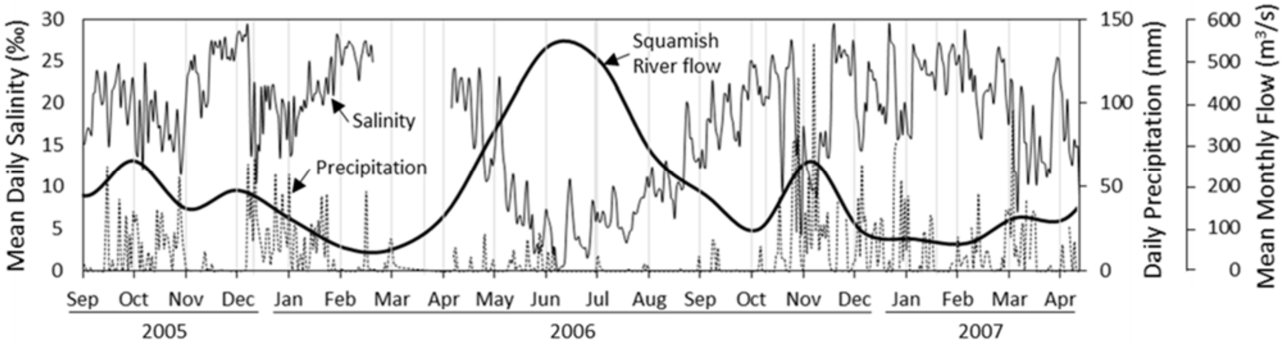

Figure 2 Relationship among precipitation in Squamish, Squamish River flow, and salinity at BB-4

2.3.2 Intertidal Community Structure

A typical intertidal community in Howe Sound, as observed near Magnesia and Furry Creeks in late summer, is dominated by the brown alga *F. gardneri*, the bivalve mollusc *Mytilus* sp., and the barnacle *Balanus glandula* (Figure 3C). Other components of the community include the green algae *Cladophora* sp. and *Ulva* sp., the red algae *Hildenbrandia* sp., *Petrocelis* sp., and *Polysiphonia* sp., and the brown alga *Pylaiella* sp. Several of the latter algae are ephemeral and typically visible to the naked eye only in spring and early summer. This algal structure and the physical substrate to which it is attached provides habitat for motile crustaceans (shore crabs, amphipods, isopods) and molluscs (snails, limpets). In total, 15 to 20 species are likely to be found in these intertidal areas. At both the near-field (Figure 3B) and exposed (Figure 3A) stations of Britannia Beach, *F. gardneri* and *B. glandula* also comprise a relatively large proportion of the intertidal community as of 2013, and depending on degree of exposure to mine-related waters, *Cladophora* sp., a copper-tolerant alga, may also be dominant. Total richness has been increasing in these areas over time and in the near-field locations was similar to that at reference stations. The lower richness is due primarily to the absence in some locations of molluscs, motile crustaceans, and some brown and red algae.

2.4 Discussion

Successional processes and distribution (e.g., zonation) of organisms along a rocky intertidal shoreline follow a general pattern influenced by abiotic (thermal and salinity extremes, waves, abrasion such as by drifting logs) and biotic (grazing, competition, source of recruits) factors (Dayton 1971). Along the west coast of Canada, typical succession starts with ephemeral algae (e.g., *Enteromorpha* spp., *Porphyra* spp.), followed by barnacles which then minimizes grazing of the algal turf by snails and limpets (Kim 1997). This allows for the establishment of perennial algae such as *F. gardneri*, which then provide more physical habitat structure and organic carbon to species such as crustaceans that may be food items for fish migrating along the shoreline.

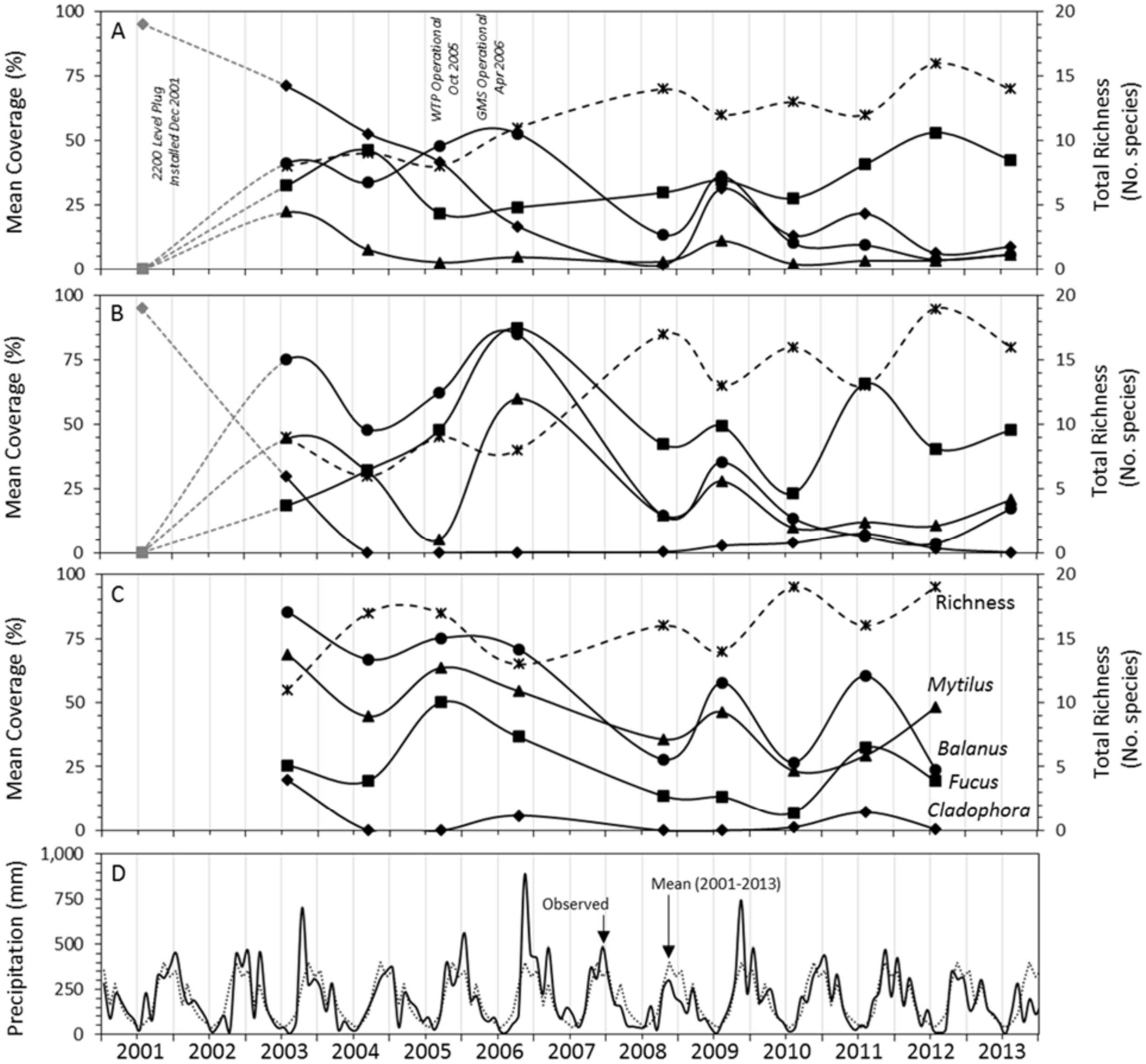

Figure 3 Temporal variability in habitat metrics during late summer at (A) exposed (BB-2, BB-3, BB-4, BB-13) (B) near-field (BB-1, BB-6) and (C) reference (MC-1, FC-1) stations, and in (D) precipitation

Prior to 2001, Marsden & DeWreede (2000) observed only a relatively thin layer of a green alga within 100 m of the creek mouth and thicker filamentous green algae and scattered barnacles (*B. glandula*) from that point to 1,000 m north and 600 m south of the creek (data points on Figure 3 for 2001 are inferred from this narrative). Within two years of installation of the 2200 Level plug which diverted mine water from Britannia Creek (Wernick et al. 2010a), the successional pattern described above was observed at near-field stations (Figure 3B) and in 2006, coverage by *B. glandula*, *F. gardneri*, and *Mytilus* sp. was similar to that observed in the reference area. In comparison, the copper-tolerant *Cladophora* sp. was a dominant species at the exposed stations until 2006 (Figure 3A) and coverage by *B. glandula* increased more slowly than at the near-field stations. This overall slower re-colonization of the intertidal zone in the exposure area is related to on-going sources of mine water in the nearshore area.

In 2008, coverage of *F. gardneri*, *Mytilus* sp., and *B. glandula* was lower in all three study areas and remained at relatively lower levels at the near-field and exposed areas. This decrease in coverage may have resulted from higher than typical rainfall (Figure 3D). As shown in Figure 2, during November 2005, a series of days with higher than typical rainfall resulted in a notable, rapid decrease in salinity. The higher than usual total precipitation in June 2007 and August 2008 may also have resulted in lower than expected salinity at those times. An additional winter with elevated precipitation occurred in 2009, followed by lower coverage in 2010. Species living in the intertidal zone are adapted to changes in salinity such as may occur during rainfall and the development of a low-salinity surface layer during freshet; however, rapid or prolonged variations from the average condition can result in osmotic stress and mortality (e.g., Kamer et al. 2000; Qiu et al. 1999).

3 Developing Resource Conservation Objectives for Remediation

The objective of the initial remediation activities at Britannia Mine was to address severe, acutely lethal conditions in Howe Sound that posed a mortality hazard to out-migrating juvenile salmon. This objective was achieved through the diversion of mine water away from Britannia Creek and to a submerged outfall. Additional site characterization is being undertaken to evaluate residual contaminant sources (e.g., the relative contribution of tidal flushing through reactive shoreline tailings versus groundwater transport via preferential pathways such as historic discharge pipes). As this work continues, realistic remediation goals need to be defined, taking into account the technical feasibility of controlling residual contaminant sources, as well as public expectations. The Britannia Mine operation dates back to the turn of the 20th century and the return of the shoreline to pre-development conditions is likely not possible as the long-term operations of the mine resulted in significant filling, and replacement of the natural shoreline with engineered surfaces (e.g., rip rap), and the construction of a transportation (rail and road) corridor adjacent to the shoreline will limit the use of intrusive remediation techniques. Moreover, when consulted on the remediation program, the local community reflected a desire to see environmental improvements but those views were balanced by an understanding that the shoreline has been impacted from mining activities and that project funds should be spent where remediation will result in the most benefits (Nikl et al. 2010).

For the Britannia Mine Remediation Project, the term “resource conservation objectives” (RCOs) is being used to describe the protection goals that will ultimately be applied to the shoreline habitat. The ecological monitoring program provides the basis for understanding the species that are expected to be present along the shoreline and the natural variability in the coverage of dominant species as they respond to varying biotic and abiotic conditions (e.g., Figure 3). Consideration of the potential variability in the reference areas and over time is important to inform site-appropriate risk management measures that reflect regional ecological conditions. This is likely to become increasingly important with climate change and associated sea level rise and ocean acidification which may cause more frequent and/or greater magnitude variability even in unimpacted areas. As demonstrated by the relationship between salinity and intertidal community composition at Britannia Beach, variations outside the “average” condition can disrupt natural successional processes and dramatically decrease coverage by the dominant species, resulting structural habitat changes. Climate change and associated oceanic changes also have the potential to change the geographic distribution of some species and therefore the composition of an intertidal community.

The selection of RCOs also needs to take into consideration the broader mandate of environmental regulatory agencies to maintain and/or restore a productive ecosystem. Feedback from consultation agrees with this perspective and has suggested that RCOs should be developed generally for ecological receptors typical of the biogeoclimatic zone and present in immediate surroundings, migratory ecological species, and species at risk. More specifically the regulatory expectation was that: water quality is protective of juvenile salmon migrating past the site; the food supply has returned to functional levels; and native species recolonize the shoreline, reflecting natural population and community structures appropriate to the locale.

Based on the considerations outlined above, Table 1 summarizes important habitat features and ecological functions, and their associated conservation objectives. As previously noted, the first objective of fish being able to migrate to sea without adverse (acute) effect has already been achieved. For invertebrates and plants, the objectives are that locally relevant species are able to survive, grow, and reproduce. Potential measures that could be used to evaluate whether those objectives are being met include: coverage by sessile species, density or presence/absence of individuals for motile species, presence of both juvenile and adult life stages, and quality/quantity of food organisms.

Table 1 **Example considerations for developing resource conservation objectives**

Habitat Feature	Ecological Function	Conservation Objective
Fish	Migration	Fish migrate to sea without adverse effect
	Feeding	Food organisms are present
		Food organisms are not a risk to consumers
Invertebrates	Rearing/ feeding	Invertebrates are able to survive and grow
	Reproduction	Invertebrates are able to reproduce
Plants	Habitat structure	The plant community includes *Fucus*
	Source of food energy	Plants are growing and amphipods are present

Options for quantifying the acceptable level of difference from reference include:

- A percent reduction of the mean reference value. For example, in ecological risk assessment a 20% reduction of a given measure at an exposed site relative to reference is often not considered an "ecologically significant" impact.
- A "control chart" approach, or within specified statistical variability around the mean (e.g., 1 or 2 standard deviations [SD]). This forms the basis of widely-used environmental monitoring techniques such as the Index of Biotic Integrity (Karr et al. 1981) and has been used to monitor contaminant concentrations in fish and other organisms (Chapman and deBruyn 2007) as well as recovery of freshwater emergent vegetation following an oil spill (Wernick et al. 2009).

As an example of the difference between these methods for a sessile species, Figure 4 illustrates *Mytilus* sp. coverage at Britannia Beach (exposed and near-field stations) versus the reference area. *Mytilus* sp. is a relevant indicator of maturity of an intertidal community, and is known to be sensitive to copper and thus can be a visual cue regarding potential presence of residual contamination. The figure also shows the overall mean coverage from 2003-2012 for the reference area and potential targets for the near-field and exposed areas based on the two methods described above. From year to year, mean coverage in the reference area can naturally fall below the 'mean – 20% line', suggesting that this target may be unrealistic for the Britannia Beach remediation area. In comparison, the control chart approach incorporates variability around the mean condition (i.e., 'mean – 1SD') and may thus be a more reasonable target.

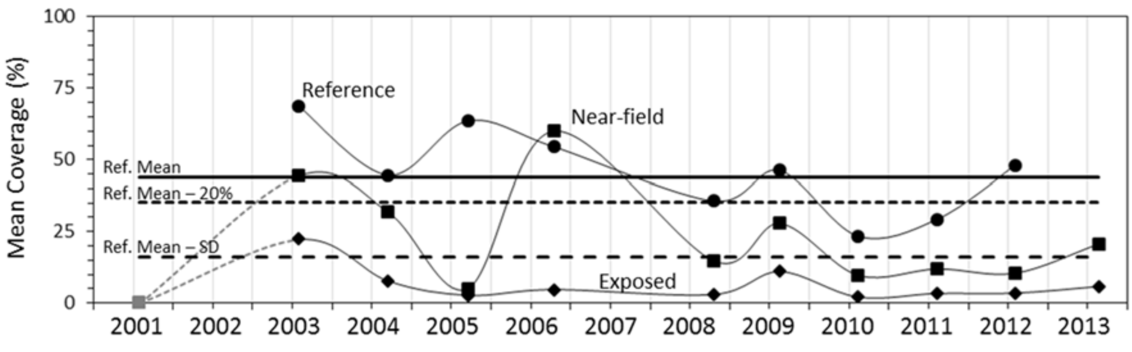

Figure 4 **Temporal variability in *Mytilus* sp. coverage for reference, near-field and exposed stations relative to potential remediation targets**

In summary, a full resource conservation objective for *Mytilus* sp. could be articulated as follows: "mussels are able to survive and grow" and "successful remediation is attained when % coverage is within or greater than the reference mean – 1SD". This approach can also be followed for *F. gardneri* and *B. glandula*, other components of the intertidal community for which quantitative RCOs should be stated.

4 Summary

The operation of the Britannia Mine resulted in significant impacts to the shoreline of Howe Sound. Following the implementation of an extensive remediation program, and in particular the collection and treatment of mine-contact water and groundwater, the intertidal zone along Britannia Beach is recovering. Given current land uses, the shoreline configuration is set, remediation objectives do not include return to pre-mining conditions. However, restoration of the ecological services, as reflected by community structure is a viable objective and progress towards that objective is reflected in the monitoring data to date. The monitoring program and its use of reference condition provides an empirical basis for determining appropriate remediation targets (resource conservation objectives) that meet regulatory and public expectations.

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Conceptual Model for Ecological Land Reconstruction — Case Study of Rovinari Mining Area

M Lazar *University of Petrosani, Romania*

F Faur *University of Petrosani, Romania*

A Florea *University of Petrosani, Romania*

IM Apostu *University of Petrosani, Romania*

Abstract

The main intervention to eliminate the environmental impact of mining activities is represented by the ecological reconstruction of the affected areas at the end of exploitation, and consists in establishing all the necessary measures to prepare the area for an environmentally compatible reuse. The problem of ecological rehabilitation of the lands, degraded by mining, is settled by mining and environmental laws, witch impose their reintegration into the surrounding ecosystems or in the economic circuit after the mining activities are stopped. The decision process regarding the development of mining areas at the end of operations represents a challenge for all political actors involved in planning the use of land, landscape planning and environmental planning, representing at the same time a great responsibility. In the present paper we have considered the largest lignite open pits in Romania, which are located in Oltenia, south of the middle Carpathians Mountains. In this region coal mining activities occupied and degraded large areas of land, amounting almost 19,000 ha. The major negative impact from brown coal mining in Oltenia is bound to the pressures exerted on the land, vegetation, fauna and landscape. The paper also exposes the arguments backing up the necessity of a global approach of the concept of ecological rehabilitation and suggests practical solutions for the Romanian coal mining areas.

Keywords: *brown coal, ecological reconstruction, mining, open pit, reuse of land*

1 Introduction

In Romania, brown coal produces 20-35% (depending on the season) of the electrical power and about 20% of the thermal energy of the country. In the region of Oltenia, brown coal is extracted in 12 open pits, grouped in five mining basins (figure 1).

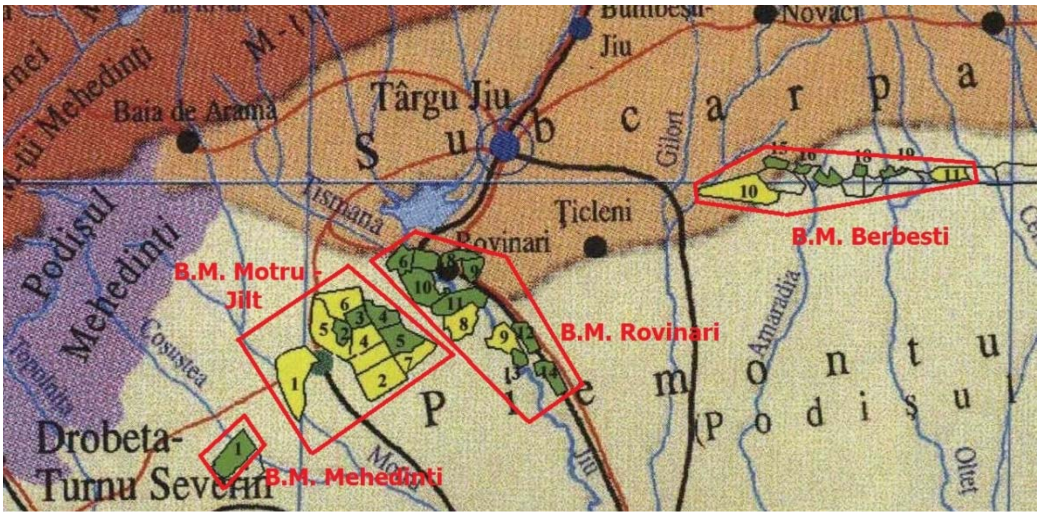

Figure 1 Oltenia brown coal mining region

Extraction of brown coal in Oltenia began in the 60’s of the past century, and closed to 900 millions tones of brown coal and over 5,000 millions m^3 of sterile have been extracted. On medium term, the contribution of brown coal in the energetic balance of Romania will be constant (according to the present strategy) (*** 2017), which means that the production from the Oltenia open pits will have about the same level as during 2015–2017. The 12 open pits use exclusively the continuous technological fluxes, consisting of bucketwheel excavators combined with high capacity conveyor belts and dumping machines (Figure 2).

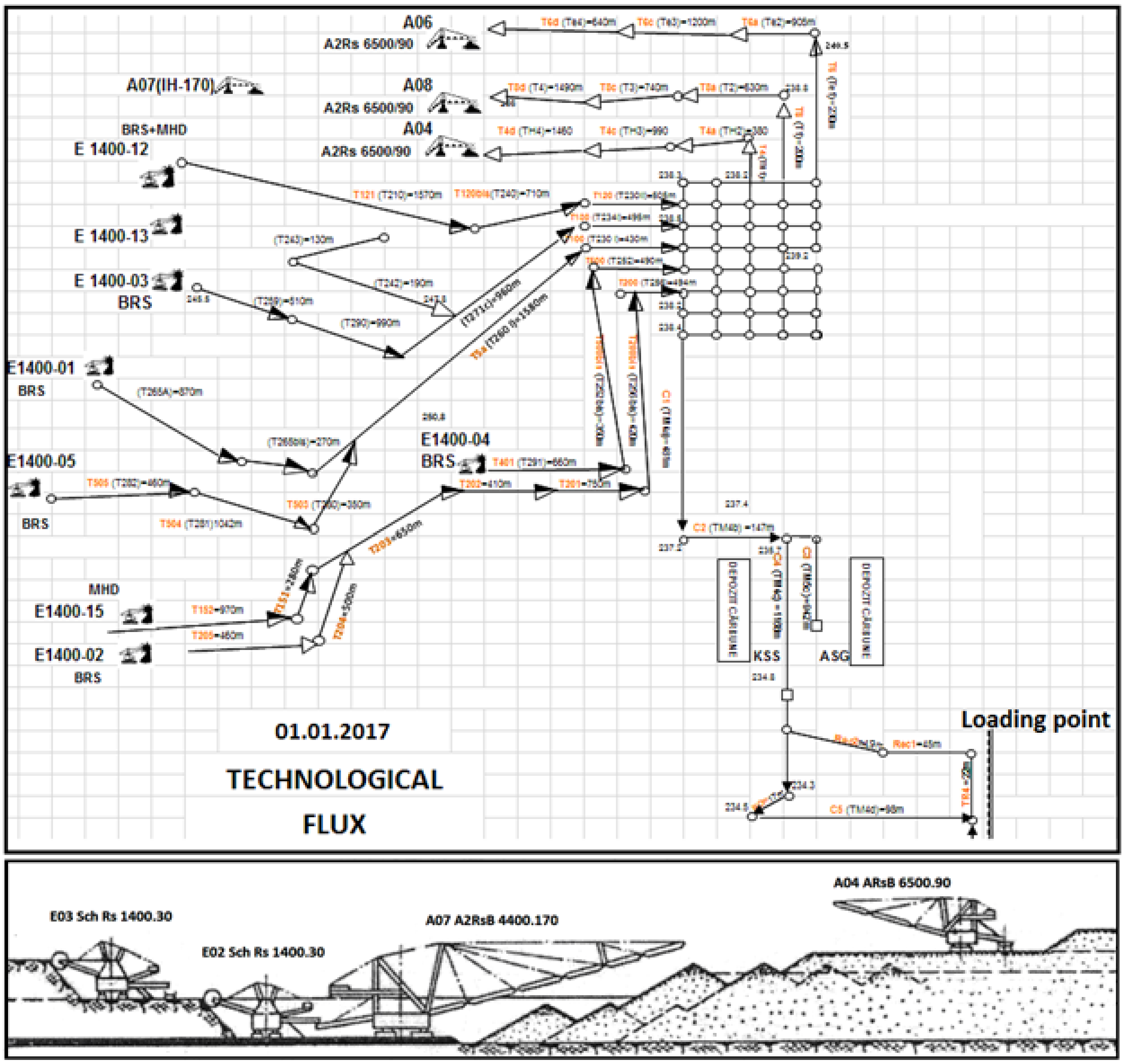

Figure 2 Example of a technological flux

The extraction of brown coal in open pits includes the following operations: selective excavation, transport, deposition of waste rocks in dumps and deposition of brown coal in storage facilities. Excavation is performed by bucketwheel excavators, types: SRs1300, SRs1400, SRs2000, in steps with heights of 25-30 m.

2 The impact generated by the extraction of brown coal on land

Estimations are that the areas affected by the mining industry will be about 1% of the national agricultural surface. There is a special situation in the mining basins of Rovinari, Motru and Jilţ from Gorj country, where the affected surface exceeds 16,500 ha, 18% of the agricultural surface of the county.

Although, there are no real statistics about the surfaces affected by mining in the world and in Romania, we can say that the surfaces driven out of the economic use are increasingly greater, due to the extension of the open pit exploitation, and yet small if compared with the surfaces needed for industrial installations or transportation systems. As extraction begins, hills and plains are disappearing and the newly constructed waste dumps represent, for the beginning, a total change of the landscape. Another bad influence on the land is that great surfaces are occupied by waste dumps, transport and sorting installations, coal deposits etc. for a short or a long period of time. The main bad influences of the waste dumps on the environment are:

- bad visual impact;
- destroying and occupying large surfaces of natural or agricultural land;
- pollution of the surface and underground waters with chemicals or small particles transported from the waste dumps by rain or infiltrations;
- air pollution with dust and gases resulting from the oxidation (self infliction) of coal fragments present in the waste dumps;
- risk for human life and for the environment, or the destruction of infrastructure due to landslides (lack of stability) especially in the case of exterior waste dumps, etc.

The waste dumps also changed the landscape, as artificial hills with heights ranging from 15–20 m up to 90–100 m appeared in flat areas. As a result of open pit mining, large surfaces of land, partly or completely affected, were driven out of the agricultural, forestry or natural circuit.

According to the Romanian laws, the mining operators must rehabilitate ecologically the areas affected by their activity and thus, in time, a part of them were recultivated. In the Oltenia area, form the almost 17,000 ha of land degraded by open pit mining, more then 3,000 ha have already been reintroduced in the agricultural or forestry circuit, and the rest are to be rehabilitated and reintroduced in the economy as soon as possible (progressively as the extraction process advances and the designed geometry of the waste dumps is achieved and immediately after the end of operations). Out of the affected areas, 80% were agricultural lands (from which, 25% were pastures and feedlots, which gave low and instable productions, 5% were orchards and vineyards with great variety but low productivity, the rest being cultivated with vegetables and cereals) and 20% were covered with forests.

At present, in Oltenia mining basin, for each million tones of brown coal extracted an area of 31 ha of land is degraded (destroyed). There are surfaces affected by the open pit mining of brown coal in other areas of Oltenia (in Berbești mining basin situated in Vâlcea county and Mehedinți mining basin situated in the county bearing the same name), but they represent maximum 17% of the affected areas located in Gorj county (in Rovinari, Motru and Jilt mining basins).

3 Experience regarding land recultivation

Recultivation has been done on stages, as surfaces were freed by technological tasks, without following any preexisting plans or projects for rehabilitation. Due to the climate, average temperature of 10.3°C, average precipitations of 753 mm per year, winds, influenced by the nearby mountains and hills and taking into account the deforestations, changes of the river flows, formation of artificial lakes and temporary or permanent puddles which produced changes in the micro-climate, more plantations have been experienced, as follows:

- Orchards (66 ha) using: apple tree, plum tree, cherry tree, sour cherry tree, nut tree, mirabelle tree, hazelnut tree, etc. The apple tree and the plum tree gave good results;
- Vineyards (40 ha) using: Royal Fetească, Muscat Otonel, Italian Riesling, Merlot and Cabernet Sauvignon. Best results were obtained for Royal Fetească;
- Forests (over 1,000 ha) using: acacia, oak, poplar, pine, wildcherry tree, nut tree and chestnut tree. Best results were obtained by acacia tree, poplar, oak and esculent chestnut tree with double use, for fruits and for wood;
- Cereals and technical plants (over 1,000 ha): rye, wheat, sun flower, corn, potatoes and peas;

- Feedlots and pastures (over 700 ha). Best results were obtained by alfalfa and clover.

In the last years a few experimental lots (of no more then 10 ha) were cultivated with species of energetic willow and paulownia trees, the results being under analyses.

4 Global approach of ecological reconstruction

For all the cases of re-modelling of the affected areas we must start from the economic activity that generated the degradation and take into account the future use. There is a fundamental relation between the shape and the morphology of the land and the type of re-use that should be regarded as crucial for choosing the new utilization. If a specific use is not foreseen, than re-modelling must be done in order to offer multiple options (Lazar 2017). Best is to take a specific utilization into account from the very beginning and to adopt the best techniques according with the influence factors (Figure 3).

Figure 3 Factors influencing the recovering techniques of the degraded land

The decisions about developing a mining area at the end of the productive activities is a challenge for all those with responsibilities regarding land use planning, landscape planning or ecological planning. Such a decision must take into account a lot of elements, regarding the ecological characteristics of the area on one side and on the other side the social and cultural structure and needs of the population. Some of the reasons underlying the necessity for land re-modelling and ecological reconstruction in the areas affected by human activities (in this case mining) are:

- To eliminate the risk of landslides occurring in artificial land forms resulted from the industry (waste dumps, ash dumps, industrial or domestic dumps);
- To eliminate the negative visual impact of the areas having a moonscape aspect (specific to open pits);
- The need for reintegration of the affected surfaces in the economical and/or ecological circuit of the surrounding areas, leading to their total regeneration;
- Improving the environmental quality;
- Reducing the slopes (especially the final slopes of the pit) and thus reducing the erosion and stimulating the apparition of the vegetation.

The main objectives of such works are:

- To identify the possibilities to reuse the materials and installations;
- Leveling the land with or without materials from other locations;
- Filling the remaining holes with waste rocks (from other open pits) or water;
- Decontamination of the lands (if necessary);
- Reuse of the remaining holes for deposition of domestic or industrial waste materials from other regions.

The global approach of the ecological rehabilitation for an extended area is necessary because, according to the principle of 'globality and intercausality', the territory is a big and complex living organism, with multiple cultural and natural components that interacted in time and has an autonomously, self-sustainable life (McHarg 1969). Any landscape is unique and irreproducible, the result of superposing in time of components of different origin (natural and cultural) producing always original situations. For such regions, planning and use of the land must take into account a unique design, capable to take into account the inside of the landscape with all its components. One of the causes of wrong planning of the landscape is taking the landscape on pieces or leaving out parts of it (Lazar et al. 2017).

5 Solutions for ecological reconstruction of Rovinari mining basin

For this example, Rovinari mining basin has been chosen because it is the most affected by the open pit mining, as in this area are located 5 of the 12 active open pits from Oltenia (Figure 4).

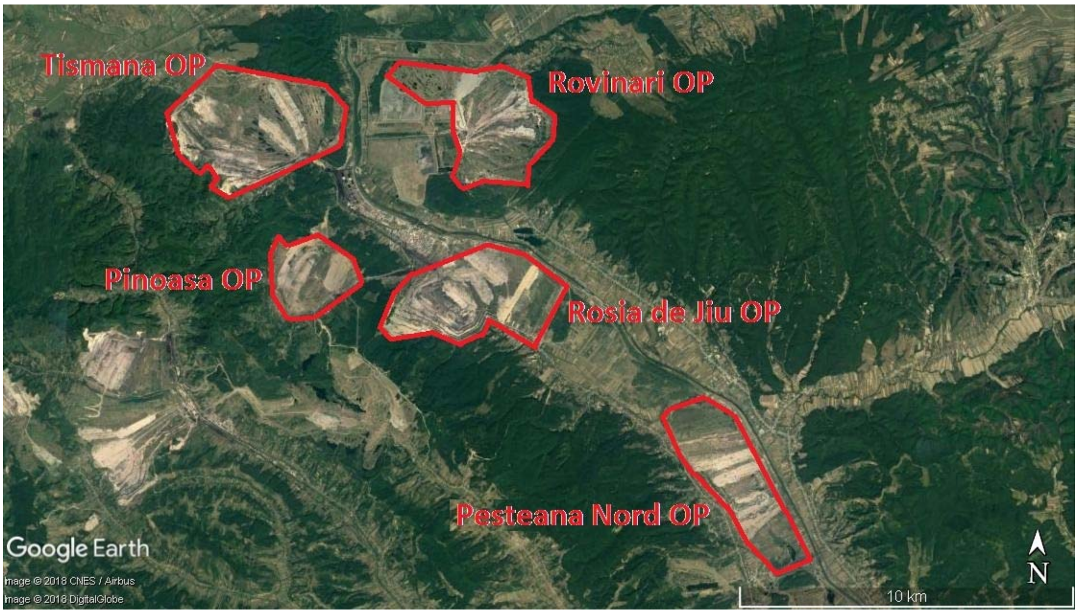

Figure 4 Satelite photo of Rovinari mining basin in 2017

Remaining holes of former open pit mines can be filled with water, thus taking over various functions, ranging from industrial to recreational ones, or can be used for storing industrial waste or household waste. Such directions can be identified for the redevelopment of empty mining spaces (Figure 5).

Figure 5 Possible reuse types for the remaining holes of open pits

The global approach of ecological rehabilitation of areas affected by mining industry involves multiple reuse of the land. This means overlapping different uses and functions of land, as long as they are complementary (Lazar et. al 2006). The choice of the combinations of different possible reuse types for the open pits from Rovinari mining basin can be made quickly using the matrix from Table 1 (Drebenstedt 1998, Lazar 2017).

Table 1 Possible combination between different types of reuse

Land / Water	Natural reservations	Agricultural recultivation	Forestry recultivation	Grassing	Leisure and sports	Buildings
Naturalistic lakes	3	2	3	2	1	0
Sport fishing	2	3	3	3	1	1
Water management and irrigations	2	2	3	2	1	1
Water sports and rec (Lazar 2017) reation	1	2	2	2	3	1
Fish farming	0	2	2	1	0	0

3 very good; 2 good; 1 limited; 0 excluded

To create conditions for ecological rehabilitation, both the dumps and remaining holes resulting from mining must be prepared through stabilization works, land levelling and improvement (figure 6) (Lazar 2017).

