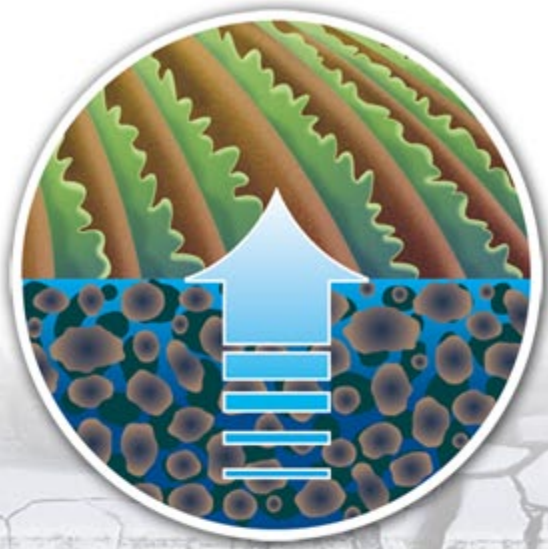


Abstracts



# Toward Sustainable **Groundwater** in Agriculture

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## Physical and Chemical Water Features as Indicators of Changes from Soil Management and Land Use

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Different land uses interferes on soil and water quality of hydrological resources. Water parameters evaluating can express the changes in a watershed over a period of time and its relationship with the management adopted as indicators of changes. With this aim the monitoring of the implementation of an Agroforestry System under different management in the water quality of four reservoirs of the Gully Watershed, Pindorama-SP, Brazil was done determining in situ four physico-chemical parameters (pH, electrical conductivity, dissolved oxygen and temperature) from July to October 2011. The water quality was monitoring in four dams under different management and water sampling was done every day when there were at least on-site activities as: fertilization, planting, hollow opening, irrigation, rotating or mowing and weekly when there were no activities. The water samples were taken before and after each activity. The revegetation after the dams construction was part of the recovery project to established a gully erosion process. The different managements resulted in 4 treatments: T1/Dam1: trees planted without tilling the soil, in hollows of 0.30 m x 0.30 m x 0.60 m deep, spaced 3 x 2m, with control of weeds using lines coupled to the tractor and mower, without annual crops between rows; T2/Dam2: trees planted in hollows, spaced 3.5m x 2m, weed control with herbicide Roundup WG and annual crops (corn) between rows of tree in no-tillage system; T3/Dam 3: trees planted in furrows with soil tillage and furrow opening using soil disk and trencher, spaced 3.5 x 2m, annual corn crop under conventional tillage; T4/Dam4: trees planted in furrows with soil tillage using soil disk and trencher, spaced 3.5 x 2m with no annual crops between rows. The proposal of the plantation was to manage differently the plantation from a minimum interference on the soil (Treatment 1) to intensive tillage and no vegetation protection (Treatment 4). The means of each parameter were compared with completely randomized design and 5 % Tukey test. The means value of each parameter varied in each of the reservoirs, the pH ranged from 7.44 (T1) to 7.76 (T4), dissolved oxygen ranged from 6.09 mg L<sup>-1</sup> (T1) to 6.43 mg L<sup>-1</sup> (T2). Considering each reservoir separately, there was statistical difference between the parameters during the four months of evaluation suggesting that the evaluation of water resources can be a useful tool to evaluate the interference of different agricultural activities and their implications on the environment.

## **Environmental Projects Relation to the Quality of Water in São Domingos River Basin Brazil, in the Period 2000 to 2010**

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The São Domingo's River Basin is a Water Resource Management Unit from the Rivers Turvo and Grande located in the northwest region of São Paulo State; Brasil. Those units were created to promote water improvements, financial support and strategy programs on water quality financing and guiding different projects for local development. This River Basin includes eight municipalities: Ariranha, Santa Adélia, Pindorama, Catanduva, Catiguá, Tabapuã, Cedral and Uchoa. The aim of this study was to make a survey of projects and actions developed and their relation to the São Domingo's river water quality from 2000 to 2010. To evaluate the effectiveness of projects some interviews were made with the managers of each town and queries to data reports from the São Paulo State government. The Environmental Company of São Paulo State (CETESB) is responsible for monitoring water quality of state rivers. Some areas along the extension of the River, using indexes as the Water Quality Index (WQI). This Index was used in this study as indicator for water quality once it is the only index that was calculated every year during 2000-2010. To confront the knowledge and participation of the local community in the process of improving water quality in the São Domingos River, 20 persons in each municipality were interviewed. Five places in the basin were monitoring during 2000 to 2010. The WQI annual average of each evaluated area from 2000 to 2010, were fitted in some categories from bad to good, according to the CETESB rating. It was observed that the WQI improved in four points monitored and in one point, in the Catiguá municipality, the WQI was lower in 2010 than in 2000. The number of projects in the São Domingos River Basin increased every year. It started in 2000 with only one project and ended in 2010 with 12 projects. The projects were distributed in the following themes: environmental education projects, reforestation programs, waste recycling campaigns, springs restoration projects, nucleation techniques for environmental restoration, erosion and flood containment works, constructions of sewage treatment plants and technical seminars. The results showed that all the programs and actions implanted by municipality managements from 2000 to 2010 had a straight relation with the São Domingos River water quality and that the Water Quality Index (WQI) can be considered as an efficient indicator for water quality monitoring.

## **Planning for Sustainable Management of Groundwater Resources