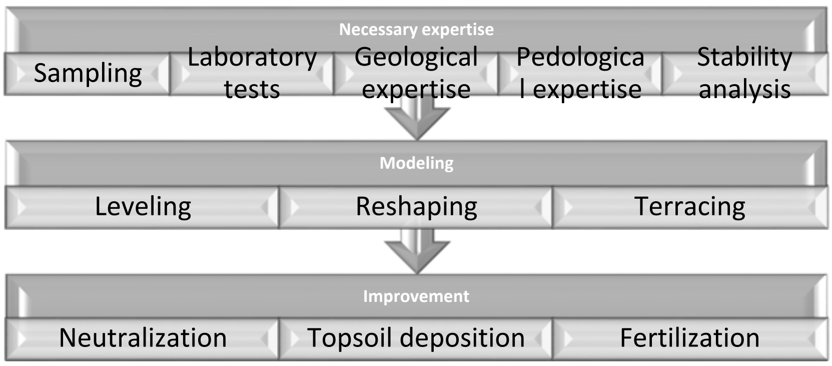

Figure 6 Steps necessary to be taken in ecological rehabilitation works

In order to make a good decision on how to rehabilitate the land affected by open pit mining situated in Rovinari mining basin we’ve taken into account two of the most important aspects, namely the natural characteristic conditions (the surrounding landscape, the use of land in adjacent areas, the climate etc.) and the needs expressed by the population resident in the nearby towns and villages.

Depending on the natural conditions, 5 possible types of reuse of the land affected by brown coal exploitation in Rovinari mining basin were identified, which formed the basis for the realization of a questionnaire.

The assessment of the population's requirements for the reuse of the remaining holes and the rehabilitation of waste dumps from Rovinari mining basin was done taking into account the partial results obtained by conducting an online survey at a regional level, involving 109 persons. The questionnaire contains 5 choices of the type of reuse of the lands affected by mining in the Rovinari basin, taking into account the needs of the individuals and the local communities, the importance of the socio-economic development of the region and the restoration of the environment, all of which being seen from point view of the respondent (Apostu 2018).

After centralization, a hierarchy of population requirements was made regarding the type of reuse of the land affected by the 5 open pits from Rovinari mining basin, the results being presented in Table 2.

Table 2 Hierarchy of population requirements

Rank	Reuse type
Tismana open pit	
1	Open pit lake (sport fishing, irrigations etc.)
2	Forestry
Rovinari open pit	
1	Waste deposit (household, municipal, industrial etc.)
2	Forestry
Pinoasa open pit	
1	Forestry
2	Waste deposit (household, municipal, industrial etc.)
Roșia de Jiu open pit	
1	Mining museum and cultural attractions
2	Forestry
North Peșteana open pit	
1	Open pit lake (sport fishing, irrigations etc.)
2	Forestry
3	Agricultural

Taking into account the options of the resident population in the areas where the open pits and waste dumps are located in the Rovinari mining basin, we have constructed a centralized table in which the final ecological rehabilitation variants of the 5 open pits and waste dumps are identified (Table 3). In the last column, for the two careers involving the creation of lakes with different functions and forestation, the compatibility of the types of reuse is evaluated according to the matrix in Table 1.

Table 3 Final choice for the ecological reuse type of the degraded lands from Rovinari mining basin

Open pit	Remaining hole	Sterile dump and final slopes of the open pit	Compatibility
Tismana	Filling the remaining hole with water (for sport fishing and irrigation)	Forestry	3
Rovinari	Ecological waste deposit (household, municipal and/or industrial waste)	Forestry	-
Pinoasa	Mining waste rocks deposit (from the overburden and sterile intercalations of Tismana open pit)	Forestry	-
Roșia de Jiu	Mining museum and cultural attractions	Forestry	-
North Peșteana	Filling the remaining hole with water (for sport fishing and irrigation)	Agricultural/Forestry	3

In general, the options expressed by participants in the online survey are well suited to what the concept of 'attraction or repulsion' of the territory represents to a certain type of reuse of a degraded land (McHarg 1969). As can be seen from Tables 2 and 3, the first two options expressed by the population, with the exception of the North Peșteana open pit, were considered for choosing the final ecological reconstruction (or more correctly said land reuse) type.

In the case of North Peșteana, although the second option of the population indicated forest recovery, the authors considered, after consulting the local development plans, that the most suitable option for the ecological reconstruction of the waste dump is the agricultural one (the third option according to survey). In fact, the open pit is located in a meadow area (favorable to farming) and is surrounded by agricultural land. Forestry reconstruction will only target the final slopes of the open pit, above the lake level.

On the whole, we can see that the options expressed by the resident population create the premises for the reconstruction of the land degraded by mining by taking multiple functions. In general, for the waste dumps and the final slopes of the open pits the resident population has opted for reforestation works, while for the remaining holes the options are slightly more diversified. Thus, for Tismana and North Peșteana open pits, they have opted to create lakes, the main uses of which are to provide a water supply for irrigation of crops from neighboring lands in periods of precipitation deficiency and to allow sport fishing.

For Pinoasa and Rovinari open pits, the remaining holes will serve as waste disposal facilities. In the remaining hole of Rovinari open pit, which is favorably located near the towns and villages (outside the residential or sanitary protection areas but near the existing roads), it is proposed to set up an ecological landfill for domestic and municipal waste, while for the remaining hole of Pinoasa open pit, it is proposed to become a storage space for a part of the mining waste rocks from Tismana open pit (considering, of course, the exploitation program of the two open pits and the relatively small distance between them).

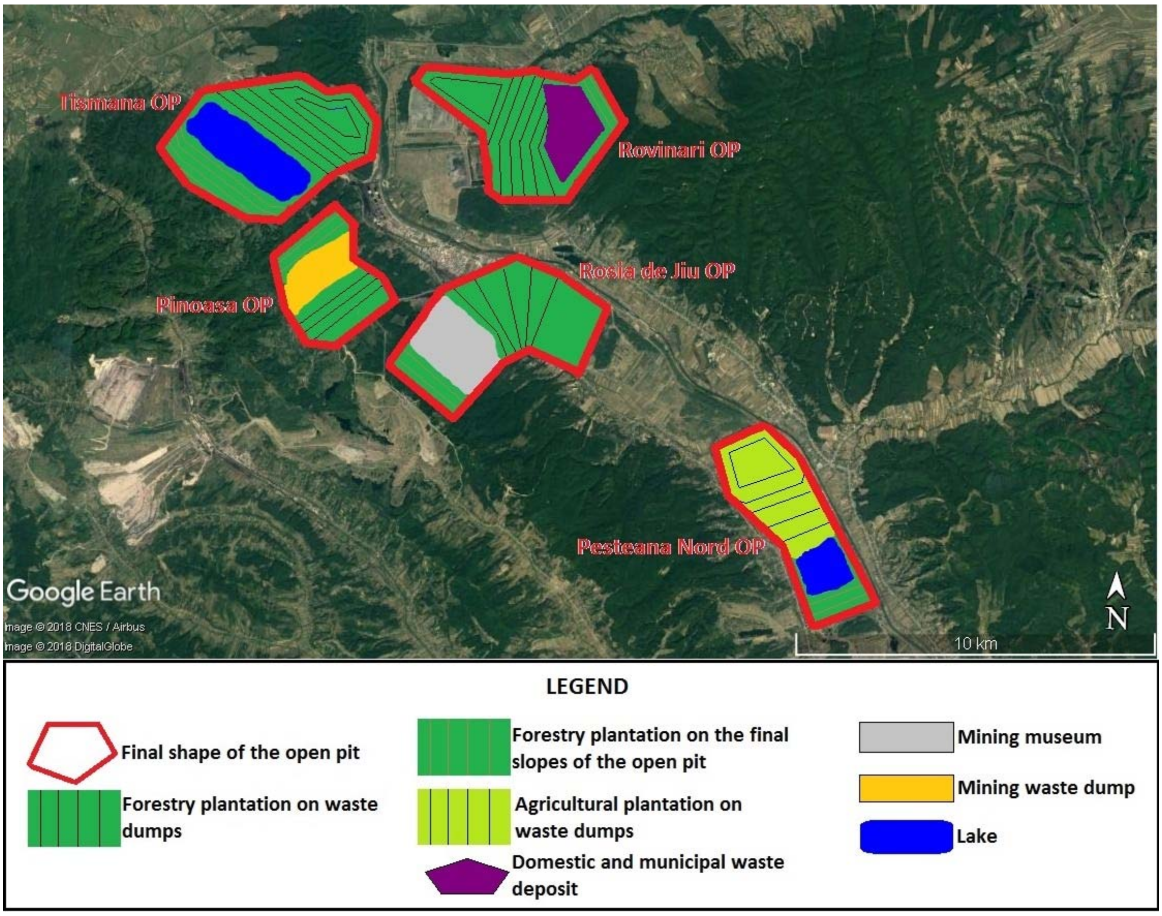

Figure 7 Final configuration of Rovinari mining basin

In the remaining hole of Roşia de Jiu open pit, the construction of an industrial museum is proposed, with the mention that other events such as open-air concerts can be organized in this space (such type of reuse was accomplished for the remaining hole of North Golpa open pit from Germany, currently known as the Ferropolis Museum, which functions as an industrial monument, theme park and exhibition area). On the basis of the above, Figure 7 presents a sketch of the way in which the land, affected by brown coal exploitation, from Rovinari mining basin, after the productive activities cease, will be ecologically reconstructed and reused. The following ideas were taken into account for determining the final destination post-utilization of the surfaces:

- The necessity for integration of the new surfaces in the surrounding landscape
- Physical needs of the population concerning the land property
- The morphology of the land and the exposure of the final slopes of the open pits and waste dumps
- Pedological characteristics of the soils
- Available water resources and the necessity for the restoration of the initial level of the underground water
- Costs of the necessary works and Cultural needs of the local population

6 Conclusions

The concept of ecological reconstruction of the mining affected areas in the Rovinari basin meets the following objectives of the national strategy for reconstruction of the mining areas, using the idea of sustainability:

- Economical reconstruction and reuse of surfaces affected by open pit mining as big as possible;
- Morphological and landscape reconstruction of the surfaces;
- Creating lakes in the remaining holes;
- Developing activities for the community in order to reuse the remaining facilities from the closed mining units;
- Involving the community members for rehabilitation and reconstruction of the environment.

As a result, the proposals presented in this paper leads to a decrease of the danger of pollution of the environment in the analyzed area as well as to a rehabilitation of the environmental factors to a state as close as possible to the situation previous to mining, all in the context of sustainable development of the society.

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9. Handling of contamination and soil formation

Using Bioaccessibility Testing in Health Risk Assessment as a Decision Support Tool for Appropriate Redevelopment of Former Mining Sites: a French Case Study

I Girardeau *BRGM (French Geological Survey), France*

A Coftier *BRGM (French Geological Survey), France*

T Conte *BRGM (French Geological Survey), France*

Abstract

In many countries, remediation is required when a site poses a risk to human health and/or the environment. In this context, risk assessment methodologies usually rely on the total contaminant concentrations measured on site without considering chemicals bioavailability. Such approach is actually irrelevant when considering former or abandoned mining sites characterised with high concentrations of heavy metals in soils as it often results in an overestimation of risks, leading to heavy, lengthy and costly remediation works. The case study was the site of a cassiterite mining exploitation that ended in 1957. At the present time, 3.7 million cubic meter of tailings and waste rocks, with rather high arsenic and other heavy metals concentrations, remain on the site. Beside these residues, and issues associated with the acid mining drainage, there is still great concern with the frequentation by the public of this site. Effectively, because of its astonishing shape, it is highly visited by a wide range of population (local and national). It offers a unique opportunity for sport and leisure activities (e.g.: mountain bike, walking, trail, horse riding) in a relatively flat region. Therefore, this site represents an opportunity of tourism and economic development for the municipality. The aim of this study was to assess the compatibility of these uses with the soils quality, given that they are especially highly concentrated in arsenic. Ingestion is one of the major routes of soil exposure, by children especially. However, data from literature indicate that the bioaccessible fraction of arsenic for human soil ingestion can vary from 2 to 90%. Therefore, it is relevant to carry out site specific tests.Bioaccessibility tests were carried out on 10 soil samples collected on site, following the Unified BARGE (BioAccessibility Research Groupe of Europe) Method (UBM). This in vitro method simulates the human digestive procedure using synthetic digestive fluids. Results indicate that the bioaccessibility of arsenic on this site ranges between 5 and 50 %, averaging out at 17%. The human health risk assessment at this specific site integrated these bioacessibility results so that health risk quantifications are more relevant, accurate and closer to reality. In this case study, we show that using standard highly conservative approach and more accurate approaches lead to rather different results in terms of possible uses. Using this approach, appropriate solution for redeveloping the site balancing health and environment protection requirements with tourism and economic issues will be available.

Keywords: *arsenic, bioaccessibility, human health risk assessment, cassiterite, redevelopment*

1 Introduction

In many countries, remediation is required when a site poses a risk to human health and/or the environment. If most of threshold or regulatory values are available on (drinking) water or air quality, no threshold value is available on soil quality in France. In order to assess if soil quality is compatible with the uses, human health risk assessment (HHRA) is the only available tool. On former or abandoned mining sites, ingestion is one of the major routes of soil exposure to heavy metals contamination, by children especially. Current approaches are usually largely conservative and exposure is currently assessed using the total soil concentration of individual contaminants.

Such approaches lead to important safety margins, and thus could be considered as less appropriate when considering former or abandoned mining sites characterised with moderate to high concentrations of heavy metals in soils resulting of both natural and anthropogenic activities. Moreover, several in vivo studies, using diverse animals, such as monkeys, juvenile swine, rabbits, and rodents, have demonstrated that only a fraction of a contaminant, the bioavailable fraction, is absorbed following oral administration (Denys et al., 2012). The BioAccessibility Research Groupe of Europe (BARGE) has developed an in vitro test, the Unified BARGE Method (UBM), to measure the bioaccessibility of soil contaminants. This method was subjected to an invivo validation and provides a robust tool for use in risk assessment of As, Cd and Pb (Denys et al., 2012).

In this paper, we present a case study of an old mining site where remain tailings and waste rocks with moderate to high arsenic concentrations. This site is widely frequented by the population and the aim of the study was to assess the compatibility of the uses with the soil quality. The bioaccessibility testing were used in health risk assessment. The aim is to obtain a quantification more relevant, accurate and closer to reality in order to define appropriate solution for redeveloping the site balancing health and environment protection requirements with tourism and economic issues.

2 Methodology

2.1 Field site description

The studied site is an old mining exploitation of cassiterite (SnO_2) located to the west of France. The main exploitation was conducted between 1952 and 1957 by open pit mining. The cassiterite deposit is related to quartz veins in schists. It contains also sulphide minerals as arsenopyrite. At the present time, 3.7 million cubic meter of tailings and waste rocks remain on the site with high arsenic concentrations, as shown on Figure 1. Because of its astonishing shape, the site is highly visited by a wide range of population (local and national).

Figure 1 Aerial view of the site (tailings (left) and waste rocks (right) deposits, water-filled open pit)

It offers unique opportunity for sport and leisure activities in a relatively flat region. Several uses have been noted, some developed by the municipality, others that have developed over time, such as mountain bike, horse riding, walking, trail, picnic. Associations often organise trail, mountain bike and BMX competitions on the site. It represents a good opportunity of tourism and economic development for the municipality.

However, arsenic concentrations in soils constitute a potential risk to human health and therefore require assessment.

Figure 2 Examples of uses identified on the site

2.2 Soils characterization

On site investigations were carried out in order to characterize arsenic concentrations in subsoils. The depth sampled were determined according the identified uses. At the tailings disposal site, the main route of exposure identified is the ingestion of soil and dust from superficial horizons. Thus, investigations concerned the horizon from 0 to 5 cm deep. 177 measures using an X-Ray Fluorescence portable (pXRF) analyser were carried out. Due to the relative homogeneity of materials, the sampling plan followed a systematic grid of 50 m. This allows a statistical analyse of results and a good representativeness of average exposure concentrations and arsenic occurrence.

10 samples were collected on site to analyse metallic trace elements in laboratory for soil characterization and site-specific linear correlation with the field analyser. The samples were selected to ensure a spatial representativeness of the site as well as a representativeness of encountered concentrations with the field analyser (selection from the lower, middle and upper range of concentrations measured at the site). Bioaccessibility testing were performed on these samples following the Unified BARGE Method (in accordance with ISO/DIS 17924).

2.3 UBM procedure

Unified BARGE Method is an in vitro method for simulating the human digestive procedure. Digestive fluids are synthetic fluids used in the UBM test to simulate the fluids present in human digestive system: saliva, gastric fluid, duodenal fluid and bile. The current procedure describes a method for simulating the human gastro-intestinal tract through 3 different compartments: mouth (5 minutes), stomach (1 hour), and small intestine (4 hours). Figure 3 shows the schematic diagram of the UBM methodology. Each sample follows two separate tests:

- The gastric phase is a digestive extract collected after 1 hour agitation with saliva and gastric fluids.
- The gastro-intestinal phase is a digestive extract collected after 1 hour agitation with saliva and gastric fluid followed by 4 hours agitation with duodenal fluid and bile.

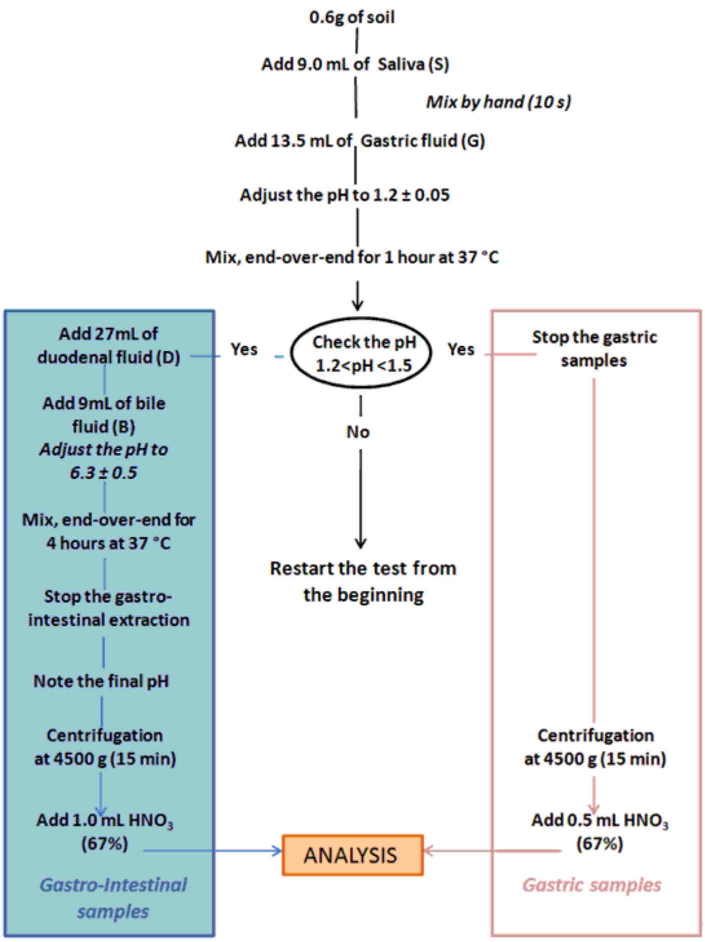

Figure 3 Schematic diagram of the UBM methodology (http://www.bgs.ac.uk/barge/ubm.html)

This method was applied on the 10 collected samples in duplicate. Blank and reference materials (NIST 2710a) also followed the complete procedure.

2.4 Human Health Risk Assessment (HHRA)

Human health risk assessment, regarding exposure to chemical substances, is performed following these different steps:

- Hazard identification - Hazard Identification is the process of determining whether exposure to a substance can cause an increase in the incidence of specific adverse health effects (e.g., cancer, birth defects) and whether the adverse health effect is likely to occur in humans.
- Dose-Response assessment - A dose-response relationship describes how the likelihood and severity of adverse health effects (the responses) evolve with the amount and condition of exposure to an agent (the administered dose).
- Exposure assessment - Exposure assessment is the process of measuring or estimating the magnitude, frequency, and duration of human exposure to a substance in the environment.

- Risk characterization - Risk characterization is the result of the risk assessment process. It aggregates the data collected in previous steps in order to quantify risk levels for human health and their acceptability with regard to standard comparison thresholds. This step also includes the evaluation of the assumptions and uncertainties that may still exist in the assessment.

This paper will not describe “Hazard identification” and “Dose-response assessment” steps.

2.4.1 Exposure assessment

Based on observations made and developments noted on the site, several areas of homogeneous use were defined, as shown in Figure 4 and Table 1. The observations supporting these scenarios were made during many site visits occurring within or out of school holiday periods during the last 3 years.

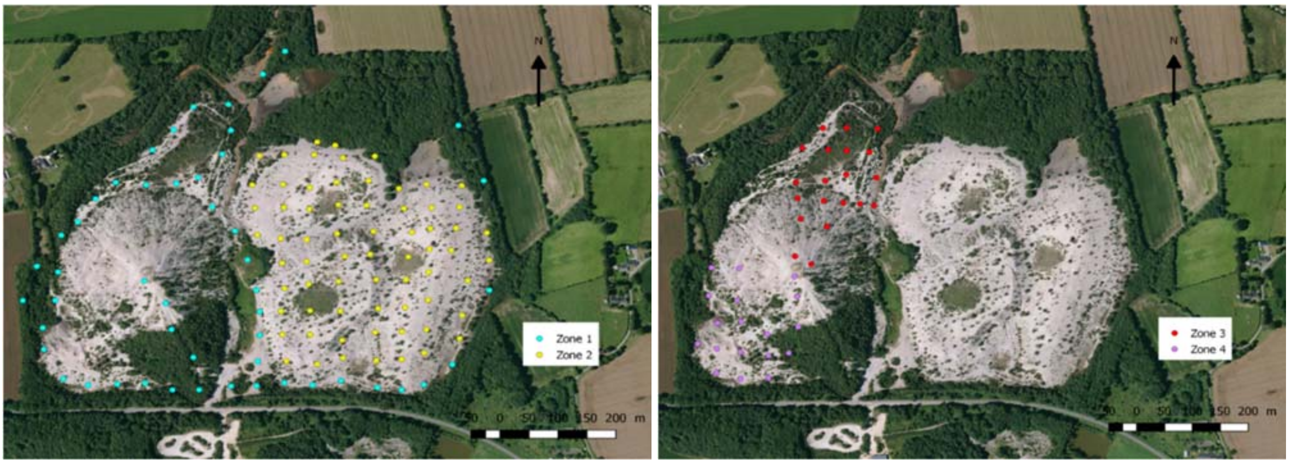

Figure 4 Localisation of selected data for the different scenarios of exposure

Table 1 Exposure scenarios defined for HHRA

Zone	Uses	Receptors	Exposure routes
Zone 1	Walking, running	Child, Adult, Child becoming adult	Soil/dust ingestion Dust inhalation
Zone 2	Walking, running	Child, Adult, Child becoming adult	Soil/dust ingestion Dust inhalation
	Moutain bike, horse riding	Adult (6 to 70)	
	BMX	Adult (15 to 50)	
Zone 3	BMX	Adult (15 to 50)	Soil/dust ingestion Dust inhalation
Zone 4	Mountain bike	Adult (15 to 50)	Soil/dust ingestion Dust inhalation

It is assumed that only adults between 15 and 50 years old engaged in “extreme” sport activities.

2.4.2 Risk characterisation

Potential non-cancer risk for individual contaminants are expressed as Hazard Quotient (HQ). HQs are calculated as the ratio of the estimated daily intake of each contaminant to the corresponding route-specific reference dose (RfD - tolerable daily intake or tolerable concentration).

$$HQ = ADD / RfD \tag{1}$$

where:

HQ: hazard quotient
ADD: average daily dose
RfD: reference dose

When the average daily dose estimated from site-associated soil contaminants exceeds the protective RfD, the HQ exceeds one. Such risk levels are therefore considered as inacceptable.

Risk characterization of carcinogenic substances consists in calculating the Incremental Lifetime Cancer Risk (ILCR). ILCR is expressed as an estimated upper-bound probability of additional lifetime cancer risk due to exposure to site-related contaminants. The upper-bound estimate of excess risk related to each contaminant is calculated by multiplying the lifetime average daily dose (LADD) estimated for that contaminant by its corresponding route-specific cancer slope factor.

$$ILCR = LADD \times CSF \quad (2)$$

where:

ILCR: Incremental Lifetime Cancer Risk
LADD: Lifetime average daily dose
CSF: Cancer slope factor

For non-threshold contaminants, acceptable incremental risk levels in Europe are defined that vary from 1.10^{-4} (The Netherlands) to 1.10^{-6} (Italy), while 10^{-5} is adopted by the large majority of country including France (Carlon, 2007). In this case study, ILCR has to be under 10^{-5} to be acceptable ($ILCR < 10^{-5}$).

2.4.3 Integration of bioaccessibility into risk characterisation

Absolute bioavaibility is the fraction of a substance present in ingested soil that reaches the systemic circulation (blood stream). But determine bioavaibility is not easily achievable due to both experimental issues linked to blood sampling and to analytical limitations.

Whereas, absolute bioaccessibility is the fraction of substance in soil or soil material that is liberated in (human) gastrointestinal juices and thus available for absorption (ISO/DIS 17924, 2016). So, bioaccessibility is the maximal fraction of a substance that can reach the systemic circulation.

The ingested matrix containing the toxic substance has an influence on the dose-response relationship of the substance. In order to integrate this parameter in risk calculation, the corrective factor is the relative bioavailability (INERIS and InVS, 2012). This variable is defined as the ratio of absolute bioavailability of the substance in the soil matrix to absolute bioavailability of the element in the matrix used to develop the Reference Toxicity Value (RTV as RfD or CSF).

Caboche (2009) and INERIS and InVS (2012) retain the equality of the absorbed fraction of As present in contaminated soil and the absorbed fraction of As present in drinking water (reference matrix for the establishment of the RTVs). In addition, Oomen et al. (2006) indicate that the metabolism of absorbed arsenic does not depend on the matrix in which the element was in the gastrointestinal tract. Finally, the absolute bioavailability of arsenic in water, the reference matrix for RTVs, is close to 100% (INERIS and InVS, 2012). Then, the relative bioavaibility of arsenic is set equal to the absolute bioaccessibility of arsenic in soil.

It is thus possible to integrate absolute bioaccessibility of arsenic from the UBM test in risk calculation for exposure by ingestion as shown in equations below:

$$HQ = ADD \times BA_{As\ absolue\ sol} / RfD \quad (3)$$

where:

HQ: hazard quotient
ADD: average daily dose
$BA_{As\ absolute\ soil}$: Absolute bioaccessibility of arsenic (= relative biodisponibility)

RfD: reference dose

$$ILCR = LADD \times BA_{As\ absolue\ sol} \times CSF \quad (4)$$

where:

ILCR: Incremental Lifetime Cancer Risk
LADD: Lifetime average daily dose
$BA_{As\ absolute\ soil}$: Absolute bioaccessibility of arsenic (= relative biodisponibility)
CSF: Cancer slope factor

3 Data

3.1 Soil characterisation

Following EPA Method 6200 (EPA, 2007), a strong correlation (r > 0.8) must be established between the in situ XRF measurements and the arsenic concentrations measured in the laboratory to be used as a definitive characterisation tool. This method also specifies that one of every 20 XRF samples should be collected and submitted for laboratory analysis. 10 samples were collected and analysed out of the 177-pXRF measures. Figure 5 shows the correlation between in situ XRF arsenic and laboratory arsenic concentrations.

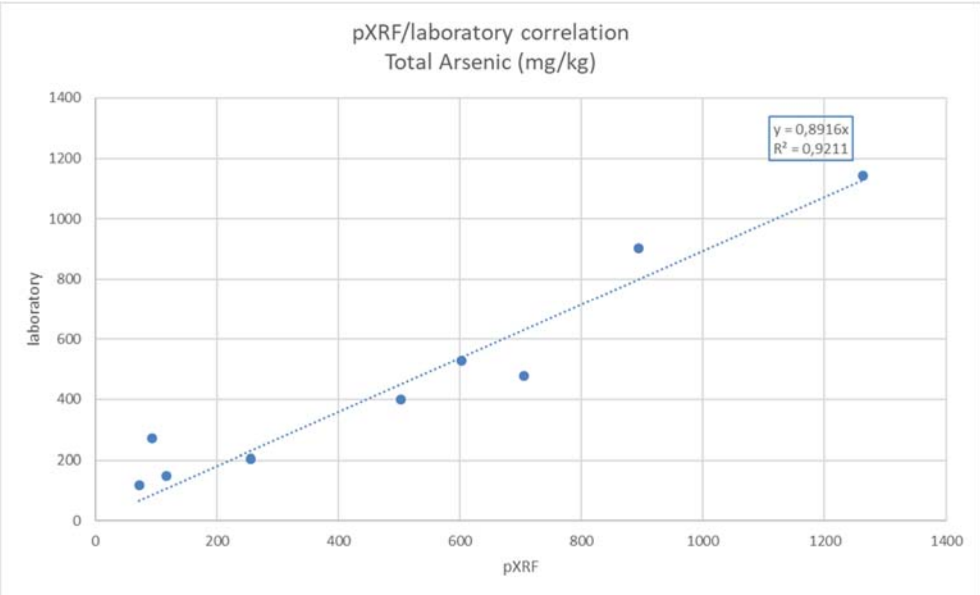

Figure 5 In situ XRF total concentration versus laboratory total arsenic concentration

A strong correlation ($R^2 = 0.92$) is shown between the pXRF arsenic measurements and the laboratory total arsenic concentrations. The equation mentioned on the Figure 5 was used to convert the pXRF measurements to laboratory equivalent arsenic concentrations at the site. Figure 6 shows the arsenic concentrations repartition on the site. Arsenic concentrations in tailings and waste rocks on site range between 20 and 1,400 mg/kg, with 67 % of concentrations between 100 and 600 mg/kg, while the local geochemical background is around 100 mg/kg. The highest concentrations are encountered on the tailings deposit, while they are close to the local geochemical background (100 mg/kg) on the north part of the site.

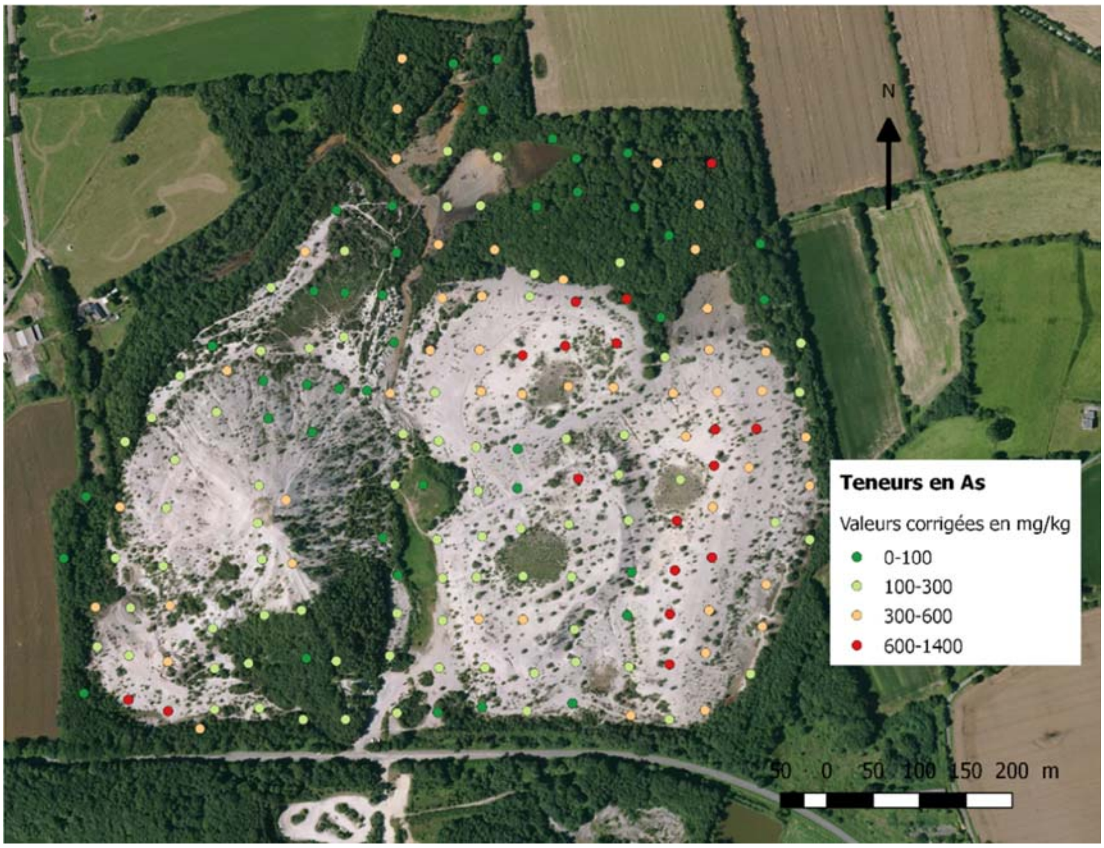

Figure 6 Total arsenic concentrations map

Given the large amount of data, chosen concentrations for HHRA is the average concentration calculated in each zone, as shown in Table 2. In a conservative approach, if the amount of data is not relevant, the maximal encountered concentration is selected leading to an overestimation of risk.

Zone	Number of analyses	Range of encountered concentrations	Selected concentration (average)	Standard deviation
Zone 1	51	26 - 1,031	199	175
Zone 2	77	46 - 1,138	368	253
Zone 3	20	26 - 417	151	123
Zone 4	18	115 - 1,031	282	234

Table 2 Selected arsenic concentrations on the different zones of exposure

3.2 Bioaccessibility

Results on the blank allow validating the absence of contamination related to the procedure that could affect the estimation of arsenic bioaccessibility in the samples. Results on the reference material (NIST 2710a) reflect a good repeatability of the results and are consistent with all previous results obtained by the laboratory. Figure 7 shows the results of absolute, gastric and gastrointestinal bioaccessibility in the 10 samples analysed (average, minimum and maximum of the 2 replicates per sample). This figure shows a low variability of the results between the replicates of each sample. Absolute gastric bioaccessibility is superior to gastrointestinal bioaccessibility for 6 samples and relatively similar for the other 4 samples. The gastric bioaccessibility measured on a waste rocks sample (51 % on ABNit154 for 537 mg/kg in soil) is higher than that measured on all the other samples (6 to 27 %). Despite this high value, gastric bioaccessibility in waste rocks is not significantly different than those in tailings (non-parametric Mann-Whitney test: p=0.11;

significance of difference for $p<0.05$). Therefore, waste rock and tailings were considered to have similar arsenic gastric bioaccessibility, averaging at 17.2 %.

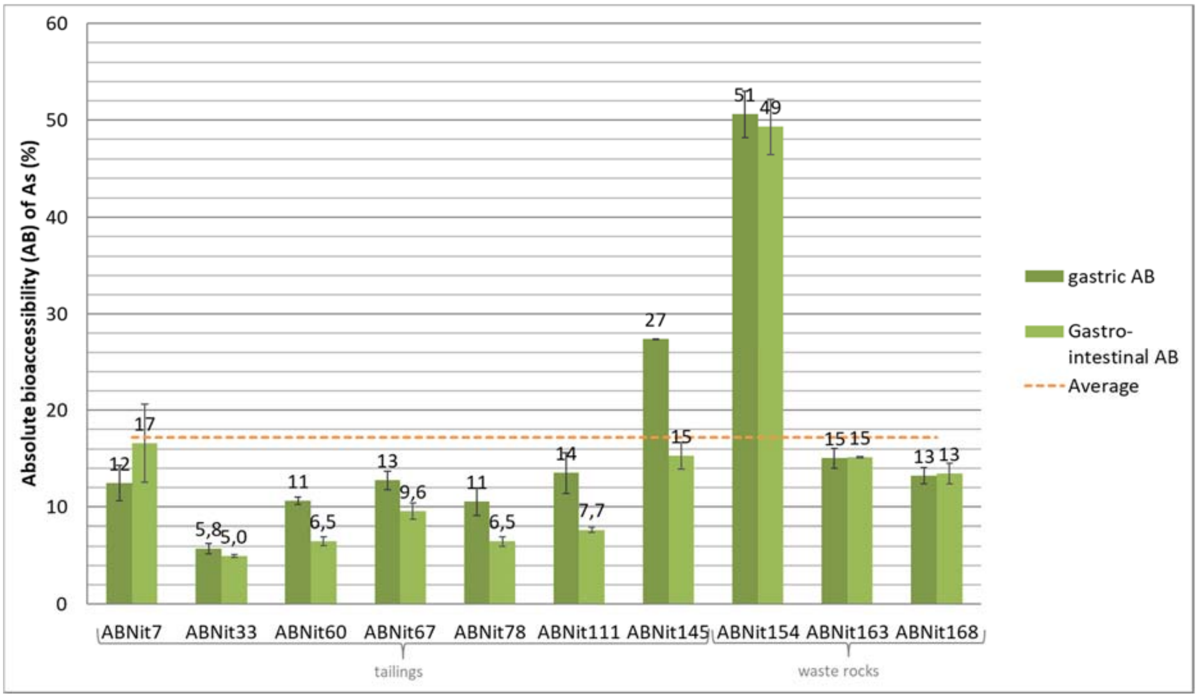

Figure 7 Bioaccessibility testing results

4 Results

Calculations of risk characterisation were performed with site specific parameters when they were available. Potential risks, calculated on the basis of the average concentrations and bioaccessibility of soils, are summarised in the Table 3 below.

Zone	Uses	Receptors	ILCR	HQ	Conclusion
Zone 1	Walking, running	Adult (6 to 70)	5,1E-06	1,2E-01	Compatible
		Child (2 to 6)	4,9E-06	4,7E-01	
		Child becoming adult (2 to 30)	8,6E-06	4,7E-01	
Zone 2	Walking, running	Adult (6 to 70)	9,4E-06	1,8E-01	Not compatible
		Child (2 to 6)	9,1E-06	7,2E-01	
		Child becoming adult (2 to 30)	**1,6E-05**	7,2E-01	
	Mountain bike, horse riding	Adult (6 to 70)	**2,7E-05**	4,6E-01	
	BMX	Adult (15 to 50)	**3,2E-05**	6,6E-01	
Zone 3	BMX	Adult (15 to 50)	**1,3E-05**	5,2E-01	Not compatible
Zone 4	Mountain bike	Adult (15 to 50)	**2,5E-05**	5,7E-01	Not compatible

Table 3 Results of risks characterisation

Results above show that HQ is less than 1 for all the considered zones and scenarios. But ILCR is higher than the threshold value (10^{-5}) on zone 2, 3 and 4 for all the considered scenarios. For the scenario "walking and running" on zone 2, the contribution of risk is the high arsenic concentration, where for others scenarios (mountain bike, BMX, etc.) on zones 2, 3 and 4, the major contribution of risk is the high ingestion rate selected due to these activities that generate a lot of dust.

5 Conclusion

Results show that one zone of the site is compatible with a tourist and leisure use despite the high arsenic concentrations encountered. It would not have been possible to draw such conclusion without a good screening of arsenic occurrence and bioaccessibility testings. Indeed, this method allow a better representativeness of human exposure by a risk quantification more accurate and closer to the reality while remaining conservative.

Site improvements will be proposed to the municipality in order to better control the uses on the site, and to ensure health and environment protection:

- In zone 1, since risk levels are close to the acceptability threshold, it could be wise for example to reduce direct contact of the walkers with soil by consolidating the paths and areas with specific attractive structures (bench, viewpoint indicators) with non-erodible safe soil materials. We could also recommend the removal of the picnic area, where As concentration is higher than the average concentration of the area, or the substitution of the topsoil with safe previously controlled soil. These simple dispositions should be sufficient to enable a safe leisure development and public frequentation of zone 1.
- However, specific dispositions should be implemented to prevent public access to zones 2 to 4. Moreover, the improvement of the trail marking could also help to limit the access to these zones.

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Fluid Fine Tailings Dewatering Processes for Oil Sands Reclamation

LK Kabwe *University of Alberta, Canada*

GW Wilson *University of Alberta, Canada*

JD Scott *University of Alberta, Canada*

Abstract

Canadian government regulatory and closure commitments for oil sands mines and tailings ponds compel oil sands companies to dewater and reclaim the fluid fine tailings in the tailings ponds. To achieve solids contents and undrained strengths sufficient to support reclamation, significant dewatering and treatment of the fluid fine tailings are required. Companies are having difficulty in meeting this requirement and are adding flocculants to the fluid fine tailings and using thickeners or centrifuges to increase the solids content. The main problem is the slow consolidation of the high water content tailings. It has been shown in our previous studies that both the centrifugation and thickening followed by freeze/ thaw cannot produce a trafficable surface. This study compares various oil sand tailings dewatering processes. The consolidation and shear strength properties of the fluid fine tailings from various treatments are compared to assess and discuss their reclamation potential.

Keywords: *fluid fine tailings, dewatering, oil sands, consolidation*

1 Introduction

1.1 The Oil Sands of Alberta

Oil sands are located in three major areas in northeast Alberta underlying 142,200 km^2 (Figure 1) and contain an estimated 400,000,000 m^3 (2.5 trillion barrels) of bitumen. With today's technology about 27,000,000 m^3 of bitumen are considered proven reserves. Alberta has proven oil reserves of 170 billion barrels, consisting of bitumen (about 168 billion barrels) and conventional crude oil (1.7 billion barrels)(Alberta Energy, 2017). These oil reserves are the third largest in the world, only exceeded by those in Venezuela and Saudi Arabia. Crude bitumen production (mined and in situ) totaled about 2.5 million barrels per day (bbl/d) in 2016 and is expected to increase to 4 million barrels per day in 2024, keeping pace with demand, (Alberta Energy Regulator, ST98 report, 2018). Only 3 % of the total oil sands surface area can be surface mined; however, 20 % of the oil sands reserves are in this area. Extraction of the bitumen is done by surface mining or by in situ methods, depending on the proximity of the resource to the surface. Surface mining extracts deposits with less than 75 m of overburden, whereas in situ extracts deeper underground deposits. Oil sands ore is a natural mixture of sand, water, clay and a type of heavy oil called bitumen. Bitumen must be removed from the sand and water before being upgraded into crude oil and other petroleum products. In surface mining operations, shovels extract the sand ore, and trucks move it to an extraction facility (Government of Alberta, 2011).

As of 2017, there were 176 operating and approved oil sands projects in Alberta. Of these, six were producing mining projects (two more are presently experimental) (Figure 2) and are producing about 900,000 barrels of bitumen per day; the remaining projects use various in situ recovery methods (Alberta Government, 2017). On average at the mining projects, approximately 1.5 barrels of tailings are produced for each barrel of bitumen produced. The tailings are made up of water, fine sand, silts and clays, residual bitumen, salts and soluble organic compounds. They also include solvents that are added to the oil sands during the separation process.

Figure 1 **The Oil Sands of Alberta**

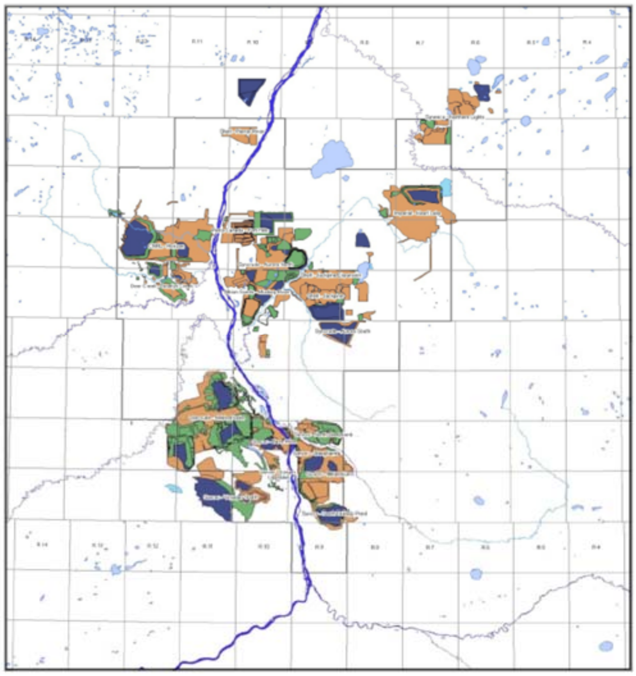
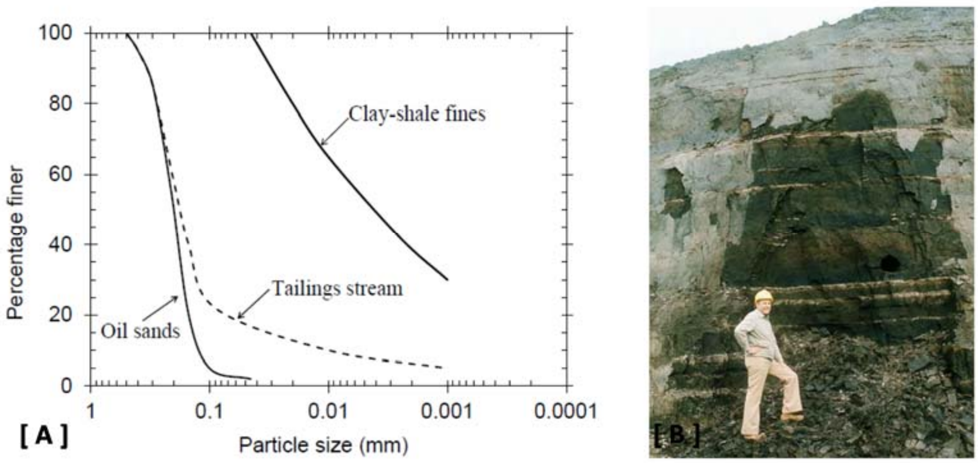


Figure 2 **Oil Sands Mines and Tailings ponds in 2020**

Tailings ponds are managed within a closed-circuit drainage system and no tailings or process-affected water are allowed off-site. Tailings ponds provide up to 90 per cent of a company's water needs through the reuse of process-affected water, significantly reducing the amount of fresh water required. As the tailings solids are about 72% fine sand, the sand settles out on deposition to form tailings dykes and beaches and much of the water and residual bitumen and about half of the fines flow into the tailings pond. With the removal of the recycled water about 1 m³ of sand and 0.25 m³ of fluid fine tailings at a solids content of about 30 to 35% are created for every barrel of bitumen produced. This has led to the accumulation of approximately one billion m³ of fluid fine tailings (FFT) which require long-term storage in tailings ponds as the water is toxic and cannot be released. The total area covered by tailings ponds in 2010 was 176 km² and as 200 million liters per day continues to be accumulated, the area is forecast to increase to 250 km² by 2020 (Figure 2).



[B]

Figure 3 **[A] Particle size distribution of oil sands ore, clay-shale inclusions and resulting tailings stream and [B] Section in the Upper McMurray Formation**

The reason for this massive accumulation is that the FFT consolidate extremely slowly. Extensive research is underway by a number of organizations to develop methods to understand the reasons for this slow consolidation and to design treatment methods for mine closure. The long term consolidation performance was monitored in the 30 year history of a 10 m high standpipe test at the University of Alberta and the results of this large, long term test has provided an understanding of the volume decrease properties of these fluid fine tailings.

The properties of the oil sands tailings are the result of the ore properties and the extraction procedure to remove the bitumen from the ore. Over the oil sands mining area the properties of the ore can change substantially with by mass 55 to 80 % sand (>45 µm), 5 to 34 % fines (<45 µm), 4 to 18 % bitumen, and 2 to 15 % water. Typical deposits of average grade oil sands contain 72% sand, 12% fines, 11% bitumen and 5% water. Figure 3A, (Kabwe et al. 2014) shows a particle size distribution (PSD) of oil sands which contains almost no fines and if the whole deposit was like this there would be no fine tailings. Figure 3A also shows the PSD of a typical clay-shale seam in the oil sands McMurray Formation. The fines in the tailings come from these indurated clay-shale discontinuous seams and layers in the oil sands. Figure 3B is a photograph of a section in the Upper McMurray Formation showing typical clay-shale layers contained in the ore. These dense but weak clay-shale materials are broken up during the mining process and the larger more indurated pieces are screened out as reject material. In the bitumen extraction process the clay-shale pieces are further broken down into clay lumps and aggregates and some clay lumps are dispersed into small clay booklets and flakes. The amount of dispersion depends on the extraction process. The sodium hydroxide dispersing agent in the Clark Hot Water Extraction process used in the oil sands extraction plants effectively disperses much of the clay aggregates into clay flakes smaller than 2 µm which have large active clay surfaces. This combination of sand and dispersed fines results in the PSD of the tailings also shown in Figure 3A.

Table 1 Mineralogy of FFT measured in 2000 and 2010

Year	Quartz and other rock-forming minerals	Clay Minerals	
		Kaolinite	Illite
	(%)	(%)	(%)
2012	36	42	22
2000	36	40	24

FFT behaviour is directly related to the mineralogy and water chemistry of the tailings. Therefore in 2000 and 2012 mineralogical tests (Table 1) were carried out on the 10 m standpipe FFT. The mineralogy of the fine tailings reflects the average clay mineralogy of the parent material, the McMurray Formation clay-shale seams, where kaolinite and illite are the dominate clay minerals. Trace amounts of mixed-layer clays, smectite, vermiculite and chlorite are also present (Kasperski 1992). The field fine tailings are characterized as dominantly kaolinite (55% to 65%) and illite (30% to 40%) with minute traces of mixed layer clay minerals (Dereniwski and Mimura 1993). Quartz is the most abundant non-clay mineral. As kaolinite and illite are not very active clays the mineralogy properties are not the cause of the poor consolidation performance. Unfortunately the extraction process water chemistry and the organic content (bitumen) affect the mineralogy and the resulting consolidation properties.

1.2 Government Regulations on Tailings Disposal

The Alberta Government regulates the disposal of the oil sand tailings through the Alberta Energy Regulator (AER) which ensures appropriate precautions are taken to develop oil sands resources in the interests of all Canadians. This happens through regulation, reviewing applications, managing conditions and approvals, surveillance and enforcement. Before any mining project begins, industry must develop and receive approval for closure plans that outline how affected areas will be reclaimed. Mine operators must also provide reclamation security as a guarantee that reclamation work will take place. The Alberta Government holds over $1 billion in reclamation security for the oil sands industry. The AER has issued in October, 2017 a revised

Directive 085, Fluid Tailings Management for Oil Sands Mining Projects. This directive, under the *Oil Sands Conservation Act* (*OSCA*), sets out requirements for managing fluid tailings volumes for oil sands mining projects, including application information requirements, the application review process, fluid tailing management reporting, and the performance evaluation and compliance and enforcement processes. The following information has been abstracted and summarized from the directive. This directive replaces *Directive 074: Tailings Performance Criteria and Requirements for Oil Sands Mining Schemes* and enables the implementation of the *Tailings Management Framework for the Mineable Athabasca Oil Sands* (TMF). The TMF provides policy direction to the AER to manage fluid tailings volumes during and after mine operation in order to manage and decrease liability and environmental risk resulting from the accumulation of fluid tailings on the landscape. The objective of TMF is to minimize fluid tailings accumulation by ensuring that fluid tailings are treated and reclaimed progressively during the life of a project and that all fluid tailings associated with a project are ready to reclaim (RTR) ten years after the end of mine life of that project. The TMF is intended to be reviewed every five years. The Government of Alberta will ensure alignment with other policies that are developed or revised and reflect changes in information, knowledge, and continuing work on fluid tailings indicators. This directive will be revised as necessary to ensure it appropriately enables and aligns with changes in the TMF and other government policy. In addition, the AER will continually improve the directive based on observations as to the effectiveness of the requirements and feedback from stakeholders.

This directive uses an outcome- and risk-based approach to holding operators accountable for managing their fluid tailings. In this approach, the AER is not establishing uniform requirements, but is instead requiring that operators identify optimum solutions for their project-specific fluid tailings management that meet the TMF objective and outcomes.

At the highest level, the AER approach can be described as follows: 1. Proponents are required to submit applications for approval for new projects or for approved projects of OSCA that include fluid tailings volume profiles (often referred to as “profiles”) and a fluid tailings management plan for new and legacy fluid tailings. Initial fluid tailings volume profiles and fluid tailings management plans are applications under the Responsible Energy Develop Act (REDA). The fluid tailings management plan must demonstrate that the profiles are consistent with the TMF profile guidelines, and that the project and individual deposits meet the TMF objective and outcomes. 2. If the fluid tailings volume profiles and fluid tailings management plan are approved, the AER will set thresholds suited to the accepted profile, adhering to the TMF policy. The AER will amend, as appropriate, existing approvals under the Environmental Protection and Enhancement Act (EPEA) and the OSCA to include project-specific site-wide and individual deposit fluid tailings management requirements and conditions of approval. The profiles, plans, thresholds, and conditions of approval are collectively used by the AER to hold operators accountable for their fluid tailings management plans and monitoring programs. 3. Operators are required to report annually on the performance of their fluid tailings management plans, including fluid tailings inventories, continuous improvement, and development of technologies and environmental monitoring results. Each year’s actual volume of fluid tailings must be within an operator’s approved fluid tailings volume profiles. 4. If fluid tailings volumes increase beyond a threshold or deposits are not meeting the proposed performance criteria, operators will take measures to resolve the issue. As well, when a threshold is exceeded, the AER will initiate a management response, reporting requirements, increased verification activities, action under the Mine Financial Security Program, third-party audits, production curtailment, or penalties. 5. Approved fluid tailings management plans must be reviewed by the AER every five years or as necessary over the course of the mine life to ensure that the profiles and thresholds are in line with projections and reflect current technology, new knowledge, and continuous improvement. 6. The AER will prepare an annual report on the state of tailings management and make it publicly available, including on its website. 7. As per the Oil Sands Conservation Rules (OSCR), the AER will make all fluid-tailings-related documents (applications, submissions, reports) publicly available, including on its website, to ensure that stakeholders have access to regulatory information about fluid tailings management.

The end of mine life is the year in which mining of bitumen is complete for an AER-approved mine plan (under the *OSCA*). Each project has a forecasted end-of-mine-life date. All fluid tailings from an approved project must be RTR ten years after the end-of-mine-life date. To ensure that this objective is met, the AER sets the end-of-mine-life target and thresholds. The TMF states that the end-of-mine-life target for all projects will be the equivalent of five years or less of fluid tailings volume accumulation. Variations of the end-of-mine-life date are expected over the life of the project, with the date becoming more certain as the project advances towards it.

2 Most Promising Oil Sands Tailings Dewatering Technologies

There are already 22 tailings technologies in commercial use, many of which are mature and others in an advanced development stage (Sobkowicz, 2012). The most promising technology is to add flocculants to the fluid fine tailings (FFT) and to use thickeners or centrifuges to increase the solids content and then use freeze/thaw (F/T) processes to further dewater the tailings. In line flocculation (ILF) involves the injection of flocculant into the pipeline at a given distance upstream from the discharge point to allow the required mixing and contact to take place within the pipe. Mixing and shear during transportation allow the formation of clay flocs followed by thin lift deposition (Figure 4A). The solids content of the product produced by ILF upon deposition ranges from 30 to 35% (Table 2). In the flocculation centrifugation (FC) tailings process, the FFT is conditioned with chemical additives (flocculant) which allows sufficient reaction time to enable the process stream to be properly processed in the centrifuge. The Centrifugation process separates the FFT on the basis of the particle size and density difference between the liquid and solid phases. The centrifuge product (cake) produced from the centrifuge is a soft soil material capturing greater than 99% of the solids (50 – 56% solids by weight) that is deposited in thicker layers using conveyors or trucks (Figure 4B). Flocculation thickening (FT) is the process by which solids are condensed to produce a concentrated 45 – 50% solids product (underflow thickened tailings (TT) and a relatively solids-free supernatant.

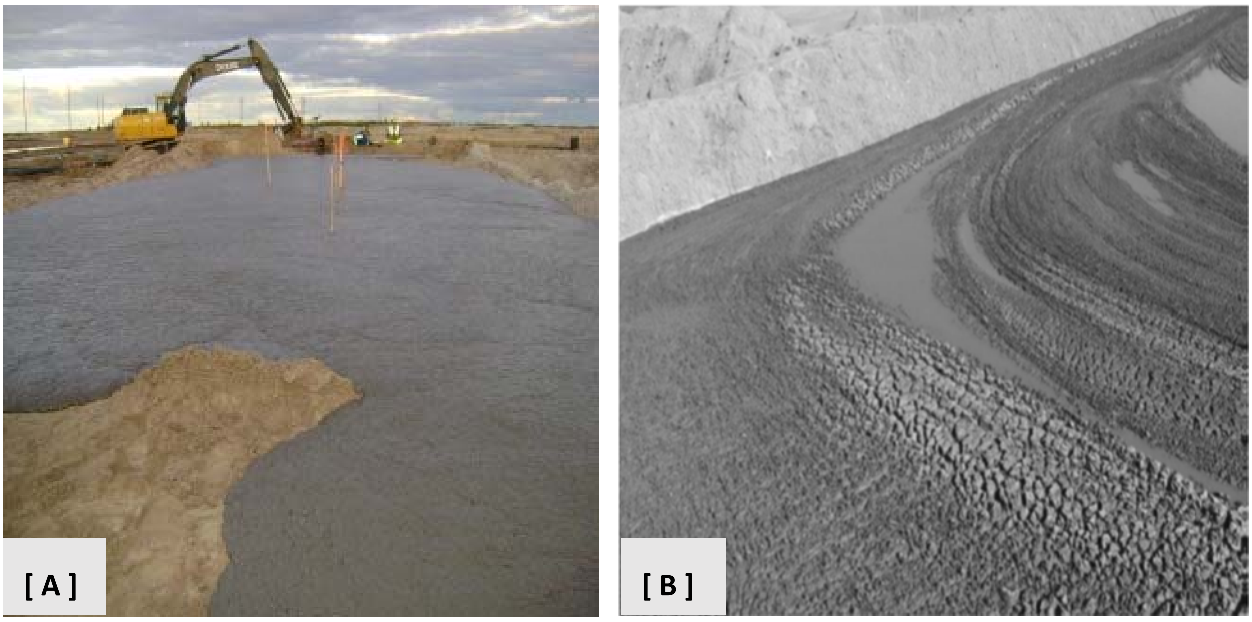


Figure 4 (A) In line flocculation and thin lift deposition and (B) FFT centrifugation and thick lift deposition

Tables 2 and 3 and Figure 5 summarized the results of various FFT treatments technologies previously conducted (Kabwe et al. 2013, Kabwe et al. 2014a, Kabwe et al. 2014b, Kabwe et al. 2017, Wilson et al. 2011, Wilson et al. 2014). The tests results indicate that the maximum solids content achieved by the current most promising technologies (Thickening and Centrifugation) can only achieve a solids content in the range of 50 – 55% associated with a shear strength of less than 1 kPa (Table 2). Table 3 indicates that further tailings dewatering by Freeze/Thaw (F/T) treatment on FTT and FCC produced a product with about 62 % solids content and about 1 kPa shear strength from 50 – 55% solids content and about 0.15 kPa shear strength respectively (Table 3). It was concluded from these findings that in-line flocculation, centrifugation and thickening with F/T treatment slightly increase the solids content and shear strength but not sufficient to support reclamation and stability necessary to establish a trafficable surface (Figure 5). Further treatments are required such as atmospheric drying and long term surcharge and self-weight consolidation.

Table 2 Characteristics for untreated and treated tailings using various technologies

	FFT	ILF-FFT	FTT	FCC
Solids content (%)	10 - 29	30 - 35	45 - 50	50 - 55
Shear strength (kPa)	< 0.1	< 0.1	~0.15	~0.4

FFT=Fluid fine tailings; ILF-FFT=In-line flocculated FTT; FTT=Flocculated & thickened tailings;

FCC=Flocculated & centrifuged cake

Table 3 Characteristics for untreated and treated tailings using various technologies + F/T

	ILF-FFT + F/T	FFT + F/T	FCC + F/T
Solids content (%)	60 - 62	60 - 62	61 - 63
Shear strength (kPa)	~ 1	~1	~1.6

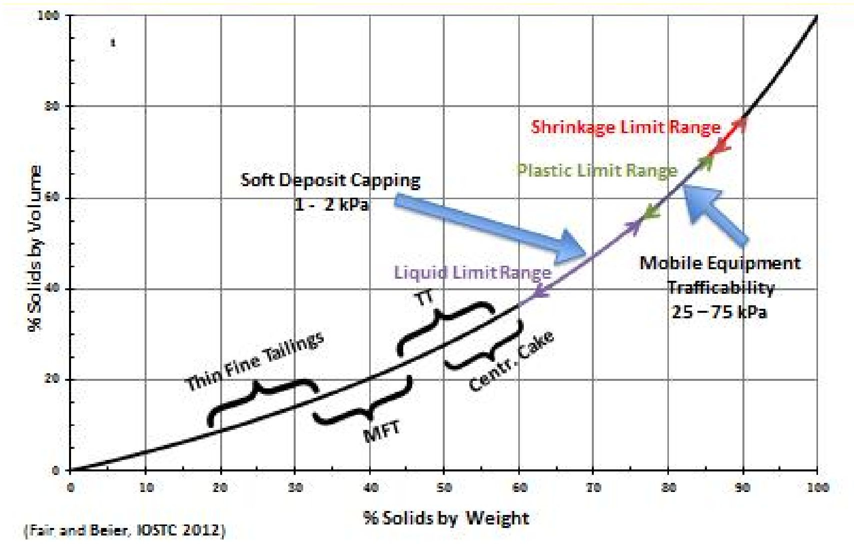


Figure 5 Fluid fine tailings FFT dewatering processes for oil sands tailings

3 Effect of Various Treatments on Consolidation of Untreated FFT

3.1 Effect of In-line Flocculation, Flocculation/Centrifugation and Flocculation/ Thickening on Consolidation of Untreated FFT

Large strain consolidation tests and shear strength tests were performed on untreated FFT sample and on three treated samples of in-line flocculated FFT (ILF-FFT), flocculated & centrifuged cake (FCC) and flocculated & thickened tailings (FTT). The consolidation and shear strength of the FFT was used as the base case to evaluate the advantages of the various treatments on oil sands fine tailings. Figures 6A and 6B compare the consolidation results of untreated FFT and treated ILF-FFT, FCC and FTT. Figures 7A and 7B compare the shear strengths. The tested samples started at different fine void ratios and they exhibited the same compressibilities at effective stresses between 5 and 100 kPa (Figure 6A) except for FTT sample which is slightly more compressible. Figure 6B shows the hydraulic conductivities of the FCC and FTT treated samples are considerably greater, about 2 orders of magnitude than that of the untreated FFT at void ratios greater than 3. Similarly the hydraulic conductivity of the ILF-FFT treated sample is about 1.5 greater than that of the untreated FFT at void ratios greater than 3. At fine void ratios lower than 1.5 there is no difference between the hydraulic conductivities except for the FTT sample. An increase in hydraulic conductivity will result in the treated samples consolidating much faster.

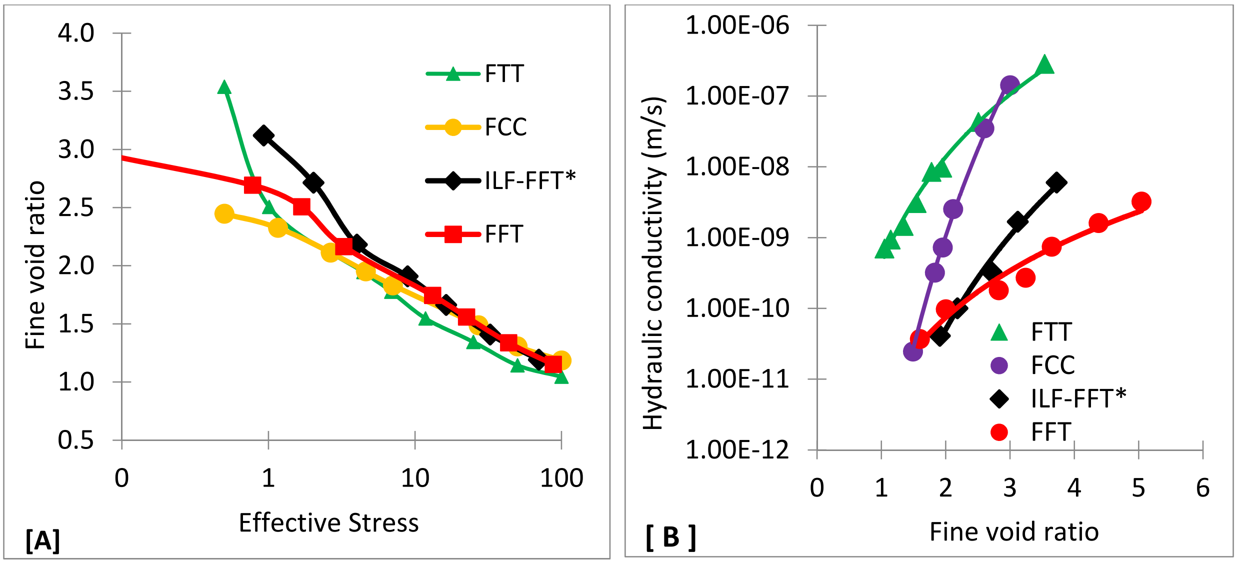


Figure 6 (A) Compressibilities and (B) hydraulic conductivities of untreated FFT and treated ILF-FFT, FCTC and FTT

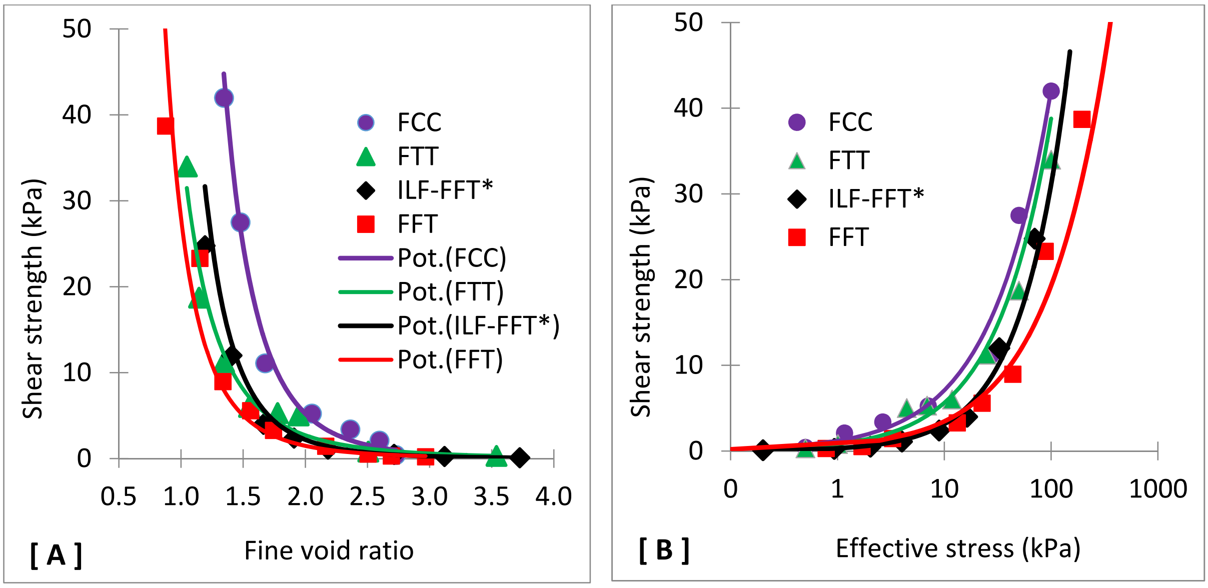


Figure 7 (A) Shear strengths vs fine void ratio and (B) shear strength vs effective stress for untreated FFT and treated ILF-FFT, FCTC and FTT

Figures 7A and 7B indicate that the shear strengths of the treated ILF-FFT, FTT and FCC are slightly higher than the shear strength of the untreated FFT at a fine void ratio lower than 2 (Figure 7A) and at an effective stress greater than 10 kPa (Figure 7B) respectively. For example, to achieve a shear strength of 30 kPa the FFT, FTT, ILF-FFT and FCC need to be compressed to fine void ratios of 1, 1.1., 1.2 and 1.5 respectively. In summary, the in-line flocculation, centrifugation and thickening treatments give the treated ILF-FTT, FTT, and FCC slightly higher shear strengths but not sufficient to support reclamation.

3.2 Effect of Freeze/Thaw on Consolidation of FCC

Figures 8A and 8B compare the consolidation results of untreated FCC and F/T treated FCC. Figures 9A and 9B compare the shear strengths. Figure 8A indicates that at consolidation effective stresses up to 500 kPa the F/T treated FCC was at a lower void ratio. This lower void ratio for the F/T treated FCC is a function of the lower initial void ratio and does not reflect that it is more compressible. The compressibilities become the same at effective stresses greater than 200 kPa. Figure 8B shows the hydraulic conductivity of the F/T treated FCC is greater, about one order of magnitude, than that of the untreated FCC at void ratios greater than 1.5. The hydraulic conductivities are the same at void ratios lower than 1. An increase in hydraulic conductivity will result in the F/T treated FCC consolidating much faster. Figure 9A and 9B show the shear strength as a function of void ratio and effective stress respectively. In Figure 9A the shear strength of the F/T treated FCC is slightly less than the shear strength of the untreated FCC at the same void ratio. It is postulated that the freeze/thaw process results in a soil structure which is weaker which then gives the F/T treated FCC a lower shear strength which in turn would make it slightly more compressible. In Figure 9B the shear strength of the treated FCC is slightly higher at the same effective stress. The conclusion from these test results is that the F/T treatment does not significantly increase the shear strength.

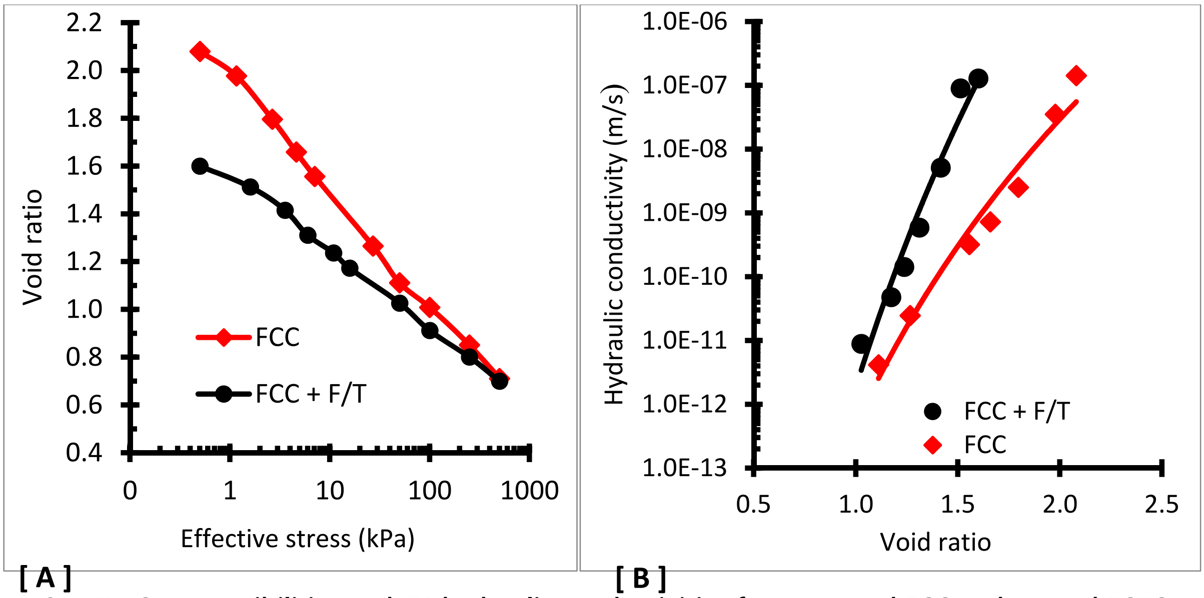


Figure 8 (A) Compressibilities and (B) hydraulic conductivities for untreated FCC and treated FCTC + F/T

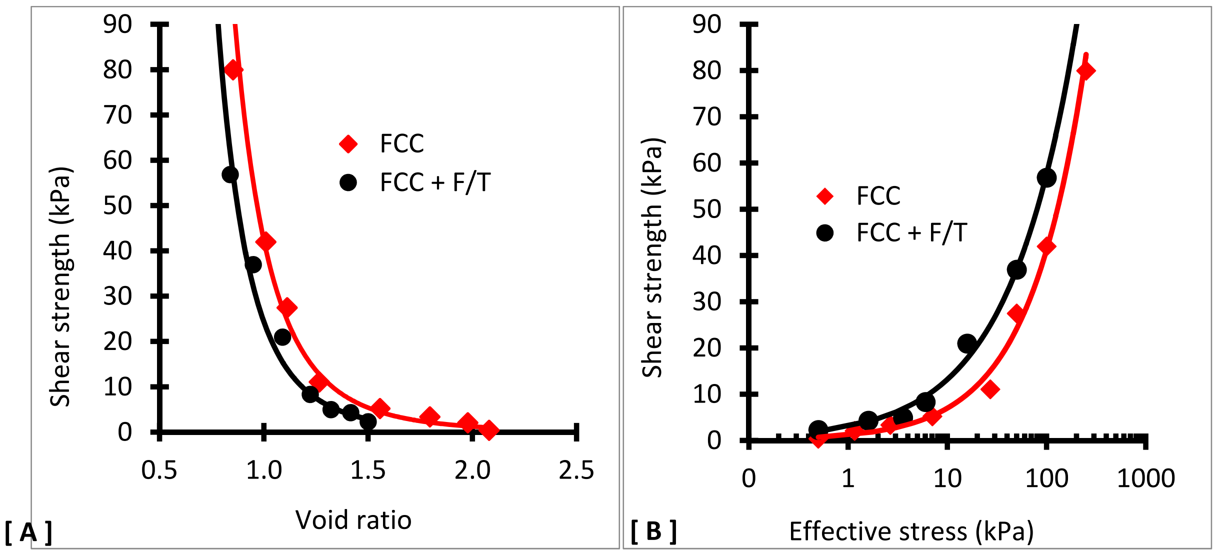


Figure 9 (A) Shear strengths vs void ratio and (B) shear strength vs effective stress for untreated FCC and treated FCC + F/T

3.1 Effect of Freeze/Thaw on Consolidation of FTT

Figures 10A and 10B compare the consolidation results of untreated and F/T treated FTT samples. Figures 11A and 11B compare the shear strengths. Results show that the F/T treatments results for the FCC and FTT are very similar but with a difference in magnitude. The most important result is the hydraulic conductivity of the F/T treated FTT which is higher than that of the untreated FTT and that will result in the treated FTT consolidating faster than the untreated FTT. The treatment produced the same effects in shear strength relationships with fine void ratio and effective stress for FTT and FCC. The conclusion is that there is no significant difference in shear strength between the untreated FTT and F/T treated FTT.

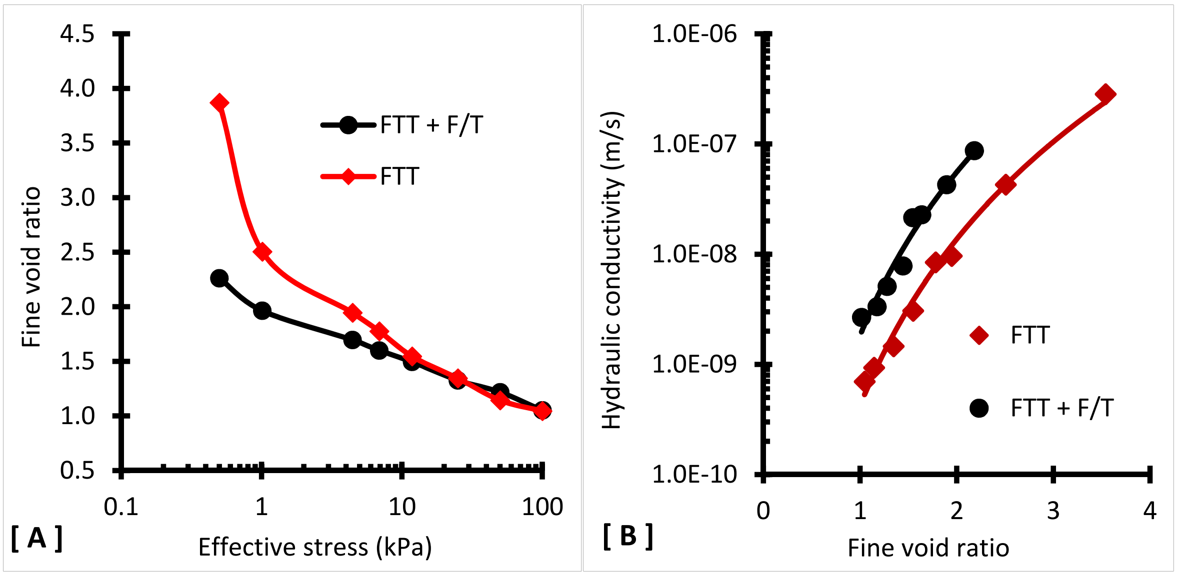


Figure 10 (A) Compressibilities and (B) hydraulic conductivities for untreated FTT and treated FTT + F/T

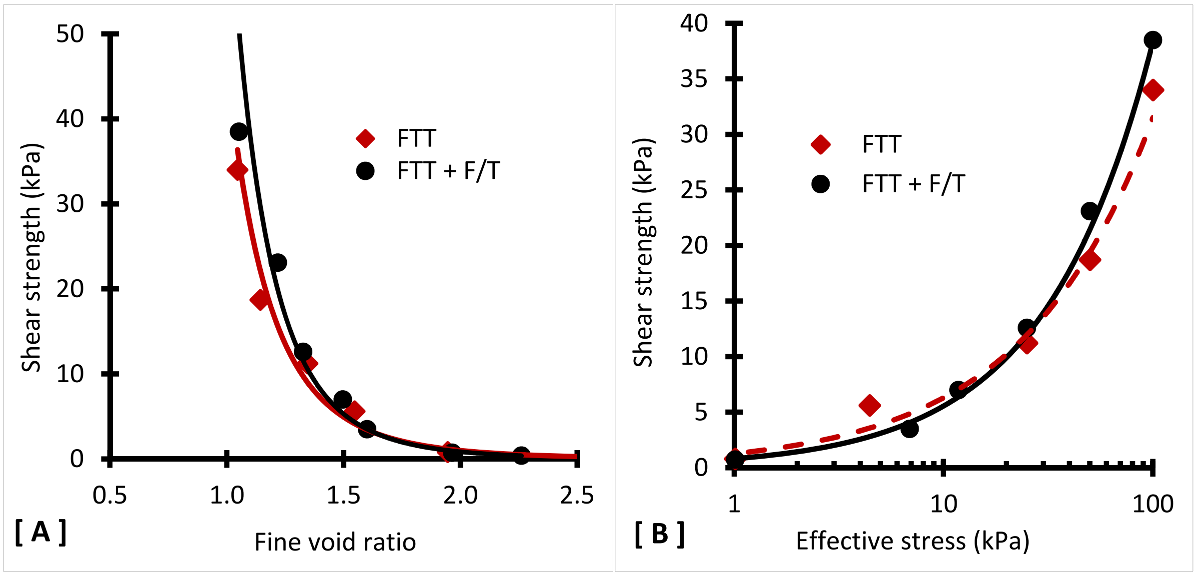


Figure 11 (A) Shear strengths vs fine void ratio and (B) shear strength vs effective stress for untreated FTT and treated FTT + F/T

4 Discussion and Conclusions

Oil sand mining and the production of tailings started about 50 years ago with the majority of mines opening in the last several decades. About 0.25 m^3 of fluid fine tailings at a solids content of about 30 to 35% are created for every barrel of bitumen produced. This has led to the accumulation of approximately one billion m^3 of fluid fine tailings which require long-term storage in tailings ponds as the water is toxic and cannot be released. The total area covered by tailings ponds in 2010 was 176 km² and as 200 million litres per day continues to be accumulated, the area is forecast to increase to 250 km² by 2020. The only tailings pond reclaimed to date is the original Suncor Tar Island Tailings Pond and this was done by pumping the fluid fine tailings to another pond and filling the area with tailings sand and revegitating it.

The Alberta Government regulates the disposal of the oil sand tailings through the Alberta Energy Regulator. The end of mine life is the year in which mining of bitumen is complete for an AER-approved mine plan. Each project has a forecasted end-of-mine-life date. All fluid tailings from an approved project must be ready-to-reclaim ten years after the end-of-mine-life date. To ensure that this objective is met, the AER sets the end-of-mine-life target and thresholds. The Tailings Management Framework states that the end-of-mine-life target for all projects will be the equivalent of five years or less of fluid tailings volume accumulation.

The current most promising technologies for oil sands tailings dewatering are thickening and centrifugation with freeze/thaw (F/T) treatment. The tests results indicated that thickening and centrifugation can only achieve maximum solids contents and shear strengths in the range of 50 – 55% and 0.5 – 1 kPa respectively. Furthermore, results also showed that thickening and centrifugation with F/T treatment can only produce tailings product with about 63% solids content and about 1.6 kPa shear strength respectively. To support reclamation,i.e., soft deposit capping and surface trafficability, solids contents of at least 70% and 80% and shear strengths of at least 2 to 60 kPa respectively are required. It can be concluded from these findings that centrifugation and thickening with F/T treatment slightly increases the solids content and shear strength but not sufficiently to support reclamation and the strength necessary to establish a trafficable surface. Further treatments are required such as atmospheric drying and long term surcharge and self-weight consolidation. The big challenge to overcome in this part of the world is the climate, as winter covers almost a quarter of the year with temperatures ranging from -10 to -30 °C. More research work is needed in the development of new dewatering technologies capable of producing tailings products with levels of solids contents and shear strengths to support reclamation.

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Managing Contamination by Considering of Contaminated Sites Legislation in a Mining Context - a Case Study

I Kwan Golder Associates Pty Ltd, Australia

K Mundle Golder Associates Pty Ltd, Australia

P Chapman Golder Associates Pty Ltd, Australia

Abstract

Typically, a mining operation is focused on production. During the course of production, impacts to soil and groundwater can occur resulting in contamination. It could be argued that select areas of a mine site are 'licensed' or 'planned' to be contaminated, where hazardous materials are known to be present or placed and specifically managed under license within a mining context, but there are many cases where hazardous materials are simply not managed in any way due to historical practices. Two examples of 'planned contamination' are tailings storage facilities (TSFs), where potentially hazardous materials are placed under license, or the area of the production plant, where potentially hazardous materials are used, spilt, stockpiled, washed down or placed as part of internal processing. In both cases, the processes can result in contamination that could have a significant impact on the costs of closure, if the Contaminated Sites legislation, which can take precedence over the Mining Act, is not well understood.

This paper presents a case study illustrating the potential areas of contamination that, under Contaminated Sites legislation, are required to be managed as part of mine closure. The interaction between the Western Australian Contaminated Sites and mining legislation is discussed and approaches to minimise liabilities in a cost-effective manner are presented. Of key interest is the varying definitions of 'contamination' and how the source-pathway-receptor conceptual site model can be used as part of mine site design and operation, to minimise risks and reduce trailing liabilities at closure.

Keywords: *contaminated sites, contamination, liability, closure, legislation, licensing, source-pathway-receptors, conceptual site model*

1 Introduction

Mine sites and mining operations occur in mineral enriched areas of the planet with the aim of extracting the resources to benefit the manufacturing of consumer goods. This inevitably results in contamination, particularly when there is a strong focus on production rather than environmental management. In cases where the operation's focus takes precedence, there is opportunity to minimise and reduce the operational footprint throughout the life of mine to reduce the overall liability at closure, sometimes at a fraction of the closure cost. In Western Australia, which is a resource reliant state, there is evolving work being carried out to understand the environmental legislative context of mine closure and liabilities. Historically, the Mining Act (1978) has been the key piece of legislation in relation to mining and mine closure. In 2015, the Western Australian Mine Closure Guidance included a statement about safe, stable, non-polluting but also added "non-contaminating" with reference to contaminated sites legislation and the statutory body/regulator required to endorse Mine Closure Plans. Does the Mining Act (1978) take precedence over the Contaminated Sites legislation or vice versa? Is there room for both pieces of legislation to coexist and work together? How do the Acts interact when mine sites change owners?

This paper aims to explore this issue and present some thoughts around operational efficiencies that may assist in reducing future trailing reputational and economic liabilities at closure.

2 Setting the Scene

2.1 What is Contamination?

To understand contaminated sites legislation in Western Australia, the definition of contaminated must first be understood. The Contaminated Sites Act (2003) defines contaminated as:

> *"… in relation to land, water or a site, means having a substance present in or on that land, water or site at above background concentrations that presents, or has the potential to present, a risk of harm to human health, the environment or any environmental value."*

A source of contamination is considered to be an activity, product or area which is known or suspected to be impacting soil or groundwater quality (above background levels) and may pose a risk to a receptor. A receptor can be ecological such as trees, wildlife or aquatic organisms through to humans in the form of site personnel and workers, or future end users of the site. Receptors can be both onsite and offsite.

For contamination to pose a risk, the source and the receptor must be connected via a pathway. In a mining context, examples include seepage from mineral enriched leachate to groundwater or windblown dust from ore stockpiles.

Therefore based on the definition, if there is no source, or receptor or pathway, then technically there is no contamination. If a linkage and contamination is present, further consideration of ongoing knowledge of the source or management of the pathway is required and the legislative framework allows for the placement of "memorials" or annotations on the Certificate of Title or Deed of Ownership.

Under the Western Australian legislation, if there is a potential for contamination or if actual contamination exists, then there is a duty to report this to the regulators.

Another consideration is what is "background"? As mines are, by definition, in areas that are enriched with minerals that are naturally occurring, is it considered contamination? It therefore requires an assessment using a risk-based approach. Has the consolidation of naturally occurring minerals into a waste facility such as a tailings facility changed the occurrence of natural minerals at the site? Has the waste consolidation placed the material into one location where in the natural environment, it exists in a dispersed manner? Under the current legislative framework, as these storage facilities contain concentrated minerals and present a different risk profile to human health and the environment, they must be considered as a potential contaminated site although they are licensed for this purpose of waste disposal.

2.2 Conceptual Site Model in the Context of Closure

In the framing of environmental impacts and understanding where the risks are present, it is important to understand what the potential source-pathway-receptors linkages are. The sources of contamination (and typically in a mining context can include chemicals used in processing, workshops and bulk fuel handling, wastes from production including tails) may present an issue if there are receptors close by either in the form of the environment and/or humans.

It is important to recognise that the presence of a source alone will not result in unacceptable risk. It is also important to understand the hydrogeological setting and potential fate, transport and toxicity of the contaminant. The pathway from the source to the receptor must be linked and result in an exposure which poses the receptor to unacceptable levels of contaminants. This may not always be the case.

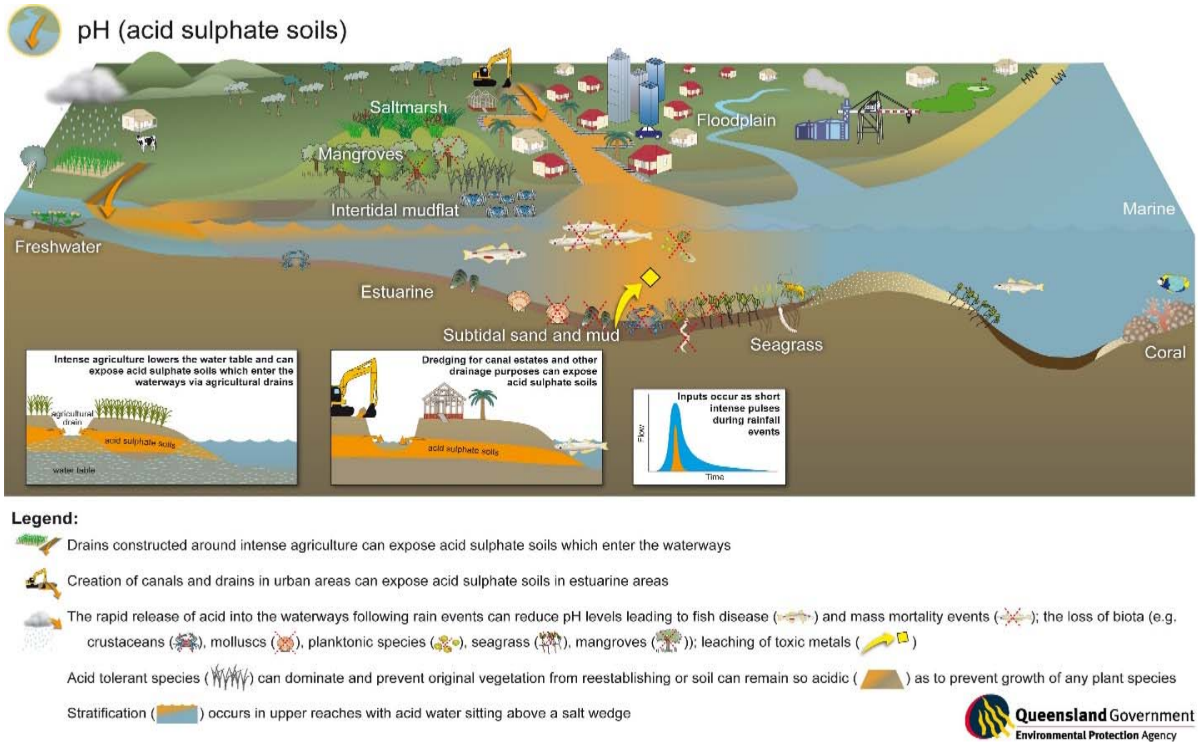

Figure 1 **pathway of acidic waters with high sulphate content (from http://www.ozcoasts.gov.au/conceptual_mods/stressors/images/pH_final.jpg)**

Generally, operational facilities have been historically set up with generic environmental compliance criteria. Often these do not consider all the relevant receptors, or may not be appropriate for the monitoring of impacts, either from the view of relevant contaminants of concern or frequency of monitoring. Sometimes, it becomes "monitoring for the sake of monitoring". The conceptual site model is critical in developing and setting the monitoring programs and confirming the validity of the monitoring parameters.

Some considerations may include:

- What is the geology of the site? Will the groundwater monitoring program assess the right geological unit where contamination is likely to occur and mobilise to reach a receptor?
- Is there beneficial use of groundwater in the area and what are these uses?
- Has an effective baseline assessment been undertaken?
- Are we comparing soil and water quality against generic criteria which has no relevance in a mineral enriched environment?
- What are the compliance criteria being used to assess for impact or breach of license?
- What are the likely chemicals used in the process and have these been assessed prior to the commencement of operations and are these continued to be monitored?

2.3 Stakeholder Engagement

As with most jurisdictions, the government owns the land which mining companies lease and extract ore. After expiration of the lease, the land is returned to the government. Sometimes, the government is left with sites that require significant financial expenditure to rehabilitate it to an acceptable state. It is therefore important to understand what relinquishment looks like and what level of impact is considered acceptable. Mining operations are typically extensive and can leave large areas of impacts and disturbance to the local environment. Early stakeholder engagement can greatly assist in setting environmental end points that benefit the stakeholders by ensuring there are no surprise remediation requirements.

It is very difficult to achieve a "walk away" scenario in relation to mine closure as there will always be some element of maintenance, inspections and potential monitoring. Ongoing management activities, for example, fencing to prohibit access or bunds to manage stormwater, will require inspection to make sure controls remain in place and remain effective as a management tool.

Some considerations for stakeholder consultation:

- Have all the relevant stakeholders been identified?
- What is the agreed end land use and what potential conflicts will arise (e.g. returning land to pastoral, encouraging cattle onto a waste storage facility vs. erosional stability)?
- What will be the duration of monitoring and what exit strategies/mechanisms are in place/will be acceptable?
- Are there community expectations with site closure, heritage and community values?
- What are the foreseeable risks based on current knowledge and science?

3 Case Study of an operational mining and associated "processing" facility

3.1 Operational Context

Mining operations in Western Australia are frequently remote sites, with minimal connectivity to support services and therefore have to be self-reliant. These may include medical services, waste disposal/landfills, sourcing of potable water and other ancillary services that may be typically available in other populated areas. There are exceptions to this with large towns built up around mining activities and minesites.

Based on experiences with sites in Australia, mining operations are often production focused and environmental management, while still considered important, frequently has less focus. Environmental staff on mine sites have some influence on site practices, but generally, site management will always ensure that production is not interrupted or delayed. Generally, initial practices on sites will be set up well and communicated, but can be lost over time due to changes in site personnel. The example site in Western Australia, is located in the Goldfields Region of Western Australia. The geology at the site is predominantly sands, gravels and loam overlying saprolite which is capped by ferricrete and silcrete. A palaeochannel runs close to the site and several salt lakes/water bodies are located within close proximity to the site. The palaeochannel is confined by a thick kaolinitic clay layer which isolates the shallow groundwater from the palaeochannel. Groundwater at the site ranged from 8 m below ground level to depths of over 20 m below ground level.

The site had good environmental management objectives and had a significant financial investment for site remediation which were quite advanced for its time period. This included a groundwater pump and treatment system which recovered cooling water with elevated concentrations of metals. However, other areas of the operations were unknowingly impacting on soil and groundwater quality as part of day to day operations through various historical waste management practices.

The example site involved the processing, concentrating and smelting of a base metal ore. Operations have been carried out at the site for well over 40 years. Ore is received on the run of mill pad and is subsequently subjected to various processes including the addition of reagents to process the ore to maximise the end product for either further processing and refining or sold as the raw material for various uses.

Licenses were in place for disposal of waste and the site operated within a tight regulatory framework with regular monitoring and submission of annual reporting of environmental parameters. As situations arose in relation to waste management, amendments would be sought to the license or the waste management practices to accommodate the situation at the time. For example, furnace bricks with elevated metals (in particular chrome) required disposal and an amendment was sought and provided by the regulators to dispose of these materials into the tailings storage facility in a safe manner.

3.2 Operational Impacts

Historically, there were impacts from waste storage areas and general site operations. Site drainage was also not well managed as any surficial impacts were typically washed into the drainage network during rain events, resulting in impacts to soil and groundwater (and not always at the source area). Due to the transient nature of the contamination and operational nature of the site, it was sometimes difficult to characterise the source or extent of impact. Instead of defining a distinct source, impacts were attributed to a collective of operational areas which may have a contributing factor, resulting in an area of impact. Therefore, an alternative approach to site investigation was required.

The use of chemicals as part of processing and concentrating ore also presented challenges. Due to the age of the facility, when technological advancements were identified or when demand for different metals were strong, the site adapted to the various market drivers. Consequently, during the operational life of the site, there were different chemicals associated with different processes and different ores. Modification in the processing were not always obvious as the majority of the historical infrastructure was no longer present and upgrades to the facility overtime meant locations that were historically used for processing and chemical use were different from present day locations.

With the primary focus on production and processing, sometimes housekeeping practices were not always considering environmental impacts as the priority. As shut downs occurred and site maintenance was undertaken, it was not uncommon for materials (which could potentially leach and impact underlying soil and groundwater) to be temporarily stockpiled on site for later removal. This often resulted in material left in locations which were not ideal from an environmental perspective, although did not impinge on operational schedules.

Areas were used to store iron hydroxide which was a potential source of product. The stockpiling of the oxide was undertaken prior to the commencement of the longest serving employee on site and it was intended that the oxide material will be recovered for future processing which did not end up occurring. The material acidified, leaching naturally occurring metals into underlying groundwater as well as lowering the pH of the localised area to levels of about pH 2.

Waste containment and disposal facilities were licensed to operate and receive waste materials within certain concentration ranges. While licensed to accept these wastes, the Contaminated Sites Act also considers impact to receptors in the context of risk. A license to dispose is not a license to pollute. Risk to receptors were not originally well understood and therefore at the example site, the government granted a license for the storage facilities to be placed in close proximity to environmental receptors.

Although there are impacts to site, the site personnel were conscious about removing spilt material as soon as practical. There were often discussions during the interviews conducted that retrieval of any spilt product, not only benefited the environment, but it was in the operations financial interest to retrieve it, as product is a commodity. Sometimes though, minor spills and leaks were not considered significant enough to require removal and management, however, over the course of over 40 years, there is considered to be cumulative impacts which may be insignificant at the time of product loss but result in larger impacts later on.

3.3 Site Contamination Investigations Undertaken

As part of closure planning, the client required a better understanding of contamination liability and costs for remediation scenarios. Golder was engaged along with other consultants to assess and evaluate the closure provision and costs for managing the various technical issues with the closure timeframe in focus. Importantly, with closure, the timeframes are sufficiently long such that impacts to soil and groundwater may attenuate within the closure period for particular contaminants. It is also important to understand that the assessment for site contamination is only representative of a point in time and therefore ongoing operational impacts may change the status of the site (both positively through site clean-up and management or negatively if additional spills occur).

All contaminated site investigations are based on identifying the potential risk to environment and human health. Consequently, the first phase of work was to consider the individual activity areas and prioritise these using a risk based approach. High risk activity areas or areas with an absence of information (e.g. spill information, potentially contaminating activities (current or historical), previous assessments) resulted in high uncertainty with respect to the potential for contamination. The intent of the investigation was to focus on contamination with the greatest potential material impact and to identify management and risk mitigation measures. Lower risk areas were noted for future investigation and assessment as the opportunity arises (in relation to access, funding or if the risk profile changes e.g. spill occurs). A desktop screening and interview process was implemented and following this, if there was insufficient information and/or suspicion of a source, the area was prioritise for further assessment.

Personnel on site had some knowledge of past operations and while the majority of staff had short tenures, there were staff at the site with over 35 years of site experience and were valuable resources for the investigation process and assisted in prioritising high risk activity areas for additional investigation.

Due to the operational nature of the site, it was considered that the standard approach to contaminated site investigation would not be appropriate or practical in this scenario. Therefore, some areas of the site was assessed as a "black box" and assessed downstream and upstream for impacts or degradation in the environmental quality investigated. These areas included part of the plant, waste storage facilities and processing areas. Other areas which were considered to be of higher risk or higher potential for contamination were assessed as a point source. These included product handling and loading areas, fire training areas and chemical storage areas.

In addition, field instruments such as X-ray Fluorescence (XRF) and photoionisation detectors (PID) were used to obtain real-time data to inform in the field decisions regarding further assessment requirements. This reduced the number of site visits required to fully characterise the potential contamination at the site. Existing site groundwater monitoring wells were verified using downhole cameras to assess the integrity for environmental contamination monitoring, acknowledging that some of these monitoring wells were installed for other purposes.

A combination of profiling, sampling and groundwater assessment was undertaken, both at point source and diffuse source locations, surrounding the site. Soil assessments included grab samples and drilling core samples to a depth of 1.0 m to evaluate migration of contaminants through the soil profile. At locations where there was potential for downward migration of contaminants to depth, deeper soil assessment was undertaken and/or groundwater assessment.

3.4 Results from Investigations and Cost of Contamination Considerations at Closure

The outcomes of the investigations provided some contextual information for the closure costing provision. Previously, there were areas which were considered to be contaminated with assumptions made on depth of soil impact and removal volumes and the contaminant loading resulting in an assumption of heavily impacted material needing to be disposed of at a waste facility able to accept higher contaminated materials. The outcomes of the investigations also demonstrated that in a risk based approach to site remediation, the impacts resulting from the mining and processing of ore, did not result in a current unacceptable risks to human health or receptors that required immediate management or remediation. While there were some contaminants that required further assessment, these did not result in immediate action and the site was suitable for ongoing use and operations.

The testing showed that the natural setting of the site in the geological conditions resulted in very little migration of vertical or horizontal impacts. Certain areas where there was stockpiled ore and/or mineralised products (e.g base metal concentrate) did exhibit impacts through the soil profile to depth but it appeared that the groundwater impacts attenuated within a short distance from the source areas. Analysis of samples from key locations also confirmed that there was an absence of impact on beneficial users of groundwater (e.g. stock watering bores which was a receptor identified as part of the site CSM).

The outcomes of the investigations and the risk assessments undertaken at the example site demonstrated that there was low likelihood for unacceptable risks to receptors within close proximity to the site due to the attenuation factor along with retardation of impacted soils, leachate and groundwater.

While it is maintained that the majority of the site is operational and impacts are predominantly associated with operational areas, what is considered contamination and what will require remediation from a closure perspective? The two concepts can be very different while resulting in the same or similar outcome. From an operational perspective, it could be viewed that the impacts can be dealt with at closure and do not form part of operational liability. When it comes to the Contaminated Sites Act, impact to soil and groundwater above background levels which has the potential to pose a risk to human health, environment or environmental values is considered as contamination and must be reported to the regulators even within an operational setting. While in an operational context, these impacts may be managed and there are appropriate management plans in place, the Contaminated Sites Act does not preclude proponents from meeting their regulatory requirements to report the site as a potentially impacted site (or "suspected contaminated site") if it has not already been reported on a statutory form and in a particular format. If the contamination information has been provided previously to the regulator but not in the prescribed format, it is not officially considered that the site has been reported under the Contaminated Sites Act which is very specific on reporting requirements.

When contamination is considered from a closure perspective, for example, impacted material that can be managed at closure rather than remediated every time a spill occurs, then there is potential for impacts to increase with time and again, in the context the Contaminated Sites Act, these impacts require reporting and management to ensure that they do not cross property boundaries and/or affect any receptors. From a closure liability perspective, the cost provisioning will increase while the facility is operational and these impacts accumulate over time.

4 Operational Efficiencies

The results of the assessment suggest that impacts left for future management is not the best approach to managing ongoing contamination liability. Leaving material spilt on ground allows for the ongoing continued impact to depth unless it is removed or managed immediately. Waste management, including consideration of disposal areas for managing stockpiles is also critical to managing long term impacts. For example, if the placement of waste is proposed in an area of shallow groundwater and high permeability soils, then the potential of impact to receptors is going to be high. During our investigations, we were informed by personnel that there was an operational waste placement management plan developed and being implemented. This not only captures the physical land-forming of the facility but also how material is placed to reduce impacts to underlying soil and groundwater.

Some areas which were sealed ground (e.g. bitumen or concrete) were observed to have lower impact although some impregnation of concrete from contaminants is inevitable. In areas such as these, stormwater management is imperative to ensure that contaminated runoff leaving the area and contaminating other areas is minimised.

Site personnel also need to be aware of potential impacts as a result of their activities. Contractors on site may not be as aware of environmental matters and site conditions, and therefore, may require additional awareness training or induction.

There is benefit in managing spills and other loss of containment immediately. Opportunistic or progressive remediation/clean up will provide a reduction in closure liability. It also makes sense to progressively remediate and clean up impacts as operational sites have the equipment and machinery available to do so, and reduce the cost of mobilising equipment to site when the site is non-operational and does not have the operational focus. As remediation often takes time and requires monitoring data (sometimes many years) to demonstrate that the remedial works have sufficiently mitigated the risks, it makes sense to carry this work out as soon as practicable.

Any monitoring program for impacts or to monitor for potential impacts need to consider the receptors and sources. There may be benefit investing in the design of an appropriate level of monitoring to demonstrate rigour to the regulators and obtaining baselines for areas prior to impact. This will allow the assignment of appropriate trigger values and identification of a robust monitoring network which can be monitored throughout operation (with minimal disruption or change in locations). In an ideal world, these locations will serve the purpose of the operations, however, it is acknowledged that there will be changes to site infrastructure and use, and therefore constant review of the monitoring network is key to obtaining the relevant data for the site and assessing the risks.

Monitoring should also consider future closure endpoint and have closure in mind. The data collected should assist in understanding contamination levels and impacts such that an appropriate provision be set aside for remediation and clean up. However, if progressive remediation is undertaken, then the liability at closure may be reduced/minimised.

5 Conclusions

Contaminated sites legislation and mining legislation can coexist and it makes practical sense to adopt both as priorities as part of running a mine/business. By understanding key sources, pathways and receptors, managing contamination in a risk based manner and progressively during operations, will reduce liability at closure. Once the receptors are well defined and understood, it is important to then ensure that the right monitoring data is collected and screened against appropriate trigger values.

Waste storage facilities that are licensed to store waste will have associated trigger values. It is important that the trigger values are reflective of the level of protection required and the receptor which it is trying to protect. To derive appropriate levels, an understanding of what would be typically encountered in the region (or background) is also required.

As demonstrated by the example site in Western Australia, there are certain administrative requirements to be met under the Contaminated Sites Act (2003) but managing contamination makes good business sense. Of importance is also to manage site operations to reduce impacts, have environmental practices in the forefront as this also helps manage future liabilities, but it improves productivity as spilt product is also material that can translate to revenue. Management of site contamination is not always through procedures but promoting environmental awareness such that other Contractors and staff not considered to be undertaking environmental related activities have a focus on management of impacts.

Pollution Vulnerability of Agricultural Soils near the Klein Letaba Abandoned Gold Mine, Limpopo Province of South Africa

TB Matovheke *University of Venda, Thohoyandou, South Africa*

C Muzerengi *University of Venda, Thohoyandou, South Africa*

Abstract

Klein Letaba mine dam is situated close to farming communities near Giyani town and the un-rehabilitated mine tailings have been reported to contain elevated levels of Pb, Zn, Cd and As. These metals are detrimental to human health due to both short term and long term exposure. Samples were taken from the farming land and risk assessment performed using SFPI, NPI and RI methods. The farming land had NPI category of 5 and thereby indicating heavy pollution. The NPI methods was found to have a bias since it did not consider the weight factor of the studied metals. Consequently, the RI which shows the sensitivity of the soil to contamination was employed in the assessment. The RI of soil was categorized as ranging from low risk to extreme ecological risk (16 to 569 respectively). It was suggested that farming activities be discouraged in the vicinity of the mine because of the possibility of uptake of these metals by crops planted, which will eventually end up in the food chain.

Keywords: *Risk assessment, Nemerow pollution index, Potential Ecological Risk Index*

1 Introduction

South Africa is well known for its rich variety of natural resources and mining has been a great economic source for the country for more than 100 years. In many developing countries, lack of proper waste disposal practises from mining activities has been recognized as the major source of anthropogenic pollution and mine tailings being one of the major sources of pollution (Jiang et al., 2013, Davies and Rice, 2001). The impact of the pollution varies in severity depending on the age of these constituents at the site, the mining technique used and the geographical and geological settings. Most severe is that this kind of pollution is covert, long term and irreversible (Zhang, 1999). Contamination of soil is a constant danger due to pollution by toxic metals resulting in the infertility and unsuitability of the soil for plant growth and thus affecting the organisms in the food web (Kuhn and Koupells, 2004). Potentially harmful contaminants are dispersed in the surrounding environment during the operational period of the mine, and will linger for decades after its closure. Aside from the large amounts of solid mine waste being deposited, one of the main concerns is the formation of acidic effluents arising from these materials. Acid mine drainage has become one of the main focus points of many studies and is considered as one of the serious problems facing the mining industry (Akcil and Koldas, 2006).

Klein Letaba mine in the Giyani Greenstone belt (GGB) was shut down in 1968 following a major cave in and huge tailings dam is a major feature at this abandoned mine site. Van Reenen et al., (1994) and Gain et al., (1986) indicated that the gold in the GGB was associated with sulphides minerals such as pyrrhotite (Fe1-XS), arsenopyrite (FeAsS), and (ZnS) sphalerite. Mulugisi et al. (2009) and Mitileni et al. (2011) indicated that tailings dams in the GGB have elevated concentration of Pb, Cr, Cd, As and Zn. The release of these elements due to wind, water erosion and leaching, can lead to negative effects, which can ultimately be observed in the fauna and flora in the area. Leaching may result in bioaccumulation and bio-magnification processes being set in motion, while erosion causes the dispersal of the elements in the surrounding environment through transport of soil particles. Clearly not only the ingestion or inhalation of contaminated particles but also the ingestion of plants produced in the contaminated area is another principal factor contributing to toxic metal exposure to the population. This study focused on assessing the vulnerability of farmland near Klein Letaba mine to As, Zn, Pb and Cd pollution as the mine tailings has been reported to contain elevated toxic metal levels.

2 Methods

2.1 Site Description

The area is located 15 km west of Giyani town in Limpopo Province and northwestern edge of the Kaapvaal craton. It is also within the subtropical zone and is characterized by warm, dry, frost free and subtropical climate with summer rainfall. High amounts of rainfall occur between November and February (SAWS, 2013). The dominant soil in the study area is moderately loamy soil and clayey soil, which is reddish to dark brown in colour. The vegetation in this area is classified under the lowveld mopane veld savannas of both short and tall bushes (Rutherford, 2006). Dominated by a succession made of ultramafic schists such as chlorite schist, talc schist, tremolite-actinolite schist, and amphibolite schist, associated with cherts and banded iron formation and garnet rich meta-quartzite (Brandl and Kroner, 1993 and Potgieter and De Villiers, 1986).

2.1 Soil sampling and Chemical Analysis

Surface soils samples were collected from a depth of 10-30 cm around the tailings dam and the sample spacing being 200 m. At least 22 samples were collected at the agricultural field whilst, an additional 2 were collected 10 km from the tailings dam to represent background metal concentration. In all, 24 samples of approximately 2 kg of each were collected using a steel spade and stored in sealed polythene bags and transported to the laboratory for pre-treatment and analyses.

The samples were oven dried at 105-110°C, sieved to -2 mm and then milled to 85% -75 µm. Weights of 50 g were digested in 200 ml aqua regia (1:3 HNO3: HCl) on a hot plate for 2 hours. Calibration standard were prepared from stock solutions of As, Pb, Cd and Zn. The standards were prepared in 100 ml volumetric flask and stored in well-sealed sample bottles. Metals were determined using a Flame Atomic Absorption Spectrometer (AAS PerkinElmer Analyst 400) with the instrument being calibrated before analysis of each metal. All the samples were analysed for As, Pb, Cd, and Zn with quality control protocols that included incooperation of certified reference standards (CRMs) and blanks.

3 Risk Assessment

In this study, a risk assessment model that only considers the concentration of metals in the agricultural farmland is presented. This model is called the traditional soil toxic metal risk assessment model and uses the single-factor pollution index (SFPI) and Nemerow pollution index (NPI) to evaluate toxic metal pollution in farmland soils (Gasiorek et al., 2017 and Xiao et al., 2015, Liang et al., 2011). The SFPI was used to evaluate the pollution status of a single toxic metal element. It was calculated as follows:

$$P_i = \frac{C_i}{S_i} \qquad (1)$$

Where Pi is the environmental quality index of soil pollutant i; Ci is the measured value of soil pollutant i in mg.kg-1; Si is the evaluation standard of soil pollutant i in mg. kg-1.

The NPI takes into account both the average pollution status of a single heavy metal element and the degree of heavy metal pollution was calculated as follows:

$$P_i = \frac{\sqrt{(P_{i\max})^2} + (P_{iave})^2}{2} \qquad (2)$$

Where P is the comprehensive pollution index of Nemero, Pimax is the maximum pollutant value of all investigated single factor pollution indices, and Piave is the average pollutant value of all single factor pollution indices. When using the NPI, the soil quality is classified into 5 categories being; as non-pollution (NIPI≤0.7), warning line of pollution (0.7<NIPI≤1), low level of pollution (1<NIPI≤2), moderate level of pollution (2<NIPI≤3) and high level of pollution (NIPI>3) (Yang et al., 2010).

3.1 The Potential Ecological Risk Index (RI)

The excessive accumulation of heavy metals in agricultural soil can affect food quality and safety and further increase the morbidity of severe diseases, such as cancer, leukemia, and kidney or liver damage (Hakanson, 1980). The RI, defined by Hakanson (1980) based on the different toxicities of trace metals and the responses of the environment, is calculated as follows:

$$RI = \sum E_i \qquad (3)$$

$$E_i = T_i f_i \qquad (4)$$

$$f_i = \frac{C_i}{B_i} \qquad (5)$$

where RI is calculated as the sum of all four risk factors for the studies metals (As, Zn, Cd and Pb) in agricultural soils, Ei is the monomial potential ecological risk factor, fi is the metal pollution factor, Ti is the toxic response factor of the trace metals. According to Hakanson (1980), the toxic response factor values for different trace metal elements are in the order of Zn=1<Pb=5<As=10<Cd=30, Ci is the practical concentration of metals in soil, and Bi is the background value for metals. The adjusted evaluation criteria for the potential ecological risk index were RI ≤ 50, low risk; 50 < RI ≤ 100, moderate risk; 100 < RI ≤ 150, high risk; 150 < RI ≤ 200, very high risk; and RI > 200, extreme risk.

4 Results and Discussions

A descriptive statistical summary of the concentrations of the trace metals in the agricultural soil near Klein Letaba mine (Table 1) was obtained and the mean values of the metal contents can be ranked in the order of As>Zn>Pb>Cd. Arsenic concentration was elevated in the farming land ranging from <5 to 292 mg/kg and a mean concentration of 113 mg/kg. These levels of As were above the USEPA (1995) and WHO (2001) threshold limits of 10 and 20 mg/kg respectively. Pb had a maximum concentration of 17 ppm and this was more than twice the threshold concentration of 1 and 6 mg/kg as defined by the USEPA, (1995) and the SA, (1996). However, Zn and Cd concentration in the farming soil were below the USEPA (1995), WHO (2001) and the SA (1997) threshold limits. The pH of the soil ranged from 6.2 to 7.1 which represents a near acidic to neutral soil.

Table 1 Basic statistical parameters for trace metals in agricultural soils near Klein Letaba abandoned mine (units are mg/kg)

	As	Zn	Pb	Cd	pH
Number of values	20	20	20	20	20
Minimum	<5	0.4	4	0.2	6.2
Maximum	292	47	17	0.8	7.1
Range	287	46	13	0.6	0.9
Mean	113	20	9	0.4	6.8
Median	113	19	8	0.4	6.9
Standard deviation	59	11	3	0.2	0.3

4.1 Single-factor index analysis

The pollution indexes of the metals in the farming land were calculated by equation 1 and shown in Table 2. The results showed that As is the most serious pollutant in the farming land, and especially the pollution index of As which was 10 times high as the normal value. Except for As, the other metals Pb, Cd and Zn were graded $1 \leq P_{ij} < 2$, this being potential pollutants.

Table 2 Pollution index of each metal in the farming land

Metal element (mg/kg)	As	Cd	Pb	Zn
C_{ij}	140	0.4	8.7	21.3
S_j	14	0.4	5	20
P_{ij}	10	1.0	1.7	1.1
Quality grade	Heavy pollution	Potential pollution	Potential pollution	Potential pollution

4.2 Neremo Index Evaluation method

The SFPI method employed to evaluate the pollution of the four metals in the farming land did not express accurately the comprehensive impact caused by each kind of pollutants. Consequently, the NPI method which takes not only the extreme value but also the environmental quality index based on weighted multi-factors was also employed. This was calculated as the sum of the four metal elements using equation 2 and results are shown (Table 3). The NPI was obtained to be 39 and consequently falling in the highest category 5 of heavy metal pollution. However, although Zn, Cd and Pb had lower SFPI averages, the calculated results of the comprehensive evaluation was higher due to the maximum SFPI obtained from Arsenic of 55. It there implies that the NPI value of 39 obtained does not consider the weight factor and treats every pollution factor equally. Therefore, any high value of pollution factor will cause the composite value higher as shown by the results.

Table 2 Nemero index of the farming land near Klein Letaba mine

$Pi_{avarage}$	Pi_{max}	Pi	Pollution grade
3.34	55	39	5

To handle the problem which existed in the NPI method, a correction through analyzing the weight factor was obtained using equation 3 to 5. The potential ecological RI shows the sensitivity of the study area to soil metal contamination and presents potential ecological risk to the agricultural farm land (Fig. 1). The RI of the study area for all sampling points was from low risk to extreme ecological risk (16 to 569 respectively). The RI data also indicated a certain degree of uneven distribution within the farming land. Only three points had RI<50 whilst the other sampling points had RI values ranging from moderate to extreme risk. Two sampling points indicated extreme risk with RI values of 221 and 569 respectively.

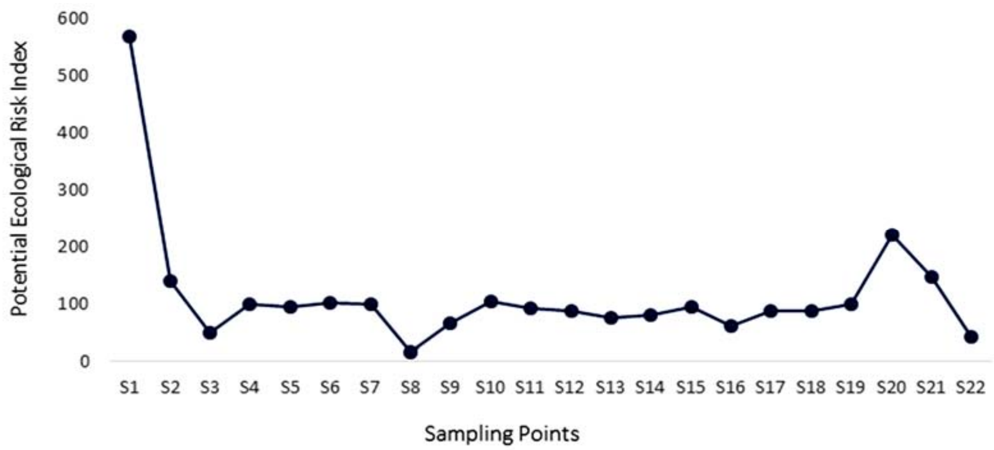

Figure 1 Potential Ecological Risk Index of farming soils near Klein Letaba mine

5 Conclusion

This study provided important information about the distribution of Pb, Cd, As and Zn in agricultural soils near Klein Letaba mine. The studied metals were ranked in the order of As>Zn>Pb>Cd and As being the most serious pollutant in the farming land. The SFPI analysis of As was 10 times the threshold whilst, Pb, Cd and Zn were graded potential pollutants and NPI assessment ranked the farming land to the highest category of 5 and this being heavy pollution. In addition, the results of RI and NPI indicated that almost the whole farming land near Klein Letaba mine is facing considerable potential ecological risk caused by metal pollution. It is suggested that effective measures should be taken to reduce trace metal contamination in agricultural soils in order minimize risks to human health, ensuring food safety, and managing contaminated soil. Farming activities should be discouraged in the vicinity of the mine because of the possibility of uptake of these metals by crops planted, which will eventually end up in the food chain.

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Identification of Indicator Species Around Coal Mining Area, Accredited to Air Pollution and Soil Properties: a Community Level Study

S Singh *CSIR-Central Institute of Mining and Fuel Research, India*

B Pandey *CSIR-Central Institute of Mining and Fuel Research, India*

M Agrawal *Banaras Hindu University, India*

KKK Singh *CSIR-Central Institute of Mining and Fuel Research, India*

PK Singh *CSIR-Central Institute of Mining and Fuel Research, India*

Abstract

Studies related to plant community structure on derelict sites can provide a significant insight into vegetation dynamics to ensure the success of future revegetation projects in such areas. Therefore, the present study was conducted to evaluate the changes in air quality, soil physico-chemical and biological properties around coal mining areas (CMA) compared to residential (RS) sites, along with their consequent impacts on the plant community structure. An effort was also made to identify the indicator species that thrive only under unfavourable conditions due to coal mining activities. Concentration of particulate matter, $PM_{2.5}$, PM_1 were significantly higher around CMA as compared to RS. Air pollution index, calculated on the basis of PM_{10}, SO_2 and NO_2 concentrations was highest near the coal mining area. The ambient concentrations of heavy metals also showed significant spatial variations. CMA showed significantly higher bulk density, soil temperature, electrical conductivity, sulphate and heavy metal contents and significantly lower water holding capacity, porosity, moisture content, soil pH, total nitrogen and available phosphorus contents in soil compared to RS throughout the year. Soil microbial biomass C and N, microbial biomass C/N ratio and soil respiration were showed minimum values in soil near CMA. The importance value index of sensitive species minified and those of tolerant species enhanced with increasing air pollution load and altered soil quality around CMA. Although the species richness plants decreased around CMA, a large number of species acclimatized to the stress caused by the coal mining activities. Woody plant community was more affected by coal mining than herbaceous community. Canonical correspondence analysis along with principal component analysis revealed that structure of herbaceous community was mainly driven by soil C/N ratio, whereas woody layer community was influenced by sulphur dioxide in ambient air. Dichanthium annulatum, Eclipta alba, Solanum nigrum and Adina cordifolia are most sensitive as these were present at RS and completely absent from the CMA. Eragrostis cynosurides, Setaria glauca are indicator species as these were only present around CMA.

Keywords: *air pollution, soil, plant community structure, herbs, trees*

1 Introduction

India is typically a land-short economy. Its requirement for usable land is rising at an exponential rate. Centuries of mining have resulted in many mining land beyond any commercial, recreational or social use. It is now important to restore such land for fruitful use and also to plan the future mining in a way so that the used land can be reused after mine closure. India's coal consumption ranks third in the world, and the country's demand for coal continues to grow much faster than the world average. Indian coal sector is poised to grow at a very fast rate in the near future due to steep increase in coal demand for providing power to all. The quantum jump in coal production from opencast operation and consequent overburden removal will put significant stress on the environment due to total destruction of the vegetation and soil cover, formation of waste dumps, depletion of water tables, increase in dust pollution and deterioration of landscape and aesthetics of the area.

Plant community and their species carry out variety of biological services in an ecosystem viz., protecting areas from soil erosion, defending from floods and other destructive weather conditions, reducing the risk of local and global climate change, recycling nutrients (Harrison et al., 2014). Plant species are distributed in variable habitats, but within the limits of the area, species are most abundant in places which represent their ecological optimum, and hence the composition of plant communities is a function of changing habitat conditions along the environmental gradients (Ulrich et al., 2018).

Different air pollutants and altered soil physico-chemical properties may affect individual plants and their population via various mechanisms of action and thus influence the plant community structure, because the optimum value of environmental gradient is different for different species. Plant community structure of an area tends to be modified by the selection pressures of the environment. The superimposition of severe pressures on plant community sometimes occurs to allow for feedback mechanisms to operate for selection of resistant species. The stability of various plant communities has been shown to be negatively affected by increasing concentrations of air pollutants and disturbed soil quality (Ulrich et al., 2018).

On the basis of above discussed literature the present study was conducted to evaluate the changes in air quality, soil physico-chemical and biological properties around coal mining areas (CMA) compared to residential (RS) sites, along with their consequent impacts on the plant community structure. An effort was also made to identify the indicator species that thrive only under unfavourable conditions due to coal mining activities. Studies related to plant community structure on derelict sites can provide a significant insight into vegetation dynamics to ensure the success of future revegetation projects after closure of mines.

2 Study area

The present study was carried out in Dhanbad district of Jharkhand, India, between latitudes 23 37' to 24 56' N, longitudes 86 08' to 86 50' E and 227 m above mean sea level. Dhanbad district have the most exploited coal mines because of available metallurgical grade coal reserves. The northern boundary of Dhanbad district is surrounded by Barakar River and southern boundary by Damodar River (Figure 1).

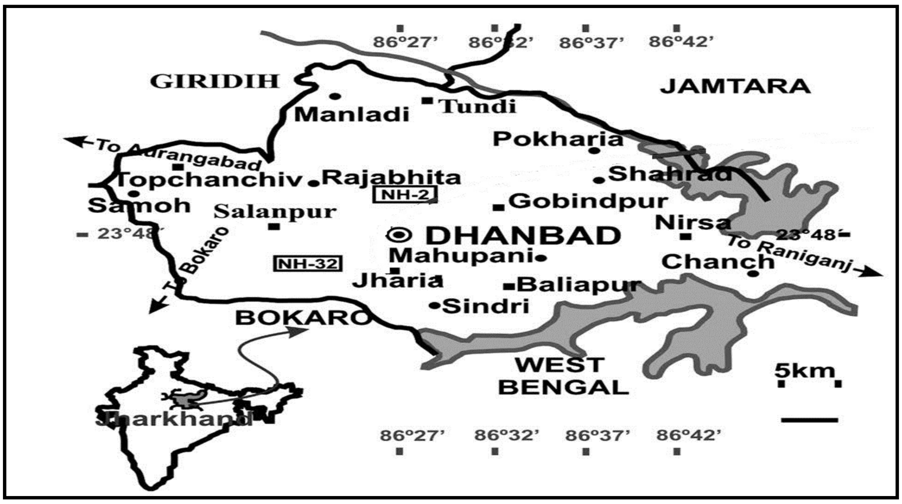

Figure 1 Location of the study area

3 Materials and methods

The air quality was monitored for PM_{10}, $PM_{2.5}$ and PM_1 portable aerosol spectrometer (Model 1.109, Grimm technology Inc., USA), SO_2, NO_2 (wet chemical method) twice in a month at each site for 8 h during 2014. The methods in detail are given in Pandey et al. (2014a). Particulate matter accumulated glass fiber filter paper was digested in HNO_3 and $HClO_4$ (9:4) solution for the analysis of heavy metals in PM_{10}, as per the methodology of Gaidajis (2003). The extracted solution was filtered and washed by double distilled water before analyzed by using atomic absorption spectrophotometer (Model Aanalyst 800, Perkin–Elmer, USA).

Analyses of soil samples were carried out for pH, total porosity (TP), bulk density (BD), water holding capacity (WHC), total nitrogen (N), available phosphorus (P) and sulphate (S) contents. Soil samples were collected up to 15 cm depth with the help of an auger from three places every 3 months for the year 2014. Soil temperature (ST) was monitored by probe connected to LICOR 6400 IRGA (Li-Cor Inc., NE, USA). Moisture content, electrical conductivity and soil pH were determined just after collection of samples, and rest of the soil was air dried and ground to pass through 2 mm sieve. For bulk density, water holding capacity and porosity soil was collected up to 15 cm depth using the soil corer (6.5 cm diameter). Total N in soil was determined using Gerhardt Automatic N Analyzer (Model KB8S, Frankfurt, Germany). Available P was extracted following Olsen et al. (1954) and estimated by the method of Dickman and Bray (1941). Available sulphur in soil was estimated following Williams and Steinbergs (1959).

Microbial biomass carbon (MBC) and nitrogen (MBN) were determined following chloroform fumigation and extraction method (Brookes et al., 1985). Soil respiration (SR) was measured by a LICOR 6400 IRGA connected to a 6400-09 type soil chamber (Li-Cor Inc., NE, USA). Air dried sample of 1.0 g soil was digested and anylyzed for heavy metals.

Biodiversity analysis of the flora was conducted at residential areas (RS) and coal mining areas (CMA) respectively, at the time of peak canopy biomass. At both sites, 25 sub sites were stabilized and 1 m × 1 m size quadrats were used for herbaceous layer and 20m × 20m size quadrats were used for sampling woody layer community. Presence and absence of species, number of the individual of species and their basal area in each quadrat were recorded. From these data, relative frequency, relative density, relative dominance, important value index (IVI) were calculated (Pandey et al., 2014b).

We conducted the multivariate statistical analysis, CCA using XLSTAT-Pro (Version 2013.1, Brooklyn, NY, USA) software, which can relate the quantitative changes of plant community to environmental gradient directly. Air monitoring and soil analyses data are taken as environmental gradients. Since CCA assumed non-collinearity in environmental variables, all the air monitoring and soil properties data were subjected to principle component analysis (PCA). The number of components extracted was determined by Kaiser criteria (eigen value more than one). Only variables, which showed high loading values on particular component, were used as environmental variables.

4 Results and discussion

The mean concentration of PM_{10}, $PM_{2.5}$ and PM_1 SO_2 and NO_2 was recorded high at CMA and lowest at RS during study period (Figure 2). Figure 4 shows the mean concentrations of heavy metals in PM_{10} obtained from ambient air from both monitoring sites. The highest mean concentration was found for Fe followed by Cu, Zn, Mn, Pb, Cr, Cd and Ni during complete years of monitoring (Figure 2). The mean concentrations of Pb, Ni and Cr were recorded highest at CMA. The sources of fugitive dust, gaseous pollutants (SO_2 and NO_2) and heavy metals at CMA include overburden removal, blasting, active mine fires, combustion processes, including vehicle exhaust, coal, oil and natural gas, with some emissions during blasting mineral haulage, mechanical handling operations, minerals stockpiles and site restoration (Pandey et al., 2014a).

Data of soil physical properties showed significant spatial variation during study (Table 1). High values of bulk density and low soil porosity were recorded at CMA (Table 1). WHC and soil moisture followed a reverse trend than bulk density for sites. During study period, the high values of soil temperature were recorded at CMA than RS. The soil pH was found to be lower at the sites near the coal mining areas (Table 1). Soil electrical conductivity and SO_4 values showed their maximum at CMA. Soil of RS had highest N and P contents during the study (Table 1). Among analyzed heavy metals, Pb, Mn, Fe, Zn and Cd showed the highest values at CMA. The trend of heavy metal contents at CMA was Fe>Mn>Zn>Cu>Ni>Cr>Pb>Cd, while, it was Fe>Mn>Zn>Ni>Cu>Pb>Cr>Cd at RS. MBC, MBN, microbial C/N ratio and SR were the highest at site RS.

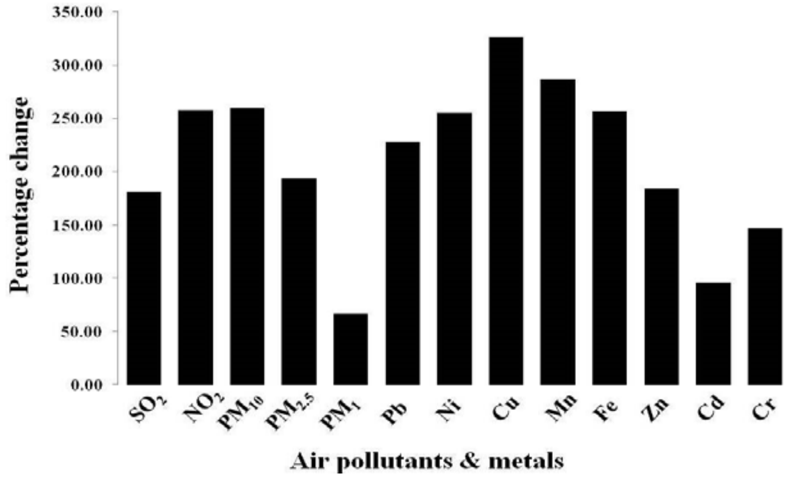

Figure 2 Percentage change in the values of different air pollutants at CMA with respect to RS

Table 1 Variations in soil parameters at residential (RS) and coal mining sites (CMA) (Mean±SEM)

Variables	RS	CMA
Soil pH	6.80 ±0.05	5.19 ±0.14
Electrical conductivity (µs cm^{-1})	236.3±50.17	432.14±34.09
Bulk density (g cm^{-3})	1.26 ±0.03	1.30 ±0.04
Porosity (%)	46.03±1.24	38.03±1.67
Soil temperature (°C)	28.46±0.09	31.8±0.19
Soil moisture (%)	10.62 ±0.56	4.34 ±0.32
Total Nitrogen (%)	0.15 ±0.00	0.07 ±0.00
Available phosphorus (mg g^{-1})	0.05 ±0.00	0.02 ±0.00
Soil-SO4 (mg g^{-1})	0.03 ±0.00	0.06 ±0.00
Water holding capacity (%)	46.64 ±1.90	28.97 ±1.76
Soil microbial biomass C (%)	0.05±0.00	0.03±0.00
Soil microbial biomass N (%)	0.004±0.00	0.001±0.00
Soil respiration (µmole CO_2 m^{-2} s^{-1})	10.05±0.29	2.40±0.10
Pb (µg/g)	16.96±0.90	30.88±1.49
Ni (µg/g)	21.50±1.09	48.30±2.13
Cu (µg/g)	20.15±1.23	65.60±1.41
Mn (µg/g)	393.45±27.04	592.17±51.78
Fe (µg/g)	23565.48±910.94	44387.54±482.78
Zn (µg/g)	96.10±6.14	124.88±10.47
Cd (µg/g)	0.17±0.01	0.47±0.03
Cr (µg/g)	13.02±1.10	34.17±0.81

The total number of herbaceous species was 23 at RS while CMA has 15 herbaceous species (Table 2). Importance value indices (IVI), which is the sum of relative frequency, relative density and relative dominance showed variation for the plant species at both areas. Among herbaceous species *A. paranychiodes, C. dactylon, T. purpurea* and *C. alata* showed high IVI at RS while, *S. cordifolia, C. rotundus, D. trifolium and A. paranychiodes* showed high IVI at CMA. The number of woody species was 22 at RS and 16 at CMA (Table 2). Tree density and canopy cover were higher at RS, compared to CMA. High IVI of *B. ceiba, B. lanzan, F. benghalensis, B. flabellifer* at RS and *B. monosperma, F. benghalensis, F. religiosa*, P.guajava at CMA were reported for woody species.

Table 2 Importance value index of herbaceous and woody vegetation at RS and CMA

Herbs	IVI		Trees	IVI	
	RS	CMA		RS	CMA
Solanum nigrum	7.6	0	*Ficus religiosa*	7.6	36.3
Eclipta alba	7.0	0	*Azadirechta indica*	7.0	15.9
Cassia alata	20.1	56.0	*Ficus benghalensis*	76.1	38.0
Amaranthus Spinosus	6.1	11.6	*Psidium guajava*	17.8	30.1
Osimum basilicum	6.1	4.6	*Acacia catechu*	10.7	12.5
Sida cordifolia	7.5	32.4	*Borassus flabellifer*	40.0	0
Boerahaavia diffusa	6.8	8.2	*Corymbia citriodora*	15.0	11.1
Tephrosia purpurea	28.3	0	*Aegle mermelos*	28.3	12.2
Achyranthus aspera	6.7	0	*Delonix regia*	6.7	0
Eragrostis cynosuroids	0	0	*Syzygium cuminii*	0	10.9
Solanum xanthocarpum	5.9	4.2	*Butea monosperma*	10.1	45.9
Sphaeanthus indicus	5.8	5.0	*Atrocarpous heterophyllus*	10.8	0
Digitaria sanguinalis	7.0	13.2	*Ficus racemosa*	20.2	10.6
Ageratum conyzoides	10.4	9.5	*Albizia lebbeck*	20.0	20.0
Alternanthera paranychiodes	63.6	27.3	*Bombax ceiba*	90.9	10.2
Chrysopogon aciculatus	7.1	0	*Holoptelea integrifolia*	7.1	10.3
Convolvulus alsinoides	6.1	0	*Alstonia scholaris*	6.1	0
Cynodon dactylon	45.0	41.0	*Buchanania lanzan*	86.0	0
Cyperus rotundus	7.6	30.9	*Adina Cardifolia*	38.5	10.8
Desmodium trifolium	8.7	28.8	*Ficus tomentosa*	37.5	0
Dichanthium annulatum	7.6	0	*Madhuca indica*	7.6	14.0
Evolvulus alsinoides	13.9	0	*Terminalia arjuna*	13.9	0
Parthinium hysterophorus	7.0	0	*Saccopetalum tomentosum*	7.0	10.6
Setaria glauca	0	15.1			

Prior to CCA, PCA was conducted to decide appropriate uncorrelated environmental variables (Table 5). The variables, which showed high loading values on particular component, were used as environmental variables. High loading values were fixed as having absolute values inside 10% of the highest loading value. PCA on air and soil analyses data gave three PCs with eigen values 3.50, 3.35 and 2.44 were extracted with 71.43% cumulative variance for coal mining areas. SO_2 and PM_{10} concentration in air and pH, SO_4-S and water holding capacity (WHC) of the soil were found to be the most pertinent environmental variables, suited on selection criteria (Table 3).

Table 3 Results of principal component analysis of air and soil parameters assessed at different sites

Parameters	RF1	RF2	RF3
SO_2	**0.736**	0.061	-0.093
NO_2	0.667	-0.009	-0.316
PM_{10}	**0.776**	0.449	-0.035
$PM_{2.5}$	0.717	0.394	0.086
PM_1	0.639	0.498	0.058
Soil pH	-0.218	-0.097	**0.865**
Electrical conductivity	0.121	-0.342	-0.214
Bulk density	0.044	0.674	-0.011
Porosity	-0.012	-0.512	0.213
Soil temp.	0.213	0.113	0.312
Soil moisture	-0.492	-0.61	0.522
Microbial biomass carbon	-0.131	0.103	-0.826
Microbial biomass N	0.132	0.453	-0.231
Total nitrogen	-0.542	-0.542	0.576
Available phosphorus	-0.514	-0.536	0.427
Soil - SO_4	0.271	**0.787**	-0.273
Water holding capacity	-0.23	**-0.831**	0.149
Eigen value	3.504	3.346	2.435
% Variance	26.957	25.736	18.733
Cumulative Variance	26.957	52.692	71.425

Within the CCA eigenvector analysis, we observed that most of the inertia was carried by the first axis. With the second axis, we obtained 82.2% and 79.1% of the total inertia for herbaceous and tree species, respectively. Therefore, the relationships between the species and the variables were analyzed by two-dimensional CCA map. The synthetic gradient extracted by CCA ordination diagram consists of the points showing species and classes for qualitative environmental variables, triangle showing sites and arrows for quantitative environmental variables (Figure 3). The total inertia (the summation of canonical and non-canonical eigenvalues) was 5.521 for herbaceous vegetation and 4.593 for woody layer. The eigenvalues for two axes were 0.026 and 0.011 for herbaceous vegetation and 0.027 and 0.026 for woody layer.

In the present study, *A. paronychioides* and *C. dactylon* were dominant species of the herbaceous community at both sites (Figure 3). *A. paronychioides* is not a native of the area, but become very widespread (Pandey et al., 2014b). High IVI of *C. dactylon* and *A. paronychioides* and suggested its growth under a broad range of environmental conditions. It has also been suggested that wide distribution of some species is a result of evolution rather than innate physiological tolerance and pollution level. The polluted sites, CMA was species poor compared to RS. *A. aspera*, *D. annulatum* and *E. alba* are most sensitive as these were present at RS and completely absent from CMA. *Setaria glauca* is polluphilic species as this was only present at CMA. *A. spinosus*, *B. diffusa*, *C. alata*, *C. rotundus*, *D. trifolium*, *D. sanguinalis*, *H. contortus and S. cordifolia* also showed an increasing trend of IVI as stress increases and showed lower IVI at RS compared to CMA, therefore are also tolerant for the study area. *A. scholaris*, *B. lanzan* and *F. tomentosa* are described as native species in the area (Bauri et al. 2013).Their lower IVI suggests their sensitivity to altered air and soil conditions. Species such as *F. beghalensis*, *F. religiosa*, *P. guajava*, showed high IVI at CMA and are resistant comparatively. *B. monosperma*, *F. benghalensis*, *F. religiosa* and *P. guajava* are the most dominant species at CMA. *A. scholaris*, *B. lanzan*, *D. regia* and *F. tomentosa* were absent at CMA and therefore they are sensitive to coal mining activities.

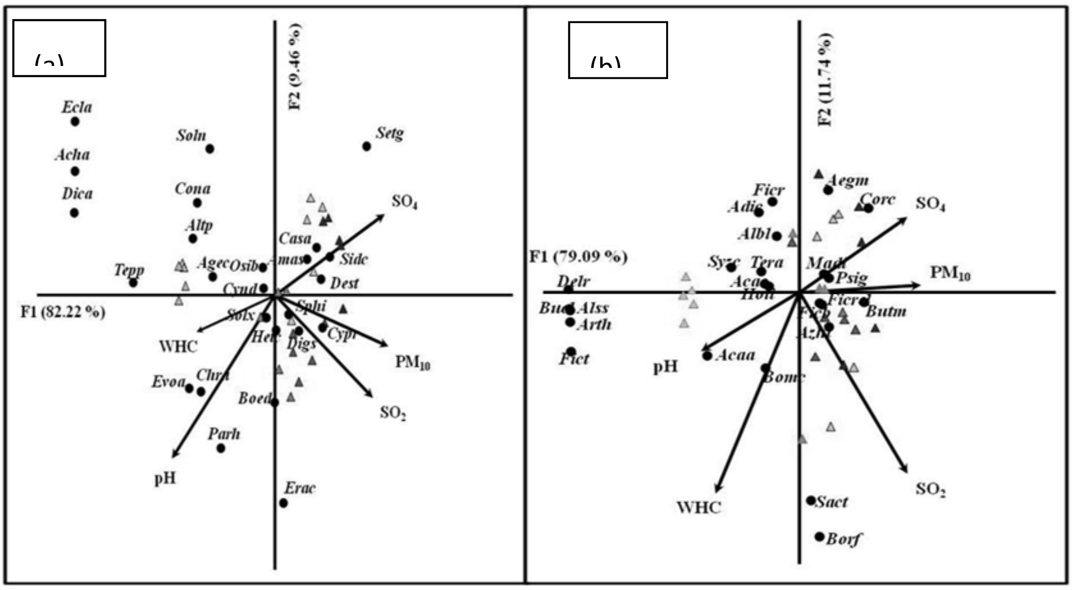

Figure 3 Ordination of the herbaceous (a) and woody species (b) species by canonical correspondence analysis. Aa: Achyranthes aspera ; Ac: Ageratum conyzoides; Ap: Alternanthera paronychioides; As: Amaranthus spinosus; Bod: Boerhaavia diffusa; Ca: Cassia alata; Cha: Chrysopogon aciculatus; Coa: Convolvulus alsinoides; Cd: Cynodon dactylon; Cr: Cyperus rotundus; Dt: Desmodium trifolium; Dia: Dichanthium annulatum; Ds: Digitaria sanguinalis; Ea: Eclipta alba; Ec: Eragrostis cynosuroides; Eva: Evolvulus alsinoides; Hc: Heteropogon contortus; Ob: Ocimum basilicum; Ph: Parthenium hysterophorus; Sg: Setaria glauca; Sc: Sida cordifolia; Solanum nigrum; Sn: Sx: Solanum xanthocarpum; Si: Sphaeranthus indicus; Tp: Tephrosia purpurea Aa: Acacia Arabica; Ac: Adina cordifolia; Ah: Artocarpus heterophyllus; Ai: Azadirachta indica; Al: Albizia lebbeck; Am: Aegle marmelos; As: Alstonia scholaris; Aca: Acacia catechu; Bc: Bombax ceiba; Bf: Borassus flabellifer; Bl: Buchanania lanzan; Bm: Butea monosperma; Cc: Corymbia citriodora; Dr: Delonix regia; Fb: Ficus benghalensis; Fra: Ficus racemosa; Fr: Ficus religiosa; Ft: Ficus tomentosa; Hi: Holoptelea integrifolia; Mi: Madhuca indica; Pg: Psidium guajava; Sc: Syzygium cuminii; St: Saccopetalum tomentosum; Ta: Terminalia arjuna

This result suggests that a large number of species acclimatize to stress conditions created due to coal mining related activities. The species susceptible to the air pollution and altered soil properties are removed and more tolerant species become prevalent (Wiens, 2016). Air pollutants and altered soil properties at CMA modified the response of the flora.

The relative significance of a particular parameter is interpreted in the CCA ordination diagramme by the length of their corresponding lines (Ter Braak, 1995). CCA analysis revealed that structure of herbaceous community was mainly driven by SO_4-S and soil pH, whereas woody layer was influenced by soil WHC and SO_2 concentration in the air. For herbaceous and woody layer, the first axis showed strong positive correlations with SO_4-S and PM_{10}. For herbaceous vegetation first axis showed strong negative correlation with WHC, while for woody vegetation, it showed strong negative correlation with soil pH (Figures 2). The second axis, for herbaceous vegetation showed strong negative correlation with pH and SO_2, whereas for woody vegetation second axis showed strong negative correlation with WHC and SO_2 (Figure 3).

S. glauca, *C. alata*, *S. cordifolia*, *D. trifolium* and *A. spinosus* are common, where SO_4-S concentration was high, with low soil pH and WHC (Figure 3). These species seem to be resistant to change in soil characteristics caused by coal mining activities, suggesting that response of these species are mainly depended on stress in soil. Species such as *C. rotundus*, *D. sanguinalis*, *H. contortus* and *S. indicus* are common at the sites where concentrations of PM_{10} and SO_2 were high, therefore these species are resistant to the air pollutants released by coal mining activities (Figure 3). *E. alba*, *A. aspera*, *D. annulatum* and *S. nigrum* are the sensitive species towards air pollutants released through coal mining activities. *E. alsinoides*, *P. hystrophorus* and *C. aciculatus* are common at the sites with high soil pH and WHC, and low SO_4-S and are also seemed to be sensitive species. In the ordination diagram of woody vegetation, *F. benghalensis*, *F. religiosa*, *B. monosperma*, and *P. guajava* showed positive correlations with positive side of first axis. The position of these species revealed their higher presence at the sites where SO_4-S, PM_{10} and SO_2 were high and thus are resistant towards stress condition caused by coal mining activities (Figure 3).

5 Conclusion

The changes in species diversity observed at mining areas indicated an increase in the proportion of resistant herbs and grasses showing a tendency towards a definite selection strategy of ecosystem in response to air pollution and altered soil characteristics. Principal component analysis and Canonical correspondence analysis revealed that structure of herbaceous community was mainly driven by soil pH and soil sulphate, whereas woody layer community was influenced by sulphur dioxide in ambient air, water holding capacity of soil. Among woody species *Ficus religiosa, Psidium guajava, Butea monosperma, Ficus benghalesis* are the tolerant while *Sphaeanthus indicus, Solanum xanthocarpum, Digitaria sanguinalis and Cyperus rotundus* are tolerant herbaceous species in coal mining affected environment so these native plantation can be used as a key to successful rehabilitation after closing of mines.

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Use of Biocrusts Forming Cyanobacteria to Promote Plant Establishment and to Improve Soil Quality for Mine Rehabilitation

C Ortiz *University of Santiago de Chile, Chile*

D Barros *University of Santiago de Chile, Chile*

J Bolton *University of Santiago de Chile, Chile*

M Wilkens *University of Santiago de Chile, Chile*

Abstract

Mining activities provoke degradation of land that requires to be rehabilitated after the mining operations have stopped, starting with an improvement in the quality of soils. Biocrusts (BC) are biotic communities formed after cyanobacteria have colonized a degraded site which provide nutrients and favour ecological successions. This work shows the isolation of BC-forming cyanobacteria from three geographical zones of Chile, their effect on mining polluted soil quality and on the germination and growth of two species of grasses. The soil samples presented a differential microbial diversity. Bacterial metagenomic analysis showed that cyanobacteria represent up to 91 % of the bacteria present in the soil samples, mostly represented by Leptolyngbya sp., Microcoleus sp., and Trichocoleus sp. Enriched cyanobacterial cultures were inoculated on substrates composed by a mix of soil and tailing sands or tailing sands alone, and the growth of the microorganisms on substrates was observed by confocal microscopy. The results showed that cultures of native cyanobacteria control tailing sands dust emission, increase organic matter content, alleviate the electrical conductivity of the substrate, and favour the establishment of two plant species. BSC-forming cyanobacteria inoculation might be used as a first step for a successful revegetation in mine sites rehabilitation.

Keywords: *biocrusts, cyanobacteria, dust emission, rehabilitation*

1 Introduction

Biological Soil Crusts (BSCs) are a complex and intimate association between soil particles and microorganisms such as algae, lichens, mosses and fungi and that are promoted by the establishment of cyanobacteria (Belnap & Lange, 2003). These microorganisms associate with soil particles conferring to the substrate cohesion and stability and also improve the soil fertility playing an important role in the germination, growth and survival of native species of plants (Zaady et al. 1997). The cohesive characteristics of BSCs in arid and semiarid lands are provided by the polysaccharides produced by the cyanobacteria that allow the chelation and bioavailability of nutrients to other microorganisms (García-Pichel & López, 2001; Lin et al. 2013). Meyer et al (2011) used lyophilized cultures of Sporosarcina pasteurii to develop a crust-like layer on the surface of eroded soils observing a significant reduction in mass loss. In a tailing dam of the Valenciana gold mine in Mexico, the use of biological crusts demonstrated to be useful to initiate the rehabilitation of the site (García-Meza, 2008). A study by Bowker et al (2005) investigated the impact of inoculation of native strains of cyanobacteria on the physical characteristics of poorly aggregated soils in South Africa, finding that inoculated samples improved some physicochemical characteristics. On desert soils in China it has been demonstrated that there is a positive correlation between the formation of biological crusts, the improvement in the microstructure of the treated soil and the emergence of cryptogamic plant species (Li et al., 2002). The interest in the study of biological crusts and their functional relationship with soils of specific environments has stimulated in Europe the formation of a research initiative called Soil Crust

International (SCIN) (Büdel et al., 2014). The formation of BSCs needs pioneer species like soil cyanobacteria, which supply nutrients to the soil allowing the colonization by other microbial species and by plants in what is called ecological succession (Hu et al., 2002). The polysaccharides production by the BSCs forming cyanobacteria improves the quality of the substrate and stabilizes the particulate material of the substrate (Colica et al., 2014). Considering the benefits that cyanobacteria confer to soils, we evaluated the effect of inoculating native cyanobacteria on a soil mixed with tailing sands, on the quality of the soil mix and on the germination and growth of Polypogon australis and Lolium perenne. We propose that BSCs forming cyanobacteria can be used in the first stages of mining sites rehabilitation, to improve the quality of soils impacted by mining activities and consequently favors the establishment of plant species.

2 Methodology

2.1 Characterization and culture of BSCs-forming cyanobacteria

Soil samples for the isolation of the cyanobacteria were taken in three distant geographical sites of Chile: the Fifteenth Region of Arica and Parinacota (18°28'30''S, 70°18'52''W), the Fourth Region of Coquimbo (29°54´28´´S 71°15´15´´W) and the Eleventh Region of Aysen (45°34´12´´S 72°03´58´´W). Discrete subsamples from adjacent sampling points, evenly spaced, and composited laterally, were collected in an area of similar size and shape, except where it was not geographically possible. A maximum of six discrete constituents were included in each composite sample. Each discrete subsample was thoroughly homogenized before stored in sterile bags and maintained at 4°C for further analysis. Extraction of DNA was performed with the FavorPrep™ Soil DNA Isolation Minikit. DNA samples were maintained at -20°C. Quantification was performed in a multi-detector microplate reader Synergy™ HT of Biotek instruments measuring absorbance at 260 and 280 nm. Massive sequencing of 16S rRNA was performed by Macrogen using the Illumina MiSeq platform. The results obtained were processed with the Nephele metagenomic analysis tool (https://nephele.niaid.nih.gov/#home) using Qiime software. A portion of the soil samples was cultured in order to obtain axenic cultures of cyanobacteria. For this purpose, a BG-11 medium growth was used (mix of salts and micronutrients). DNA was extracted from positive cultures and 16S rDNA specific molecular markers were used to identify the different isolates. From the identified cultures, a mix of the species *Leptolyngya boryana* and *Triccholeum desertorum* was prepared. The culture was incubated in a shaker at 120 rpm for 2 weeks at 25°C with a photoperiod of 12 h light:12 h darkness and used for the inoculation experiments.

2.1.1 Colonization of cyanobacteria

The cyanobacterial cultures were inoculated on a soil mixture with different proportions of tailing sands (0, 25, 50, 75 and 100%). All mixtures were sieved through a 1000 µm mesh, autoclaved and dried at 100°C for 24 h. For the inoculations, 2 mL of cyanobacterial culture were poured on top of the mixed soils. The establishment of the cyanobacteria in the substrates was qualitatively observed by confocal microscopy by autofluorescence of chlorophyll (Solé, 2001). Three different samples of inoculated substrate were placed on a microscope slide that was sealed with a coverslip and adhesive tape. The sample was observed on a Zeiss LSM 510 Axiovert 100M laser scanning confocal microscope, exciting the sample at 488 nm with an Argon laser and detecting the fluorescence with a 505-550 nm filter.

2.1.2 Wind erosion assays

The tests were carried out in a wind tunnel, according to Valenzuela et al. (2014) and following the standards of the Chilean Regulation for Dust Suppressant Quality Control (NCh3266-2012). The test cells were prepared by filling metal trays with tailing sands at loose bulk density, using a funnel to allow the free and constant fall of the sand until full capacity of the mold. Finally, the surface was leveled to leave it uniform. The average volume of the test cells was 3,804 cm^3. The test cells were left at room temperature for 12 hours before they were irrigated either with the cyanobacterial culture, with the nutrient solution or water by spraying a total volume of 150 cm^3 on a surface of 726 cm^2 at a rate of 2,06 L/m^2. After the irrigation, the test cells were installed in the adjustable flat support of the wind tunnel. The inclination for the cells was between 9° and

10° with respect to the horizontal. Once a test cell was installed in the support, the trial began applying wind at a speed of 12 m/s for 6 h. Each of the trials performed was recorded photographically every 5 min until completing 20 min, then at the first hour and then every hour until completing 6 hours of trial.

2.2 Plant growth on soil inoculated with cyanobacteria

Three groups of 70 wells of plastic plant trays were prepared with autoclaved soil:tailing sands mixture in different proportions (0, 15, 25, 50, 75 and 100 %). The composition of the tailing sands obtained from a facility located in the Second Region of Chile and used in the experiments is shown in Table 1. All the experiments were performed under greenhouse conditions with an average temperature of 27°C.

Table 1 Chemical parameters of pure tailing sand used in the experiments

pH	EC	OM	$N\text{-}NO_3$	Olsen-P	Cd	Cu	Mn	Ni	Pb	Zn
	$mScm^{-1}$	%	$mgKg^{-1}$	$mgKg^{-1}$	$mgKg^{-1}$	$mgKg^{-1}$	$mgKg^{-1}$	$mgKg^{-1}$	$mgKg^{-1}$	$mgKg^{-1}$
8.3	45.6	1.0	216.5	21.7	2.4	1359.2	277.1	33.5	11.7	52.9

EC: electrical conductivity; (OM): organic matter, $N\text{-}NO_3$: total nitrogen, Olsen-P: total phosphorus

One third of the wells containing the soil mix were inoculated with 2 mL of the cyanobacteria culture and the surface was irrigated by spraying water daily for 4 weeks. At the end of this period, *Polypogon australis* or *Lollium perenne* seeds were germinated in each well was. Three experimental groups were prepared: Cb, wells that were inoculated with cyanobacteria; Bg, wells irrigated with 2 mL of BG-11 medium without cyanobacteria; and Ct, control wells without cyanobacteria and irrigated with water. The monitoring of germination and plant growth was performed up to four months post-germination for *P. australis* and during 20 days for *L. perenne*.

2.2.1 Soil characterization

To measure water content, a surface sample was weighed and then dried at 50°C in a Drying Oven DHG-9053, and then the mass was determined again. To measure pH and electrical conductivity, the dried sample was mixed with water in a 1:5 soil:water ratio, and shaken for 1 hour. The mixture was allowed to settle and the pH was measured with an Oyster® pp-201 pH-meter and the electrical conductivity was determined with a CDM92 Radiometer instrument. For the measurement of organic matter, the Walkley & Black (1947) colorimetric determination was used.

2.2.1 Seed germination and plant growth

After sowing the seeds, cumulative germination on experimental soils was registered. At the end of the experiment, the total chlorophyll and the total protein content were determined in *P. australis* plants as a measure of the physiological condition of the plants. The chlorophyll content was determined by spectrophotometric analysis according to Lichtenthaler & Wellburn (1983). The protein content was measured according to Bradford et al. (1976). When indicated, the data were analyzed using a 2-way ANOVA with Dunnett's multiple comparison post-test.

3 Results

3.1 Characterization of BSCs-forming cyanobacteria

The soils of the Fourth Region of Coquimbo presented a greater microbial diversity with respect to the samples of environmentally extreme conditions Regions, Arica and Parinacota (desert climate with low rainfall and daily temperature fluctuation among 15-30°C) and Aysen (rainy or steep oceanic climate, with winter temperatures between -19°C and -37°C and rainfall between 3,000 to 4,000 mm water/year). The bacterial metagenomic analysis performed showed that between 55 and 91% of the bacterial genera present in the Coquimbo Region samples correspond to cyanobacteria. In parallel, the soil samples were cultured in

BG-11 media at a light intensity of 3,000 lux, agitation of 120 r.p.m., temperature between 25°C and 35°C, photoperiod of 14/10 h and humidity between 40% and 60%. The identification of the microbial cultures is shown in Table 2.

Table 2 Characterization of cyanobacterial cultures isolated from environmental samples.

Sample	Taxonomic classification
1	Trichormus sp.
2	Leptolyngbya badia
3	Microcoleus sp.
4	Microcoleus steenstrupii
5	Trichocoleus sociatus
6	Trichocoleus desertorum + Leptolyngbya boryana
7	Leptolyngbya sp.
8	Nostocales cyanobacterium
9	Planktothrix agardhii

After the inoculation, a structural modification of the surface of the mixtures was observed, showing a crust formation on all the substrates. The samples with higher percentages of tailings (75 to 100%) showed an agglomeration of the particles and a change of color of the surface. The growth of cyanobacterial filaments was observed in all samples, including the substrates composed solely of tailing sands (Figure 1).

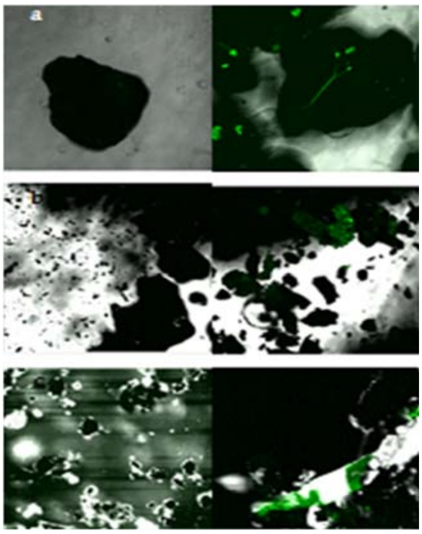

Figure 1 Confocal microscopy of cyanobacterial filaments. a) Sample of soil mixture without tailings sand; b) sample of 50% soil mixture and 50% tailings sand; c) sample of 100% tailings sand. All samples were inoculated with 2 mL of cyanobacterial culture (right row) or with water (left row)

The wind erosion assays showed that the test cells without irrigation were completely emptied in 20 minutes (Figure 2), the control sample watered only with culture medium was emptied in 3 hours (Figure 3), and the test cells irrigated with cyanobacteria culture remained without loss of mass up to 6 hours of assay (Figure 4).

Figure 2 Wind tunnel test of tailing sands without treatment. (a) Time 0 (b) 5 min after applying wind at a speed of 12 m/s; (c) 20 min after applying wind at a speed of 12 m/s.

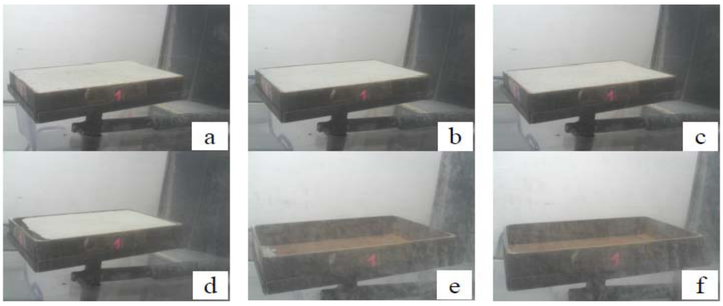

Figure 3 **Wind tunnel test of tailing sands irrigated with culture media at different times after applying wind at a speed of 12 m/s: (a) Time 0; (b) 10 min; (c) 20 min; (d) 1 h; (e) 2 h; and (f) 3 h.**

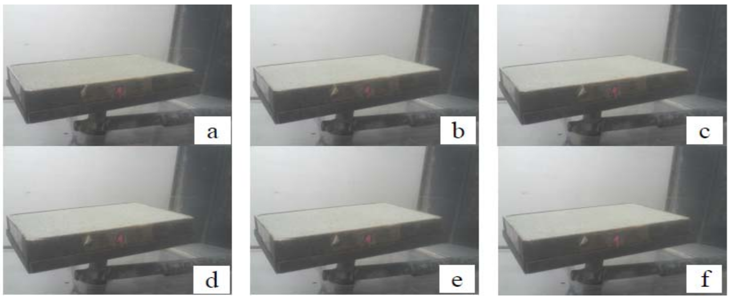

Figure 4 **Wind tunnel test of tailing sands irrigated with cyanobacterial culture at different times after applying wind at a speed of 12 m/s: (a) Time 0; (b) 10 min; (c) 20 min; (d) 1 h; (e) 3 h; and (f) 6 h.**

3.2 Effect of cyanobacteria on soil quality and the germination of plants

The results showed that the cumulative germination of both plant species was significantly higher in the presence of the cyanobacteria than in the controls with bacterial culture media or water (Figure 5) showing a stimulating effect on the growth of the leaves of the plants compared to the controls (Figure 6). The chlorophyll and protein content measured in P. australis plants after four months in the experimental soils was significantly higher in soils inoculated with the cyanobacteria compared with the control non-inoculated and irrigated with water (Figure 7).

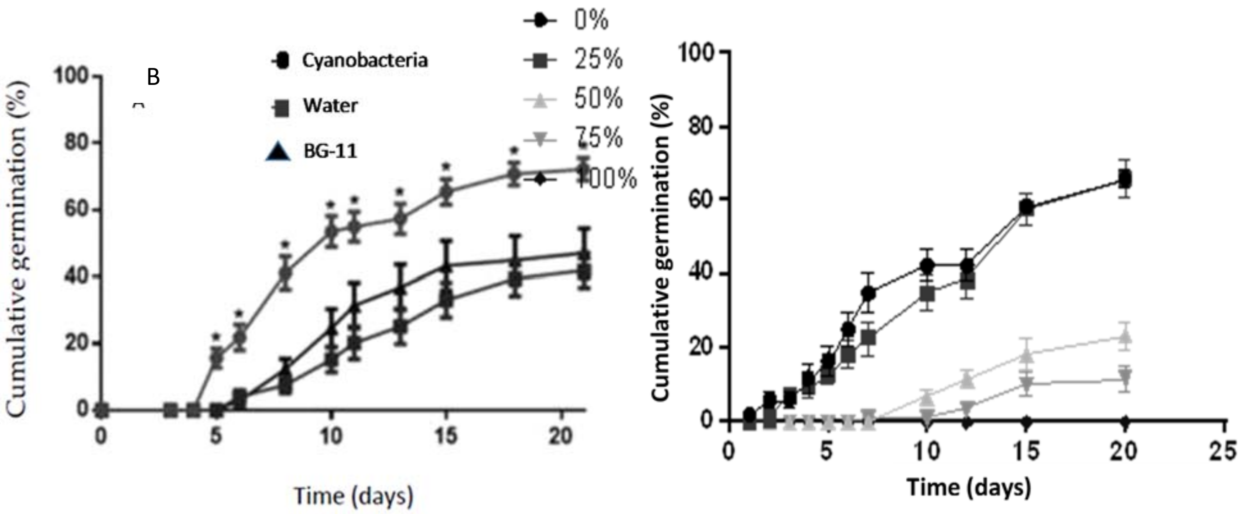

Figure 5 **Cumulative germination of plants on experimental soils inoculated with cyanobacteria. A) *P. australis* on soil mixed with 15% tailing sands and watered with a cyanobacteria culture or water or BG-11 media (insert in panel); B) *L. perenne* on soil mixed with different proportions of tailing sands (insert in panel). When present, asterisks indicate significant differences among the data.**

Figure 6 ***P. australis*** **plants germinated and grown on soil mixed with 15% tailing sands during four months. A) Soil inoculated with cyanobacteria; B) Soil irrigated with BG-11 culture media; C) Soil irrigated with water.**

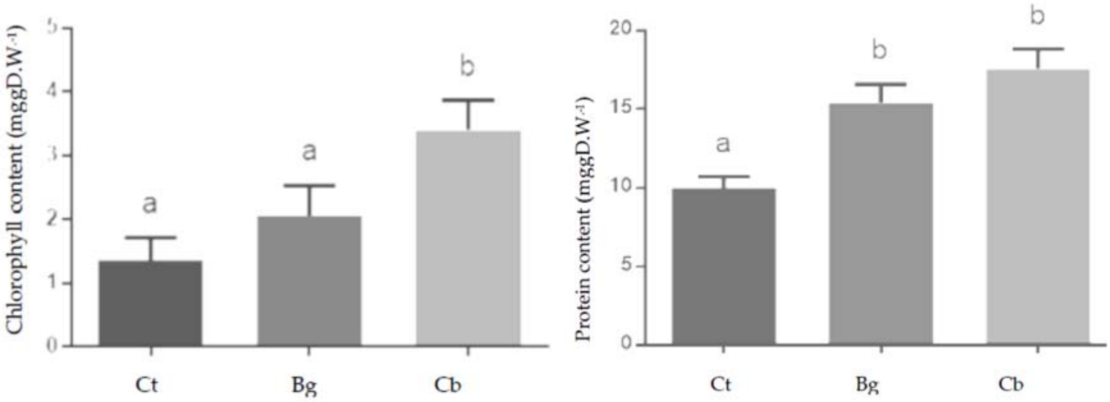

Figure 7 **Chlorophyll and protein content of** ***P. australis*** **plants germinated and grown on soil mixed with 15% tailing sands during four months. A) Chlorophyll content; B) Protein content. (Cb) soil inoculated with cyanobacteria; (Bg) soil treated with culture medium; (Ct) water irrigated control soil. Different letters on top of the bars indicate significant differences. The results show the average of triplicate determinations +/- SD for each point.**

The water content and the pH did not show significant changes among the three different experimental soil conditions (Table 3). The Electrical Conductivity (EC) was significantly higher when the soil was irrigated with the culture media, probably due to the mix of salts present in the nutrient media. However, the cyanobateria inoculation decreased the EC, with values lower than in the control soil irrigated with water. Cyanobacteria are able to retain the salts present in the soil, by the exchange of inorganic cations between the bacteria and their environment, and also by the releasing of compounds that retain ions present in the soil (Pade, 2014). It is noteworthy that when BG-11 culture media was added to the soil the EC increased twice, which is an effect of a media that contains salts like sodium nitrate 0.15 %. Therefore, the presence of cyanobacteria not only decreased the salinity present in the soil containing tailing sands, but also decreased the salinity added to the soil by the nutrient medium in which they grow.

Table 3 **Physicochemical parameters of experimental soils. The determination was performed after four month at different initial conditions. (Ct) water irrigated control soil; (Bg) soil treated with culture medium; (Cb) soil inoculated with cyanobacteria.**

Soil sample	Water content %	pH	Electrical conductivity $mScm^{-1}$	Organic matter %
Ct	24.58 ± 1.41	7.59 ± 0.05	1.90 ± 0.09[a]	3.50 ± 0.05 [a]
Bg	25.57 ± 1.10	7.35 ± 0.15	3.73 ± 0.21[b]	3.44 ± 0.20 [a]
Cb	27.37 ± 0.96	7.74 ± 0.08	1.22 ± 0.05[c]	4.33 ± 0.07[b]

Different letters indicate significant differences. The results show the average of triplicate +/- SD.

The Organic Matter (OM) content in the soils inoculated with the bacteria was significantly higher than in the non-inoculated soils, showing that in four months, there is a supply of organic matter to the soils by the cyanobacteria. This can be a result of the carbon fixation by photosynthesis and/or the production of exopolysaccharides released by the microorganisms.

4 Conclusion

The inoculation with BSCs forming cyanobacteria of soil mixed with tailing sands improved the cumulative germination and growth of two grasses. The chlorophyll and protein content in one of the plant species grown during four months under the treated soils, is higher than plants in non-inoculated experimental soils. The organic matter content increased and the electrical conductivity decreased after the inoculation of the soil with the cyanobacteria. Cyanobacteria improve the physicochemical condition of the substrate and facilitate the establishment of vascular plant species. BSCs-forming cyanobacteria inoculation can be used on mining polluted soil to favor the establishment of plant species for rehabilitation purposes.

Acknowledgement

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10. Aftercare, marketing, reorganization of land, geotourism

Researches Regarding the Population Exigencies in the Conditions of Recovery and Reuse of the Remaining Gaps of the Quarries

IM Apostu *University of Petroșani, Romania*

M Lazar *University of Petroșani, Romania*

Abstract

Open-pit mining exploitation involves the radical change of land morphology and geomorphology, primarily as a result of the excavation and the development of deep open-pits. The remaining gaps resulting after the cessation of open-pit mining exploitation have a major negative impact on the environment. The recovery of the remaining gaps in former quarries and implicitly of the surrounding degraded lands represents an extremely important stage for the sustainable development of the environment, economy and society. This stage ensures the reduction of the negative impact of mining operations, which can not be avoided during exploitation but can be offset by the application of practices aimed at recovering the remaining gaps, degraded lands and their reintegration into the landscape. Remaining gaps of quarries can be reused in different directions, with major benefits regardless of the final form of reuse. The establishment of the optimal direction and the final form of reuse of the remaining gaps can be achieved by applying methods or methodologies that take into account a number of criteria (site conditions, morphology, hydrology, hydrogeology, climate, stability conditions etc.) which allow exclusion of inappropriate reuse forms. Among the most important criteria for determining the optimal form of reuse of remaining gaps is the criterion of population exigencies. Assessing the needs of the population can be done in the form of surveys, interviews, opinion polls (online or printed forms), etc. The aim is to meet the needs of the population, taking into account the opportunities offered by the local conditions and the sustainable development strategy of the region. This paper presents the partial results of a survey which follows the requirements of the resident population of the Rovinari Mining Basin from Romania. Early knowledge of the final form of reuse of remaining gaps allows accomplishing the appropriate modeling, rehabilitation and restoration works and reintegration of the degraded lands into the landscape and into the ecological or economic circuit, in the shortest possible time.

Keywords: *former quarries, population demands, reconstruction, remaining gaps, reuse*

1 Introduction

The decision-making process regarding on the development of a mining area after the cessation of exploitation is a major challenge and responsibility for all decision-makers involved. The planning and use of degraded land of open-pit mining exploitation must take into account a whole range of requirements, ranging from the natural features of the site to the social and cultural structure and exigencies of local communities. (Lazăr, 2016)

Proper rehabilitation of areas affected by open-pit mining activities must be clear (naturalistic, recreational, industrial etc.). Multiple reuse of mining areas is a relatively new practice and involves overlapping the various uses and functions of the land, as long as they not only do not interfere with each other but also complement themselves. (Lazăr, 2016)

An integrated approach of the planning and use of degraded land presumes involving all stakeholders in decision-making process on the future of the land. It is necessary to identify and establish a land-use technically, socially and economically acceptable and ecologically non-degrading. Decisions regarding the land use must be implemented taking into account the physical, biological, aesthetic or economic requirements of those who will use them in the future. (Lazăr, 2010)

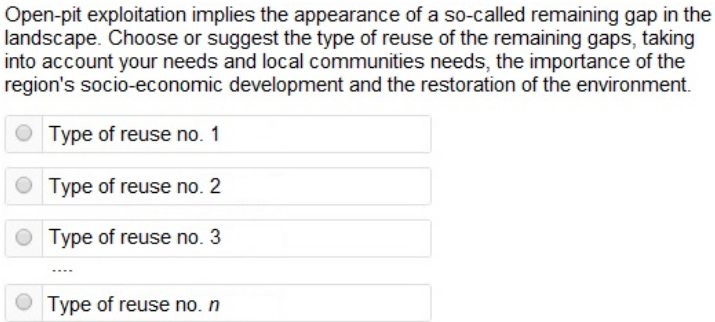
According to the Rio Declaration, people have the right to a healthy and productive life, in harmony with nature. This is reflected in the principle of respecting the requirements of the population, one of the fundamental principles of ecological planning. (Lazăr, 2010)

2 Methodology for assessing the population requirements

Before undertaking any operation, it is necessary to draw up a list of exigencies and priorities for the sustainable development of communities. These practices favor the involvement of the population and lead to its effective participation in the planning process of the territory. The needs of local communities reflect individual needs and refer to housing, premises, productive areas, green areas, hygiene needs, mobility or resettlement in the territory, the quality of the environment, services and the complex image of the landscape or their requirements (Lazăr, 2010).

This aims to follow the requirements and needs of the resident population regarding the type of reuse of a given remaining gap, taking into account the needs of the individual and the local communities, the importance of the socio-economic development of the region and the restoration of the environment, all these aspects being seen from the point of view of the respondent. (Apostu, 2018)

Evaluation of public opinion can be done on the basis of questionnaires, opinion poll, surveys, interviews or other research methods, conducted locally or regionally, depending on the area of influence (Figure 1). Such surveys can also be carried out at national level, but more concrete data provides when conducted at the level of the studied region.


Open-pit exploitation implies the appearance of a so-called remaining gap in the landscape. Choose or suggest the type of reuse of the remaining gaps, taking into account your needs and local communities needs, the importance of the region's socio-economic development and the restoration of the environment.

- Type of reuse no. 1
- Type of reuse no. 2
- Type of reuse no. 3
- ....
- Type of reuse no. *n*

Figure 1 Example of opinion poll

Prior to requesting the opinion of local communities, it is important to study the possibilities of reuse and to determine the opportune variants. These variants can then be subjected to public opinion, avoiding the occurrence of errors, such as obtaining answers that make inappropriate reuse and impossible to achieve depending on the conditions.

There are many directions for reuse of remaining gap of former quarries, but the optimal choice of reuse type must take into account many aspects so as to achieve the objectives of sustainable development at regional level, namely environmental protection, security and safety, health and well-being human communities and economic and social development.

Remaining gaps of former quarries can be filled with water, thus taking up various functions, from industrial to recreational, or can be used to store different types of waste, from house hold to industrial. (Lazăr, 2010) These are the most common types of reuse of the remaining gaps, but depending on their characteristics and opportunities, the remaining gaps are also used in many other forms such as: silviculture, pomiculture, museums or other cultural attractions, circuits for extreme and off-road sports, film or music scenes etc. Also, a remaining gap offers multiple possibilities of combining the uses, this practice having particular cumulative advantages. (Figure 2)

Quarry lakes	Waste deposits	Others
☐ pisciculture	☐ household	☐ silviculture
☐ lake for recreation	☐ industrial	☐ pomiculture
☐ water tank for irrigation		☐ museums or other cultural attractions
☐ potable/industrial water tank		☐ circuits for extreme and off-road sports
☐ retention basin for rainwaters, torrents etc.		☐ film or music scenes etc.

Figure 2 Reuse types of the remaining gaps

Taking into account the fact that there are many variants of reuse of the remaining gaps, in order to obtain more precise results, it is recommended to apply the following methodology in order to establish a hierarchy of opportunities for reuse according to the requirements of the population:

- establishing the optimal reuse variants and their number (n);
- conducting the opinion poll;
- questioning the local communities in the studied region regarding the type of reuse of the remaining gap after its recovery;
- analysis of the answers obtained after conducting the opinion poll;
- ranking of population requirements (establishing a hierarchy). (Apostu, 2018)

When pursuing the position of a certain type of reuse in the hierarchy of population requirements, for which it is desired to establish an appropriate score for the assessment of the reuse opportunity (e.g. the opportunity of flooding of the reamining gap, the opportunity of building of a waste deposit in the remaining gap, the opportunity of cultivation of fruit trees etc.) of a remaining gap according to an established evaluation scale (evaluation intervals) at a certain time, the methodology described below will be followed.

The score always varies between the limit values of the evaluation scale established at a certain time, the lower limit describing the inopportunity of reuse for that purpose and the upper limit describing the major opportunity of reuse for the desired purpose.

Regardless of the number of proposed reuse variants, there are 3 situations:

1. the analyzed type of reuse occupies the first position in the hierarchy of the population requirements - in this situation, for evaluation, the remaining gap will receive the maximum score (the upper limit of the evaluation scale/interval).
2. the analyzed type of reuse occupies the last position in the hierarchy of the population requirements - in this situation, for evaluation, the remaining gap will receive the minimum score (the lower limit of the evaluation scale/interval).
3. the analyzed type of reuse s between the first and the last position in the hierarchy of the population requirements - in this situation, to determine the score and the opportunity of the reuse, the following method will apply:
   - establishing the position of the analyzed reuse variant in the hierarchy of the population's requirements (pvr).

   determination of the value of a constant, k, (1):

$$k = \frac{P_{max}}{n-1} \tag{1}$$

where:

P_{max} - maximum value of the evaluation scale (or the upper limit of the evaluation scale);

n - the number of the optimal reuse variants offered in the questionnaire;

- the final score will be determined by applying the following calculation relation (2):

$$P_f = (n - p_{vr}) * k \tag{2}$$

where:

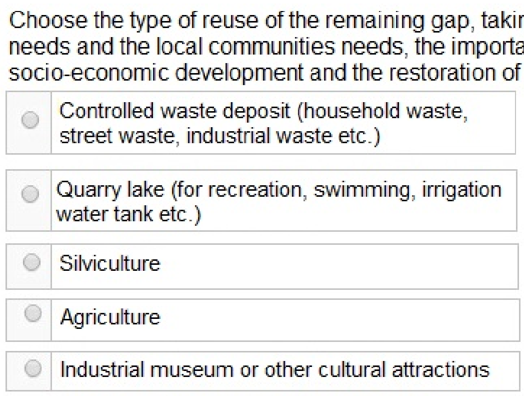
p_{vr} - the position of the analyzed reuse variant in the hierarchy of the population's requirements regarding the reuse of the remaining gap;

P_f - the final score, which can be used to evaluate the opportunity of reuse of the remaining gap in a certain direction opportunity (e.g. the opportunity of flooding of the reamining gap, the opportunity of building of a waste deposit in the remaining gap, the opportunity of cultivation of fruit trees etc.) (Apostu, 2018).

3 Assessment of population requirements regarding the reuse types of the remaining gaps and the opportunity of flooding - Case study: Rovinari Mining Basin

The assessment of the population's requirements regarding the reuse of the remaining gaps and the opportunity of flooding of the remaining gaps from the Rovinari Mining Basin was carried out taking into account the partial results obtained by conducting an online opinion poll, at regional level, on a number of 109 persons. The questionnaire includes 5 questions regarding the choice of reuse type of the remaining gaps from the Rovinari Mining Basin, taking into account the needs of the individual and the local communities, the importance of the socio-economic development of the region and the restoration of the environment, all of these aspects beeing seen fromthe respondent's point of view. (Apostu, 2018)

In order to choose the type of reuse of the remaining gaps from the 5 mining perimeters in the Rovinari Mining Basin, five options were offered: waste deposit, quarry lake, agriculture, silviculture, or industrial museum or other cultural attractions (Figure 3). The response variants were determined by studies, analyzes and documentation at Rovinari Mining Basin level regarding the geological and geomorphological, hydrological and hydrogeological, climatical conditions, the stability of the permanent slopes of the remaining gaps, the use of adjacent lands and the regional development strategy. (Apostu, 2018)


Choose the type of reuse of the remaining gap, taking into account your needs and the local communities needs, the importance of the region's socio-economic development and the restoration of the environment.

- Controlled waste deposit (household waste, street waste, industrial waste etc.)
- Quarry lake (for recreation, swimming, irrigation water tank etc.)
- Silviculture
- Agriculture
- Industrial museum or other cultural attractions

Figure 3 Model of the questionnaire

The responses were analyzed and the following observations were made:

- the respondents had different opinions on the type of reuse of the degraded land by the open-pit mining exploitations from the Rovinari Mining Basin;
- the hierarchy of the population's requirements on the type of reuse of the remaining gaps from Rovinari Mining Basin was realized and the results were centralized in Tables 1-5;

Table 1 The hierarchy of population requirements regarding the reuse type of the remaining gap of the Tismana quarry

Rank	Type of reuse	%
1	Quarry lake (for recreation, swimming, irrigation water tank etc.)	61,5
2	Silviculture	23,9
3	Industrial museum or other cultural attractions	7,3
4	Agriculture	4,6
5	Controlled waste deposit (household waste, street waste, industrial waste etc.)	2,8

Table 2 The hierarchy of population requirements regarding the reuse type of the remaining gap of the Rovinari quarry

Rank	Type of reuse	%
1	Controlled waste deposit (household waste, street waste, industrial waste etc.)	71,6
2	Silviculture	16,5
3	Quarry lake (for recreation, swimming, irrigation water tank etc.)	6,4
4	Industrial museum or other cultural attractions	5,5
5	Agriculture	0

Table 3 The hierarchy of population requirements regarding the reuse type of the remaining gap of the Pinoasa quarry

Rank	Type of reuse	%
1	Silviculture	80,7
2	Controlled waste deposit (household waste, street waste, industrial waste etc.)	8,3
3	Agriculture	4,6
4	Quarry lake (for recreation, swimming, irrigation water tank etc.)	3,7
5	Industrial museum or other cultural attractions	2,8

Table 4 The hierarchy of population requirements regarding the reuse type of the remaining gap of the Roșia de Jiu quarry

Rank	Type of reuse	%
1	Industrial museum or other cultural attractions	44
2	Silviculture	23,9
3	Quarry lake (for recreation, swimming, irrigation water tank etc.)	14,7
4	Agriculture	13,8
5	Controlled waste deposit (household waste, street waste, industrial waste etc.)	3,7

Table 5 The hierarchy of population requirements regarding the reuse type of the remaining gap of the North Peșteana quarry

Rank	Type of reuse	%
1	Quarry lake (for recreation, swimming, irrigation water tank etc.)	74,3
2	Silviculture	10,1
3	Agriculture	6,4
	Industrial museum or other cultural attractions	
4	Controlled waste deposit (household waste, street waste, industrial waste etc.)	2,8

- according to the recorded answers, the population believes that for the sustainable development of the region, after the cessation of the lignite exploitation activities, the following directions of reuse of the remaining gaps of the former quarries from Rovinari Mining Basin correspond best to the interests pursued:
  - for the Tismana mining perimeter - 61.5% of the respondents chose the option "Quarry lake (for recreation, swimming, irrigation water tank etc.)";
  - for the Rovinari mining perimeter - 71.6% of the respondents chose the option "Controlled waste deposit (household waste, street waste, industrial waste etc.)";
  - for the Pinoasa mining perimeter - in the proportion of 80.7%, the respondents chose "Silviculture";
  - for Roşia de Jiu mining perimeter - 44% of the respondents chose "Industrial Museum or other cultural attractions";
  - for the North Peșteana mining perimeter - 74.3% of the respondents chose the option "Quarry lake (for recreation, swimming, irrigation water tank etc.) ". (Apostu, 2018)

At the level of the Rovinari Mining Basin, an assessment study was carried out on the opportunity of flooding of the remaining gaps of former quarries.

Depending on the type of reuse that interests in the conditions of assessment of the opportunity of flooding of the remaining gap, namely *"quarry lake (for recreation, swimming, irrigation water tank etc.)"* and the position of this variant in the hierarchy of the population's requirements (the position of the *"quarry lake"* variant is highlighted in Tables 1 - 5 on orange background), the opportunity of flooding of the remaining gaps from Rovinari Mining Basin was assessed. For the final assessment, taking into account the requirements of the population, there were established intervals with values ranging from 0 to 3, 0 showing the inopportunity of flooding, and 3 the high opportunity of flooding of the remaining gaps, as follows:

- [0 ÷ 0,75] - inopportunity of flooding;
- (0,75 ÷ 1,5] - low opportunity of flooding;
- (1,5 ÷ 2,25] - medium opportunity of flooding;
- (2,25 ÷ 3] - high opportunity of flooding.

The final score was calculated based on the (1) and (2) calculation relationships and the results are shown in Table 6.

Table 6 **Assessment of the opportunity of flooding of the remaining gaps of former quarries from Rovinari Mining Basin** (Apostu, 2018)

Mining perimeter	Number of reuse variants, n	The position of "quarry lake" variant in hierarchy, p_{vr}	Constant, k	Score, P_f
Tismana		1		3
Rovinari		3		1,5
Pinoasa	5	4	0,75	0,75
Roșia de Jiu		3		1,5
North Peșteana		1		3

According to the final score that gives details about the opportunity of flooding of the remaining gaps of the quarries from Rovinari Mining Basin, results that: the remaining gaps of the Tismana and the North Peșteana quarries present a high opportunity of flooding, Rovinari and Roşia de Jiu presents a low opportunity of flooding and Pinoasa shows inopportunity of flooding.

These results were observed at Rovinari Mining Basin. Approximately 70% of respondents live in Rovinari city or its surroundings (surrounding villages). The other 30% of respondents know the area and the situation of Rovinari Mining Basin, so their responses have also been taken into account.

4 Conclusion

Population is one of the most important decision-making factors when it comes to the planning and reuse of areas affected by mining. Knowing and respecting, as far as possible, the needs and demands of the population regarding the direction of reuse of degraded land ensures a sustainable future development of the region and numerous social, economic, cultural, ecological benefits.

According to the results of the opinion poll onthe population exigencies regarding the choice of the type of reuse of the remaining gaps from Rovinari Mining Basin, most of the population wants the remaining gaps of the Tismana and North Peșteana quarries to be reused as quarry lakes, Rovinari as a waste deposit, Pinoasa for silviculture, and Roşia de Jiu as an industrial museum or other cultural attractions.

Assessing the opportunity of flooding of the remaining gaps from Rovinari Mining Basin according to the methodology established in this paper, results that the remaining gaps of the Tismana and the North Peșteana quarries present a high opportunity of flooding, Rovinari and Roşia de Jiu presents a low opportunity of flooding and Pinoasa shows inopportunity of flooding.

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Bioenergy Production as a Post-Mining Land Use

ASH Haagner *Agreenco BioEnergy, South Africa*

R Cloete *Agreenco BioEnergy, South Africa*

Abstract

In South Africa, rehabilitation practises have most often failed to deliver ecologically and economically sustainable post-mining landscapes. This is due to many factors, chiefly poor soil management practices, inadequate rehabilitation funds, lack of rehabilitation aftercare and degraded land capability. Furthermore, post-rehabilitation mined landscapes are often characterised by excessive compaction, soil nutrient deficiencies, high erosion rates and poor productive potential. The forecast climate change scenarios are likely to worsen this status quo if they are realised. The nett result is depletion of rehabilitation funds without reduction in environmental risk or socially acceptable end land-use.

Renewable energy production on mining-impacted land is a concept that is gaining significant traction in the South African mining sector. Solar generation projects exist and pumped storage schemes are in the planning phase. However, bioenergy generation provides a greater array of benefits both during and after active mining. Some of these benefits include:

- *Climate change opportunity and resilience;*
- *Emission reductions;*
- *Reduced land contamination through phytoremediation;*
- *Reduced energy costs over time;*
- *Feasible post-mining economy.*

Generation of compressed natural gas (CNG) from biomass grown on mine-impacted land, such as mine waste footprints, rehabilitating open-cast, spillage sites and others has been proven and is continuing to be proven from different sites and across commodities. The CNG generated is being used for metallurgical processing, providing backup generator fuel and has great potential to power mine vehicles at lower costs than conventional fuels.

Establishment of biocrops is more expensive than conventional rehabilitation but delivers superior returns when compared to intensive or extensive grazing systems, or food crop production. Our case study has shown project break-even after five years, with an expected infrastructure lifespan of >20 years. Feasibility studies on other projects have shown five to seven-year payback periods. The economic model strengthens where significant mine-impacted water exists in proximity to impacted biocrop areas, as the cost of water treatment shifts to biocrop production to improve biomass yields and therefore CNG production.

Where CNG plants and biocrop production is established during active mining to reap production and compliance benefits, the model can be extended to post life-of-mine through long-term energy offtake agreements that ensure ongoing plant operation and therefore job creation, whilst continuing land cleanup via phytoremediation.

Challenges exist within the regulatory environment, particularly irrigating on mine-impact land and compliance with independent power producer requirements. Furthermore, producing acceptable biomass yields from mine-impacted sites requires extensive site characterisation, trials and testing. Lastly, spatial considerations such as distance from biocrop sites to CNG plants, as well as distribution networks are key to financial feasibility.

Keywords: *Rehabilitation, closure, sustainable development, renewable energy*

1 Introduction

Mining in South Africa has a long legacy and has consistently been a top performer in contributing to the national Gross Domestic Product (GDP). It peaked in 1980 at 21% of GDP and has reached its lowest point in 2016 at 8% contribution (Statistics SA, 2017). Various factors such as poor investor confidence, an uncertain regulatory environment and shrinking resource base, coupled with improvements in other economic sectors, have greatly contributed to the decline in mining production and output.

Despite the lower production, mining remains an important direct employer, with 490,146 individuals directly employed (Statistics SA, 2017), apart from a significant supportive economy that creates substantial informal employment (1.4 million jobs, according to the SA Chamber of Mines, 2015). The perceived economic opportunities had led to migration away from traditional rural areas to the mining centres, but these are now faltering and are predicted future declines of economic wellbeing for these centres is set to further decrease as mines reach end of life. The mining 'ghost town' phenomenon is set to hit many South African cities within the next 20-30 years, unless suitable post-mining economies can be generated to support the large populations that mining has attracted.

Currently, the *status quo* for mined land is that it is mostly rehabilitated to an end land use confirming to grazing practices. There are requirements in some areas for land previously under crop production or commercial forestry to return to these, but attempts have largely been unsuccessful, with low productivity yields rendering them commercially unfeasible. This is often exacerbated by poor rehabilitation practices (soil horizon mixing during stripping and placement, compaction of placed soils, insufficient soil cover thickness, attempts at *in situ* rehabilitation of mineral wastes, organically and biologically depauperate soil due to extensive stockpiling, lack of maintenance and aftercare, amongst others), resulting in land with low productive potential, high erosion rates and some residual or latent environmental risk (Coaltech, 2007). Rehabilitation financial provisions are thus depleted, but without delivering a sustainable end-land use that absolves environmental and human health risk nor company liability. The end result is a string of decommissioned operations that are unable to attain formal closure. South African legislation essentially requires mined land to conform to the principles of sustainable development, thus no latent or residual environmental impacts, no instability or human health risks, and an end land use that generates sustainable and productive income, whilst affording sustained job creation.

Very few mining operations in South Africa have achieved formal mine closure, with many companies deferring closure to the end of collective operations, or adopting the principle of mining a resource only until it remains sufficiently lucrative to sell on. Even relatively benign mining sectors, such as quartzite or limestone extraction, whilst having no latent or residual environmental impacts, are unable to close due to the lack of sustainable end land use, as required by law.

Theoretically, commercial-scale agriculture as a post-mining land use should allow for attainment of closure, but in reality the high costs of transforming mined land into productive land parcels renders them unable to compete and be financially sustainable. Furthermore, in many metalliferous mines, the remnant footprints of mining infrastructure such as Tailings Storage Facilities (TSFs) and Waste Rock Dumps have levels of plant-available metals that would preclude the potential for crops grown there to be fit for animal or human consumption.

Therefore, an opportunity exists to install a post-mining land use that generates sufficiently high production value and economic performance to justify the high costs associated with remediation of residual contamination and dealing with the legacies of poor rehabilitation practises. Bioenergy crop (biocrop) production, for the purposes of generating renewable energy, is one such sector that shows promise and local case studies have proven its feasibility. Utilising biocrops for the purposes of generating compressed natural gas (Bio-CNG) has high input costs, but the profits from energy production is far higher than the value generated through meat or crop production (although direct competition with food production should be avoided, limiting biocrop production to unsuitable, contaminated or marginal lands only). The high feasibility and potentially lucrative margins attract investment that can be in place for the foreseeable future, post-mining, and could contribute significantly to local economies once mining has moved on, as it inevitably will.

This paper specifically focuses on bioenergy generation through production of Bio-CNG through biofermentation, although producing other biological fuels (biodiesel, biochar) via other methods (pyrolysis, burning) can also be feasible.

2 Methods

2.1 Analysis of markets

During the concept phase, a sufficiently detailed analysis of the market for using Bio-CNG must be undertaken. Typically, the first step to proving feasibility is that at least a portion of an existing mine's energy usage can be supplemented or replaced by Bio-CNG. The energy avenues range from replacement of diesel by a hybrid/gas-powered vehicle fleet, replacement of diesel in generators or backup energy systems, replacement of boiler oils in boilers and kilns, replacement of fossil gasses in boilers and kilns and elution circuits, and other possibilities. In countries where electricity generated from fossil fuels, such as coal, is relatively expensive, there is potential to replace this generation as well, although in South Africa, the relatively low cost of coal-generated electricity is currently sufficiently low to render Bio-CNG unable to compete on a direct basis.

Our approach entails that the economics of a Bio-CNG energy replacement project must be financially viable on a stand-alone basis, without considering secondary economic benefits (discounted rehabilitation provisions, carbon offsets and credits, potential phyto-extraction of metals, etc.) or secondary markets. However, once financial viability is proven during life-of-mine, then secondary benefits can be quantified during feasibility stage, as well as long-term offtake agreements outside of mining to start to build the case for post-mining viability.

2.2 Land availability and suitability

Due to relatively high energy demand within active mining operations, even partially substituting energy requirements through Bio-CNG requires high total bioenergy production. This, in turn, can require large parcels of land that need to be grown under biocrops to render the required volumes of biomass to be fed into the biofermentation process.

Not all land is equally suitable, especially when there is an objective to accrue secondary benefits such as phytoremediation. The primary drivers of land suitability are soil depth, soil drainage and textural profile, phyto-toxicity profile, distance from bioenergy production plant, security of infrastructure (particularly irrigation infrastructure), ecological sensitivity and zoning in relation to a regional development framework. Whilst soil fertility and nutrient status are important, these can often be addressed via increased production inputs. Climate naturally has an overarching influence and certain regions will not be suitable either due to insufficient water resources (via rainfall or irrigation) or temperature extremes. Biocrops typically have high water demand to sustain yield production. Detailed land capability assessments are generally performed during the feasibility phase of project development.

The total energy requirements are reverse-engineered to establish the requisite biocrop yields, which, in turn, determine the hectarage requirements. As discussed in the Introduction to this paper, South Africa's long legacy of mining has resulted in vast tracts of previously mined land that are not meeting rehabilitation objectives. Many of these are in areas that were previously prime agricultural lands, particularly in the coal and gold sectors. Furthermore, the situation in South African coal and gold mines is that there is often excess mine-impacted water that is unsuitable for discharge or human consumption. This water may require no, or little treatment to comply with irrigation standards, with the cost of treatment being offset against the cost of energy production, rather than from mining operating costs.

2.3 Biocrop establishment and yield trials

Once land availability calculations have indicated the crop yield requirements, a formal process of selecting suitable biocrop species that can produce the requisite yields within the biogeoclimatic characteristics of the site. We set the following criteria for biocrops:

- The biocrops should be a non-food source for humans.
- The biocrops must be able to grow on disturbed land that is not used for food production. The biocrops must, therefore, be able to grow in suboptimal substrates.
- The biocrops must require minimum water, fertilizer and herbicide usage.
- The biocrops should either be perennial that can be harvested continuously for several years before replanting is required, or annuals with high productivity and low input costs.
- The crop silage must be easily degradable by microbes to produce high quantity and quality Bio-CNG.

Suitably representative areas of current rehabilitation, legacy rehabilitation or mine-waste footprints should be selected, along with target water qualities simulating the final irrigation scenarios. The biocrops with suitable growth requirements and report yields should then be planted and monitored for germination, establishment growth rates and variability and water use. When rehabilitation overlies potentially reactive mineral waste (particularly sulphidic deposits), monitoring and managing water supply and phyto-evaporative transpiration is key to avoid further contamination of groundwater resources. Monitoring should span at least one growth season for annual biocrops (preferably more to ascertain sustainability of yields) and at least two seasons for perennial biocrops (to test the regrowth rates after harvesting).

Full harvesting should be undertaken on the biocrop trials, typically once per growth season for annual biocrops and twice or more for perennial biocrops. Yield productivity typically varies on post-mined land where rehabilitation practices are seldom entirely uniform. Relating yield variability to soil/waste chemistry, soil types, soil textures (and associated drainage patterns) and soil depths is essential information for planning and economic forecasting.

2.4 Energy productivity testing

When biocrops have been harvested, a set of samples from each of the biocrop types: one set (with replicates) from each trial block under irrigation (if applicable) and one set (with replicates) from each trial block under dryland conditions, should be analysed for energy generation potential, and related back to the wet biomass of the sample and the area required to produce that mass.

The energy generation potential will be dictated by the Carbon : Nitrogen (C:N) ratio as well as the absolute biomass yield. An optimum C:N ratio of 25-30:1 is sought for anaerobic biogas production. The closer to that figure achieved, the better the gas yield will be. N should be tested for as Nitrate N and expressed as a percentage of feedstock by weight, as will the C content.

Following this, a Biochemical Methane Potential (BMP) test can be run to accurately measure the biogas yield in m^3 per tonne of feedstock. The volume of gas can be translated per unit area and biomass required to produce it, which can be fed into the financial models.

2.5 Energy production plant

Once biocrops have been grown and harvested to supply the sufficient dry mass and calorific value, the next step entails maceration of wet biomass and storage in an ensiled energy bank. In this energy bank, oxygen permeation and aerobic digestion must be kept to a minimum to preserve the gasification potential of biomass until the silage is fed into the anaerobic bio-digesters to produce biogas. The process is illustrated in Figure 1.

2.5.1 Biomass to Biogas

A precise daily quantity of silage (stored biocrop) feedstock is put into the pre-treatment process where it is milled, mixed into a pumpable format and pumped into a heated enzyme assisted pre-hydrolysis tank. Enzymes are added and the biological degradation of cellulosic material is enhanced.

From the enzyme tank the semi-hydrolysed feedstock is pumped into a buffer tank from which it is fed continuously into the first of a series of Anaerobic Reactors, the core of the biogas plant, where the feedstock composite materials are broken down through anaerobic (air-tight, airless condition), fermentation to provide the material for archaea (anaerobic microbes) to consume and produce biogas. Biogas is produced during the decomposition process of the organic matter.

Biogas is a mixture of biomethane CH_4 (65-75%), CO_2 (25-35%) and small amounts of other gases. It is created by anaerobic digestion of organic material. The biomass will produce about three time as much energy per ha, comparatively, through the anaerobic pathway, as it would through the fermentation pathway (ethanol) or the extraction pathway (biodiesel), for instance. In addition, the production of Biogas creates a practically closed cycle of materials, with the fermentation by products returning as fertilizer to the field from which they came.

Anaerobic Digestion to produce biogas is an established technology, as is the biogas clean-up process to produce Bio-CNG and CO_2. It must be noted that the crops have differing input costs and differing growth requirements therefore the cost-benefit analysis may not necessarily indicate the higher yielding crop as the preferred choice in any given circumstance.

2.5.2 Biogas to Bio-CNG (Renewable, Bio-derived Natural Gas)

In the next step the biogas produced in the anaerobic digester (AD) is upgraded. Carbon dioxide, (CO_2) and hydrogen sulphide, (H_2S) are separated from the methane (CH_4) under pressure and absorbed into water, the methane is not absorbed and passes into the drier. After upgrading, the bio-methane (CH_4 content is typically greater than 98%), the gas is compressed (Bio-CNG) into storage cylinders for use as a transport fuel in the form of Liquid Natural Gas (LNG) or Compressed Natural Gas (CNG).

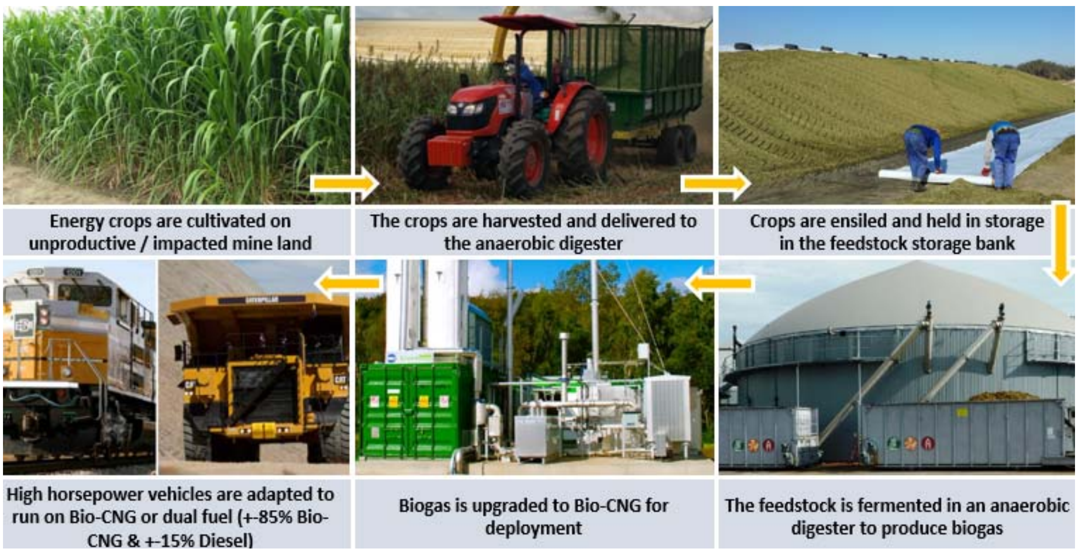

Figure 1 Process of generating Bio-CNG from biocrops grown on mine-impacted land

3 Data

3.1 Biocrop types and yield ranges

Based on data derived thus far from biocrop trials on mined land in South Africa, biomass yields have been found to range substantially according to factors mentioned previously. Typical species utilised for their tolerance to mine-impacted soils are shown in Table 1 and Table 2 below.

Table 1 Comparison between characteristics of Hybrid energy sorghum and *Pennisetum purpureum* biocrops

Hybrid energy sorghum (Figure 2)	***Pennisetum purpureum* including hybrids (Figure 3)**
Annual cereal crop Fast production cycles	Perennial biomass crop Fast production cycles under irrigation, with vigorous regrowth
Heat and drought tolerance, some susceptibility to extreme/prolonged cold	High water demand, low drought tolerance
Relatively low fertiliser requirements	Relatively high tolerance to soil metals, some soil bioremediation potential
Low acidity tolerance	High nitrogen demand and generally high fertiliser requirements
Very high dry mass yield potential and high fermentability	Susceptible to extreme or sustained cold periods, especially frost
Extensive varieties available, thus highly specific types can be selected to suit site conditions	Very high dry mass yield potential and high fermentability, although high fibre content at maturity.
Low plant moisture levels at maturity	Extensive root biomass thus less sensitive to high soil bulk density
Relatively high weed susceptibility	Many varieties available, available in either clones or seed.

Figure 2 Energy sorghum crop grown under irrigation on a gold TSF footprint two months after planting. The site is near Welkom, South Africa and was undertaken by Agreenco BioEnergy

Figure 3 *Pennisetum purpureum* is widely grown as a forage crop and for wind-hedges in South Africa, particularly in warmer and higher rainfall regions

Table 2 Comparison between characteristics of Hybrid energy sorghum and *Pennisetum purpureum* biocrops

Energy beet (Figure 4)	**High biomass pastures (typically *Brachiaria brizantha* and *Panicum maximum* varietals) (Figure 5)**
Annual crop, typically 4-month cycles	Perennial biomass crops
One or potentially two crops per annum	Fast production cycles and good regrowth
Very fast fermentation time	Good dryland production and high drought tolerance
High sugar content	Frost tolerant
Very high and consistent methane/ethanol yields per ton of dry mass	Tolerant of poorer quality soils with poorer drainage
Wide range of varieties to suit different soil types- good rotational crop	Relatively low fertiliser requirements, but responds well to nitrogen topdressing
High crop nitrogen demand	Compatible with legumes for nitrogen fixation and use
High salinity tolerance and salinity bioremediation	Very specific varietals but seed readily available on pre-order
Low tolerance for soil compaction	

Figure 4 Images of energy beet grown locally on a rehabilitating gold TSF footprint in Welkom, South Africa by Agreenco BioEnergy

Figure 5 Both high biomass pastures are grown in South Africa. Agreenco has planted experimental blocks on rehabilitating open-cast coal mines in the Witbank area, South Africa

Table 3 Biocrop dry mater yield variability for a variety of biocrops grown on previously mine land and mine waste footprints in South Africa

Biocrop	Yield on mined land	Yield on TSF footprints	Cycles per annum
Energy Beet	Not yet determined	26-52 tons/Ha/cycle DM	1
Hybrid energy sorghum	36-60 tons/Ha/cycle DM	15-30 tons/Ha/cycle DM	2
Pennisetum purpureum	24-60 tons/Ha/annum DM	42-44 tons/Ha/annum DM	1
High biomass pastures	14-40 tons/Ha/annum DM	18-32 tons/Ha/annum DM	1

Table 3 above shows the typical yield variations on previously mined land as well as on TSF footprints where trials have been undertaken.

3.2 Biocrop input requirements for sustained yields

Biocrop inputs are highly dependent on the substrates, the yields produced and the biocrop growth requirements. Typically, mined land and mine waste footprints require stormwater control, surface preparations, physical amelioration, organic amendments, fertiliser inputs and seeds to establish the biocrops. After establishment, after-care in the form of fertilisers, herbicides and pesticides may be required, particularly during periods around harvests.

Table 4 Typical input requirements for biocrop establishment on previously mine land and mine waste footprints in South Africa

Inputs	Inputs on mined land	Inputs on TSF footprints
Physical amendments	Deep ripping, disking, stormwater control, surface preparations	Stormwater control, surface preparations
Chemical amendments	Chicken manure/compost, Calcitic lime, Urea, NPK fertilisers	Compost, Dolomitic lime, NPK fertilisers
After-care amendments	Fertilisers, herbicides, pesticides	Fertilisers

Table 4 compares the input requirements for previously mined land against the footprint of reclaimed TSFs. The major difference in South Africa is that previously mined land requires far greater efforts in physical amelioration, whereas TSF footprints require more chemical amelioration.

3.3 Biocrop production cost ranges

Biocrop production costs can vary greatly depending on the scale of operations, whether irrigation will be utilised or not, and what the input costs are. Production costs are typically expressed as a cost unit per hectare of dry matter produced, inclusive of harvesting and transport costs. The lower the production costs, the greater the viability of a project.

Table 5 Typical biogas production costs for biocrop establishment on previously mine land and mine waste footprints in South Africa

Biocrop	Cost range on mined land (per Ha) irrigated, moderate inputs	Cost range on TSF footprints (per Ha) irrigated, moderate to high inputs
Hybrid energy sorghum (annual)	CAPEX USD 243-USD 270 OPEX USD 66-USD 75	CAPEX USD 319-USD 345 OPEX USD 88-USD 110
High biomass pastures (perennial)	CAPEX USD 240-USD 279 OPEX USD 40-USD 43	CAPEX USD 261-USD 289 OPEX USD 44-USD 46

As is shown in Table 5 above, annual biocrops typically have greater production costs than perennial biocrops, but, when considered in conjunction with Table 3, two planting cycles can be undertaken during optimal conditions, thus resulting in greater yields at an overall lower cost than perennials. However, in South African conditions optimal conditions (early rains and shorter frost season) are generally not experienced annually, and conservative projects may consider perennial crops due to average lower costs over a 10-year period.

3.4 Energy costs compared to conventional fuels

In South Africa project economics are underwritten by a favourable cost differential in the cost of producing Bio-CNG to replace diesel.

Table 6 Energy cost comparison between Bio-CNG and comparable liquid fuels used in mining in South Africa (at an exchange rate of ZAR 11.80 to USD 1.00)

	Energy Cost	
	Cost per litre / litre DE (diesel equivalent)	**Equivalent cost /GJ**
Bio-CNG Production Cost	USD 0.41/litre DE	USD 10.42/GJ
Discounted wholesale diesel	USD 0.79/litre	USD 20.76/GJ
Light fuel oil	USD 1.10/litre	USD 28.05/GJ
Paraffin	USD 0.84/litre	USD 23.05/GJ
LPG	USD 1.18/kg	USD 23.73/GJ

As can be seen in Table 6, Bio-CNG has the potential to replace conventional liquid fuels at around half of the cost or better. There is, however, a substantial initial cost to establish the biocrop sites and to construct the biodigesters and biogas plant. Typical pay-back periods are 5-7 years.

4 Discussion

4.1 Benefits and constraints of bioenergy production on mined land

Whilst energy production is shown to be a feasible and, often, preferable fate for mine-impacted land, not all mined areas will be suitable. Similarly, bioenergy is not he only form of energy that can be generated, and many investigations are focussing on wind generation (where geotechnical limitations can be overcome), solar generation (in suitable regions) and pumped storage schemes (where height differentials exist and safety can be proven). Bioenergy production, however, provides the most social, environmental and economic benefits, with Bio-CNG achieving these with the best economic performance.

To illustrate the differences between the South African *status quo* for rehabilitation and bioenergy crops produced under irrigated and dryland conditions, the risks and benefits are listed in Table 7. The *status quo* of pasture grassing is low-cost but is not delivering sustainable land use. Under dryland biocrop production, costs can be maintained relatively low, with improved economic production, but large (>500 Ha) land areas are required to be feasible. Under irrigation, biocrop production costs are the highest, but so is productivity and yield sustainability can be achieved, along with sensible use of mine-impacted water. In the irrigated scenario, particularly on previously mined land overlying sulphidic wastes, detailed modelling and monitoring is required to ensure that mine water is treated to adequate qualities that does not add to groundwater contamination, nor negatively impact biocrop growth. The high, sustained yields of the irrigated biocrop scenario have, in some cases been shown to be sufficiently high to justify the costs of treating mine-impacted water to irrigation standards, that would otherwise have resulted in significant costs to treat and discharge, without beneficial use.

Table 7 Risks and benefits of biocrop production on mined land, comparing the South African status quo with irrigated and dryland biocrop production scenarios

	Risks	**Benefits**
Status quo (pasture grassing)	Monoculture stands Declining productivity Unacceptable recharge rates Increased bulk density Rainfall dependence Low cost/Ha yield Erosion risk	Very low establishment costs Relatively low maintenance High demand land-use Low-technological complexity Low replanting costs No irrigation infrastructure
Dry-land bioenergy crops	Annual maintenance costs Moderate recharge rates Rainfall dependence Weeding requirements	Low establishment costs Improved bulk densities Improved soil carbon Low replanting costs Moderate cost/Ha yield High cover, low erosion
Irrigated bioenergy crops	High recharge rates Greater management required High technological complexity Infrastructure requirements Increased input costs Annual maintenance costs Weeding requirements	Use of excess/dirty water High production volumes Rainfall independence Improved soil carbon Improved bulk densities High cost/Ha yield High cover, low erosion

Additional benefits of biocropping mine-impacted land are as follows:

- Intelligent land management and climate-smart focussed rehabilitation strategies;
- Reduced rehabilitation provisions through enabling alternate budgets to resolve liability;
- Reduced greenhouse gas emissions through avoiding burning fossil fuels;
- Reduced process water and associated liability by using Bio-CNG production to pay for treatment;
- Direct financial impacts through cost savings and return on environmental investment;
- Job creation on the biocrop production side and in the bioenergy plant;
- Phytoremediation potential, particularly of metals.

A considerable challenge in South Africa is ensuring compliance within the legal framework, particularly for water use and managing the potential risks associated with increasing recharge on previously mined areas.

4.2 Market uptake, primary and secondary beneficiation

Access to an initial market, preferably during life of mine, is essential to achieving stable economics and a pay-back period within a 5-7 year period. However, for bioenergy production to be a sustainable post-mining land use there is a need to develop external markets, to get distribution infrastructure in place and to secure long-term offtake agreements from markets that will survive once mining exits. In South Africa, this requires some regional coordination but most areas that fall within suitable climatic zones do have diversified economies that would benefit from stable, sustainable and lower cost energy. Currently, social and labour project budgets are not realising their full potential, as they wane once mining funding is withdrawn. We believe that a Bio-CNG operation, with greater economic benefits, will attract investment to realise the lucrative returns and thus contribute to a greater and more sustainable long-term impact.

The greater benefit will also only be realised as regional non-mining sectors develop that are dependent on the energy produced, such as biofuel-driven public transport, airline biofuel, . Furthermore, once secondary beneficiation enters the frame, then sustainability really comes into play. A by-product of Bio-CNG production is CO_2, which is readily compressed and made available for local production uses such as food and beverages (whilst still maintaining an overall negative carbon footprint).

5 Conclusion

The concept of bioenergy production as a sustainable post-mining land use in South Africa has numerous potential benefits to decreasing current energy costs whilst setting up the framework post-mining economies that will be required to prevent mining towns becoming ghost towns as mines withdraw in the near future. We believe that the case studies, biocrop trials and proven Bio-CNG generation plants operating from TSF footprints has a wider application in other parts of the world where mining dominates local economies that will be left fragile once mineral resources are depleted. This paper shows that the concept is in the early stages of being proven at large scale , as projects are moving through feasibility stages into production.

More work is required across a broader climatic front to ensure that no conflict arises between bioenergy production and food security and that regional coordination allows for secondary beneficiation to develop, which will be the key to unlocking post-mining sustainability and successful mine closure.

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Benchmarking; Bringing the Lessons from the Past into the Future

HWB Lacy *Stantec, Australia*

CD Grant *Anglo American, Australia*

J Lambrechts *Anglo American, South Africa*

W Voigt *Anglo American, South Africa*

Abstract

The Oxford English dictionary defines benchmarking as "a standard or point of reference against which things may be compared" and can be a powerful tool applicable to capacity building within people who are engaging in, or intend to engage in, a mine closure and rehabilitation programme. Over the past 18 years, the lead author has planned and led more than 14 benchmarking programmes within the Australian mining landscape, generally tailored to a specific need of the participants. Facilitating safe and effective learning experiences in remote and active mining areas takes diligence and effort but is a greatly rewarding educational process for the group. The intent of these programmes is to broadly build knowledge and capacity within the group travelling together, preparing them for the challenges they face in mine closure activities, and to understand and learn from successful, and not so successful, mine rehabilitation and closure techniques applied at mine sites.

We discuss and present findings from a recent "Rehabilitation Benchmarking" programme that was conducted by Anglo American's South African Kumba Iron Ore team in mid-2017. The group benchmarked a series of large and small mines, predominantly mining iron ore, in the Pilbara region of Western Australia, to learn from both historic and current closure and rehabilitation activities undertaken within this large, dynamic, mineral producing province. By the time we had completed a seven-day benchmarking journey, we had learnings in relation to closure planning and land use, landform design, closure leadership and management, topsoil's and seed use, surface ripping techniques, returning ecosystem function and how to drive effective rehabilitation processes. Three practitioners committed to travel a great distance from South Africa, they gained the desired exposure to moonscaping a rehabilitation technique, developed some 20-30 years previously and assess its capacity to be sustainable in the very challenging and harsh Pilbara landscape a environment that has many similarities to the environment of the Kumba Iron operations.

In this instance, the benchmarking objectives were met in considering the moonscaping technique that has, in many of the areas we visited, stood the tests of time. The application of a structured and well considered and designed benchmarking programme can bring great educational value. This benchmarking journey demonstrated again that indeed we should all look to the lessons of the past, as restoration and rehabilitation is a time dependent process, and those learnings can be brought into the future and applied to current challenges we face in mine closure.

Keywords: *Benchmarking, landform, rehabilitation, training, moonscaping, design*

1 Introduction

The closure and rehabilitation of a mine site, and associated landforms, is much more than designs based on agreed criteria which are then implemented, and much more than the application of a system through which one can apply "best practice" via a formula worked out based on uniform standards relevant to all locations. Although science and organisational controls are essential, critical and central to successful mine closure and rehabilitation are the people who implement and make the program happen (Haymont, et.al. 2008).

The prime intent therefore, of mine rehabilitation/closure benchmarking programmes is to build knowledge and capacity within a closure/rehabilitation/environmental team, and to understand and learn from successful, and not so successful, mine rehabilitation and closure applied at mines with similarities to those that the team operate. We targeted some of the most historic of the operations in the Pilbara region of West. Australia that had applied a specific landform rehabilitation technique called "moonscaping" (Walker 1987). This technique is particularly useful in application to landforms orientated in such a way that makes them difficult to rehabilitate using currently acceptable closure and rehabilitation techniques.

In this instance we demonstrate how we used a 2017 benchmarking study of "large landform rehabilitation" for practitioners from Anglo American Kumba Iron Operations (KIO) to achieve these aims, and to build capacity in that team as they are actively undertaking rehabilitation, materials management and landform closure programmes at their operations in the Northern Cape region of South Africa.

2 Benchmarking Through the Decades

Over the past 18 years, the lead author has planned and led 14 benchmarking programs within the Australian mining landscape, generally tailored to a specific needs and primary interest of the participants. Facilitating safe and effective learning experiences in remote and active mining areas takes diligence and effort but is a greatly rewarding educational process for the group. Benchmarking builds capacity and confidence within the group travelling together, preparing them for the challenges they face in mine closure activities, gaining an understanding and learning from successful, and not so successful, rehabilitation and closure techniques applied at mine sites.

We list examples of previous benchmarking training trips and their focus below;

- Progressive Mine Closure and Rehabilitation of Waste Landforms.
- Large Waste Landform Design and Rehabilitation in Arid Areas.
- Closure of Waste Landforms and Tailings Facilities with Acid Mine Drainage Issues.
- Progressive Rehabilitation and Active Closure Planning in Wet Temperate Forests.
- Water Management at Active and Closed Mines with Acid Mine Drainage Issues.
- Closure of Large Historic Mines Situated Within and Surrounding Large Communities.

Sometimes Company environmental professionals will only benchmark within their own organization, however it is valuable to look beyond this. Time spent in benchmarking visits can sometimes appear intangible but the learning's can be invaluable including:

- Benchmarking is some of the best time spent in assisting future planning.
- Through benchmarking we can avoid re-creating the errors of the past.
- Every closed site has information about what to do and what not to do.
- Company-centric mindset can limit innovation and prevail, benchmarking opens the mind (adapted from Lacy and Haymont 2006).

In introducing the application of benchmarking as a tool for capacity building of closure teams we provide some previous examples of the application of environmental management benchmarking in further detail below.

In 2004, Newmont Mining commenced a large-scale closure program of the Mt McClure mine in the Eastern Goldfields of West Australia, a mine they acquired as a result of an acquisition. This mine had a large area of incomplete earthworks, due to the sudden end of operations in 1999 when the mine went into receivership., Little progressive rehabilitation had been completed to the standards set by the site licence conditions and commitments (Lacy and Haymont 2006). Extensive design work and modelling of options for the rehabilitation of incomplete facilities was required but the closure team (recently formed) at that time were perplexed due to the scale of the challenge. One of the key tools in resolving that issue was the benchmarking tours undertaken by key personnel involved in designing and supervising the project, and included the bulldozer drivers, contractors and consultants. Dozens of closed and abandoned mines were visited and an immense amount was learned with regard to handling certain materials, design concepts over time, and the impact of a particular weather event in the region. By visiting closed mines within a 500 km radius of the site, the project leadership group and rehabilitation operators gained first hand appreciation of trends and design concepts throughout much of the regional rehabilitation estate (Lacy and Haymont 2006).

Industry has indeed seen change in the last 20 years so that the concepts of progressive rehabilitation, and active closure planning are clearly self-evident at many operations throughout Australia. During April 2012, the lead author conducted a benchmark exercise for the Boddington mine closure team and visited five different types of mineral production (Lacy 2012). Sites included Alcoa Australia's bauxite residue disposal areas at Kwinana and Pinjarra, the Huntly bauxite mine, Bemax Ludlow mineral sands mine, BHP Billiton's Beenup mineral sands rehabilitation project, Premier and Griffin Coal at Collie, Alcoa's Hedges gold tailings closure and Newmont's Boddington Gold mine; all of these sites are located in the well populated Southwest of WA.

The team found many effective approaches evident in "progressive rehabilitation and closure" at these operations, situated within population dense, and sensitive areas, and the participants in many conversations with the environmental managers during the field trips were able to benchmark their progress at the large Boddington gold operation, in addition to gaining many valuable insights across this diverse range of mining operations.

3 Landform Design and Rehabilitation Benchmarking 2017

The benchmarking tour of Western Australia's Pilbara iron ore mines was organised by the authors in May 2017 engaging Anglo American's KIO environmental team. The focus was on the evolution of landform design techniques and associated rehabilitation prescriptions.

The purpose of the Benchmarking exercise was to:

- Inspect and learn from historic and current rehabilitation activities undertaken by the respective Pilbara mines;
- Review rehabilitation techniques used for large landforms similar to those at Kumba Iron Ore mines in South Africa;
- Interacting and learning from other site-based professional Environmental Practitioners;
- Share challenges and opportunities around rehabilitation and closure plans with peers; and
- Establish a platform for future communications and learning.

The team visited a total of 10 sites. Most were iron ore operations, but a gold mine and pivot irrigation enterprise (developed by Rio Tino) were also visited. Of the iron ore mines visited, some had been closed for more than 30 years, while others had only recently commenced production. We inspected and learnt from both historic and current closure and rehabilitation activities undertaken by Roy Hill, Spinifex Ridge, BHP, Atlas Mines and Rio Tinto facilitated site visits for the team.

Anglo American's Kumba Iron ore open cut operations are situated in the Northern Cape Province. Kolomela Mine is located near Postmasburg and has been operational since 2009. The active mining area consists of waste landforms that are being progressively rehabilitated. The Sishen mine is located 30 km from the town of Kathu and is one of the largest open pit iron ore producing mines in the world, commencing in 1953. More than 900 million tonnes (mt) of iron ore has been produced over 60 years of the mine's operation. The mine disturbance area is considerable with a waste landform rehabilitation task of ~2000ha ahead before the estimated life of mine in 2031 is reached.

The mean annual precipitation in these areas of the Northern Cape rainfall is ~374 mm/annum and the average annual evaporation rate is more than 5 times the annual precipitation. Rain is mainly received from November to April. The mean annual temperature is 19 C. January is the hottest with average of 32.9 C and July is the coldest month with an average minimum temperature of 3.1 C.

3.1 Moonscaping; Case Study

Moonscaping was a BHP developed technique for mine waste rehabilitation of large landforms at angle of repose, tipped off ridgelines in many instances, described by Ken Walker during the late 1980's (Walker 1987). Moonscaping is now less applied in WA, possibly due to the fact that some work was conducted in clay rich and oxide soils, and this resulted in erosion and reputational responses issues, whereas the technique is far more appropriate for coarse waste rock material. In addition, a wide range of alternative techniques have evolved in the Pilbara, whereas in the Northern Cape of South Africa (which is in the early stages of rehabilitation) the moonscaping technique is potentially applicable in the appropriate materials.

The Kumba operations have limited rehabilitation techniques for the large waste landforms. The team wished to look at the techniques applied in the Pilbara to rehabilitate similar large landforms. They believed these similar operations would greatly benefit from benchmarking of the historic and current rehabilitation works underway across the Pilbara. They particularly wish to look at that range of treatments i.e. moonscaping at the northern operations (Yarrie/Shea Gap), and the wider range of rehabilitation approaches applied in the Mt Newman area.

The group assessed moonscaping's effectiveness in stabilizing landforms with steep slopes (>20 degrees) of a considerable height (60 – 120 m) and therefore considerable slope length, and assessed the effects of time, and the quality of rehabilitation and stability in those landforms moonscaped during the late 1980's to early 1990's (~20-30 years hence).

3.2 Moonscaping; Findings

The following observations and lessons learnt were made in relation to moonscaping:

- Moonscapes appear stable in coarse material, some slopes to 24 degrees, can range from 80 to ~240 m slope length, and 20 to ~120 m high.
- One size does not fit all; moonscaping is appropriate in some applications but not all.
- Crest bunds and slope tie-in's are vital for water control and drainage around the moonscaping.
- Vegetation (grass and trees) establishes well in moonscape pit catchment and migrates from that point.
- Introduction of a growth medium or topsoil leads to significantly better vegetation establishment when compared to a straight waste rock substrate (Lacy and Grant 2018).

4 Benchmarking; General Findings.

Lessons from this journey across all sites can be summarised into broad areas: planning and land use; management engagement; waste characterisation; design and detail; implementation; moonscaping and concave slope designs; topsoil, ripping, seeding; and ecology – revegetation and returning the ecosystem. Bullet points summarizing lessons learnt and observations for each area are provided. A summary of our key findings from this benchmarking journey are included below:

4.1 Planning and Land Use

The following observations and lessons learnt were made in relation to planning and land use:

- Get it right the first time, this is always the cheapest option.
- Building with the end in mind.
- Having a plan so the organization/team knows what it is working towards.
- Get guidance and specialist quality input from the start.
- Have sufficient resources to do the planning from the start and during LoM and build in flexibility.
- Need to clearly identify the proposed land use for closure.

4.2 Management Engagement

The following observations and lessons learnt were made in relation to management engagement:

- Management commitment can drive the operations culture.
- Senior mine leaders can be particularly aware and interested in rehabilitation and closure, especially if their individual KPI's have rehabilitation and closure targets.
- There is great potential for sharing learnings across mining operations within regions.
- Closure work is best with staged, supervised implementation, with the right contractor and right equipment.

4.3 Waste Characterisation

The following observations and lessons learnt were made in relation to waste characterisation:

- Early and comprehensive waste characterization is critical to rehabilitation and mine closure success.
- There are many examples of failure of rehabilitation due to inadequate materials characterization.
- Advanced materials characterisation; well ahead of mining and in preparation for modelling erosion and management of material.
- The design and final surface treatment is defined by the characterised materials.

4.4 Landform Design and Detail

The following observations and lessons learnt were made in relation to landform design:

- There is potential for significant cost savings if waste is dumped to design.
- Design the landform and its water management for closure.
- Put effort into design of "cells and paddocks" for water control on benches and upper surfaces.
- Good design and associated research sets operation up for success.
- Designs have to evolve into specific "work programmes" for each landform.

4.5 Topsoil and Seed

The following observations and lessons learnt were made in relation to topsoil and seed:

- Topsoil is a critical and important resource.
- Need to use topsoil wisely to contribute to diversity.
- Direct placement of topsoil leads to significantly better plant establishment.
- While spreading topsoil can be expensive, it may be cheaper than direct seeding in some circumstances.
- Topsoil and applied seed are the most important factors influencing species richness in rehabilitation.

4.6 Ripping

The following observations and lessons learnt were made in relation to ripping:

- Ripping on the contour can be a successful erosion control mechanism but requires attention to detail.
- Contour ripping can be used successfully to rehabilitate large waste landforms up to 20 degrees.
- Use of the right ripping tines to get the appropriate depths and surface is critical for success.
- Design of ripping tine and ripping technique needs to match desired outcomes.

4.7 Return of an Ecosystem

The following observations and lessons learnt were made in relation to development of ecosystems:

- It is critical to clearly define completion criteria based on the ecology of local analogues and its links to the final land use.
- There is potential to match different plant communities with different landform aspects and topography.
- Diversity of substrate conditions can facilitate acceptable variability in vegetation communities.
- Good rehabilitation trials on a small area are generally better than committing to rehabilitate a large area without a proven prescription.
- Weed management may be required and is important during first few years until early ecosystem is established.

5 Conclusion

In this instance, the benchmarking objectives were met in considering the moonscaping technique that has, in many of the areas we visited, stood the tests of time. The application of a structured and well considered and designed benchmarking program can bring great educational value. Rehabilitation of mine waste landforms is a time dependent process. Those lessons can be applied to current challenges we face in mine closure. This benchmarking example also demonstrated that we should expose closure and reclamation/ rehabilitation professionals to the application of changing techniques.

Importantly, in the 12 months following the Pilbara benchmarking trip, moonscaping has been trialed at the Sishen Mine, with contour ripping and concave landform designs implemented at both of the KIO mines. This has realized significant value for the operations through de-risking as well as significant operational cost savings through decreased rehabilitation rates. This benchmarking journey demonstrated again that indeed we should all look to the lessons of the past and apply them to current challenges we face in mine closure.

Acknowledgement

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Master Plan of Botanical Garden: An Ultimate Achievement of PT NMR Mine Closure

AS Sembel *Sam Ratulangi University, Indonesia*

JR Witono *LIPI (Lembaga Ilmu Pengetahuan Indonesia), Indonesia*

D Sompie *PT Newmont Minahasa Raya, Indonesia*

J Kojansow *PT Newmont Minahasa Raya, Indonesia*

P Mamonto *PT Newmont Minahasa Raya, Indonesia*

Abstract

Botanical garden is a modern conservation concept that combines the role of ex situ and in situ conservations, integration of scientific aspect, socio-economic and cultural of the community. President's statement in 2004, declared every provinces throughout Indonesia shall have a botanical garden, has built the enthusiasm of local government to develop one. PT Newmont Minahasa Raya (PT. NMR) is a gold mining company that started its activity since 1984 and ended its operation in 2006. From 2002 to 2012, the company had been conducting mine closure and reclamation/ rehabilitation at the former mining area. In 2010, the implementation of reclamation/ rehabilitation on the area had been declared successful by the Indonesian government and approved the former gold mining land with a total area of 221 hectares to become a special purpose forest area for the development of a botanical garden, based on the Forestry Ministerial Decree (SK.175/Menhut-II/2014). Previously, the pre design study has been conducted to fulfil the stages of botanical garden development and become a guideline for its master plan. The vision and mission of the botanical garden have been stated in this master plan as well. Site condition, type of vegetation, buildings, infrastructures, conservation value, socio economic and community culture, have been studied and analysed in the master plan. The results of these studies support the conservation of lowland plants in the Wallacea region. The approval of botanical garden master plan shows that a former gold mining can give a lot of contributions to the sustainability of the environment and community as a whole.

Keywords: *botanical garden, conservation, master plan, Wallacea*

1 Introduction

Biodiversity is the basic capital of Indonesian development that must be utilized for the prosperity of the nation. Currently, Indonesia's biodiversity condition is threatened by the destruction of natural forest and its ecosystem. The main causes of such damage are deforestation, land conversion and mining. This factor causes many species of plants and animals to have been declared extinct or become rare before the benefits are known.

PT. Newmont Minahasa Raya (NMR) is a gold mining company that started its activity since 1984 and ended its operation in 2006. From 2002 to 2012, the company had been conducting mine closure and reclamation/ rehabilitation at the former mining area. The activities include land reclamation, construction of erosion protection structures, revegetation and maintenance (Pollo et al. 2011).

In 2010, the implementation of reclamation/ rehabilitation on the area had been declared successful by the Indonesian government and approved the former gold mining land with a total area of 221 hectares to become a special purpose forest area as a botanical garden, based on Forestry Ministerial Decree (SK.175/Menhut-II/2014). Along with its procedural process, a scientific study of the former PT. NMR mining site was carried out by LIPI (Indonesian Institute of Sciences) (Widiyono 2013), and University of Sam

Ratulangi Manado (Sembel et al. 2013). The results of these studies led to a recommendation that the former mined land can be used to develop a Botanical Garden for *ex situ* plant conservation purpose. Sembel et al. (2013) conducted a predesign analysis at the former mined area as a research report that can be used as initial guidelines for the preparation of the Botanical Garden Master plan.

However, the development of botanical garden in Indonesia needs to follow three stages based on the Presidential Regulation No. 93 of 2011 i.e. planning, implementation and management. Botanical Garden Master Plan in PT. NMR former mining area is included in the planning stage of the development stage activities which can be seen in Figure 1.

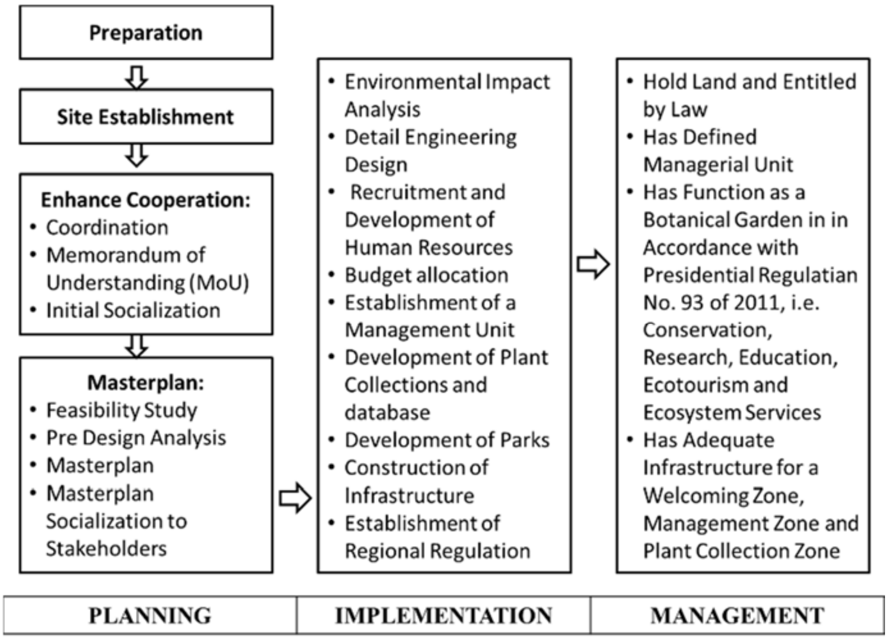

Figure 1 Development stages of botanical garden in Indonesia

Planning stage basically is a technical preparation phase before the physical development/arrangement of a botanical garden. In the outline development stages, the planning stage activities contains of several sequence procedural.

Based on the following stages above, the content of this article will deliver the master plan of botanical garden in the former mining area of PT. NMR, such as the scope of work, methods, planning concept and outputs of master plan.

2 Method

Preparation activities of botanical garden master plan follows several stages:

1. Field survey, conducted by harmonizing basic information of physical condition in the planning area with analysis needs. The main purposes of the field survey are: to produce a topography map area and situation measurement in the planning area; to ensure existing condition and infrastructure; vegetation existing and its ecosystem.

2. Analysis and concept framing of master plan, conducted based on related analysis with applicable terms and conditions of botanical garden, in technical and its activity management.

3. Master plan design, with main substance in some aspect such as, landscape design directives (zonation and infrastructure development), technical operations of vegetation collection development in line with botanical garden theme, institutional aspect (human resource in terms of quantity and capability), financing aspect to show general description of botanical garden cost development.

3 General Overview

The botanical garden at the former mining area of PT. NMR at Ratatotok is located in the northern peninsula of Sulawesi Island about 50 km from the city of Ratahan, the capital city of South East Minahasa Regency and about 136 km from Manado, the capital city of North Sulawesi Province. It is situated at an altitude between 75 to 430 meters above sea level and has various type of slope from flat to steep or hilly topography. The site for the planned botanical garden has climatic type B according to Schmidt-Ferguson, annual rainfall 1,790 mm per year, average of relative humidity 82.3%, and temperature between 21.3^0- 31.3^0 C (Witono et al. 2014). The site location belongs to lowland of Sulawesi ecoregion (Olson et al. 2011).

3.1 Scope of site review

Primary data has been gained to conform basic information about physical condition in the planning area such as, primary data (vegetation, fauna, geology, hydrology, climate, socio culture and other prominent element) and secondary data as supporting data such as topography maps and other supporting maps, government policies and earlier studies/ research by PT. NMR, LIPI and University of Sam Ratulangi (Witono et al. 2014). Based on vegetation type, reclamation status and former land-use during mining operation, site locality of botanical garden can be divided into 15 blocks (Table 1).

Table 1 Site locality of botanical garden

Block	Vegetation Type	Reclamation Status	Land-Use during Mining Operation
A1	Mixed Forest	Revegetation	Accomodation Village
A2	Secondary Forest	Non revegetation	Border A1 with Diversion Drain
A3	Mixed Forest	Revegetation	Outlook Location
A4	Mixed Forest	Revegetation	Mesel Pit
	Mixed Forest	Revegetation	ROM Area
A6	MixedForest /shrubland	Non revegetation	Heap Leach/ Leach Pad
A7	Mixed Forest /shrubland	Non revegetation	Management Office and Production Building
A8	Plantation/ shrubland	Non revegetation	Water catchment
A9	Swamp Area / Mixed Forest	Revegetation	SWP, Spillway Path
A10	Secondary Forest	Revegetation	Contractor Accomodation
A12	Secondary Forest	Non revegetation	Reserve Area
A13	Mixed Forest	Revegetation	Water catchment
A14	Swamp/ Mixed Forest	Revegetation	Sediment Pond
A15	Secondary Forest	Non revegetation	Reserve Area

4 Analysis and data review

There are several analyses to be conducted in the analysis and data review stage: activity analysis (vegetation collection, conservation, services and information, work units, and corporation), needs analysis (collection facilities and services) and site analysis (position and accessibility, land use, circulation, topography, view, ecosystem, vegetation, hydrology, geology and socio culture). These all are to be analysed in terms to produce a planning concept of botanical garden master plan.

4.1 Planning concept

The main purpose of a botanical garden is plant conservation where each garden has its own theme. Based on biotic and abiotic data analysis, the theme of the garden is centered for conservation of lowland Wallacea region plants. Whereas, the Icon of the garden was selected based on several criteria, such as: (1) local plant, (2) economical value, and (3) important species for local people such as medicinal plants. Based on those criteria, the icon of the botanical garden is a plant locally called "leilem" (*Clerodendrum minahassae* Teijsm. & Binn.) (Witono et al. 2014).

4.2 Master plan of botanical garden

Based on primary and secondary data, analysis and concept, the master plan of the botanical garden consists of four zones, i.e. welcoming zone, management zone, plant collection zone and recreation zone (Figure 2).

Figure 2 The master plan of botanical garden

Welcoming zone is an area for visitor reception. It consists of at least main gate, ticketing, visitor information centre (VIC), hall etc. Management zone is an area for managerial works. It consists of at least main office, nursery, green house, research facilities etc. Whereas, plant collection zone is an area for plants maintaining that arrange into taxonomy and thematic park patterns. Recreation zone is an area for recreation purposes. It consists of tower of view, event place, gold mining museum, amphitheatre, and lawn. These areas represent in figure 3 in clockwise.

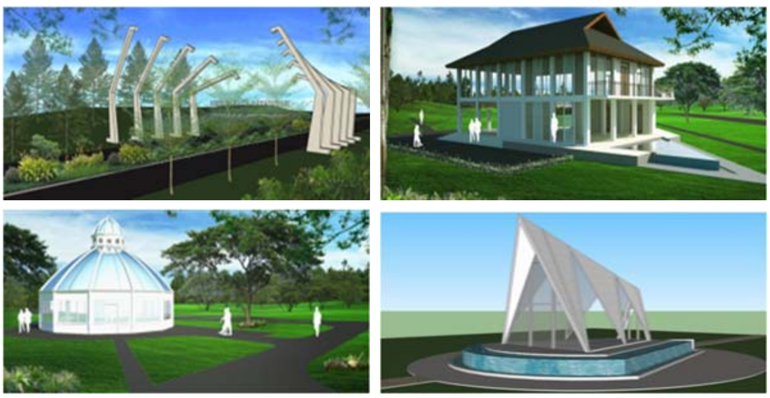

Figure 3 Welcoming zone, management zone, plant collection zone and recreation zone.

5 Conclusion

The botanical garden master plan at the former mining area of PTNMR in Ratatotok North Sulawesi, is compiled to become a development guideline to fulfil the intended purpose in sustaining the environment through conservation and for the interest of the local communities. It covers several important aspects such as, establishment of botanic garden, physical conditions including socio- culture, existing vegetation, and infrastructure that have been analysed to produce a design that could be implemented and be developed.

Acknowledgement

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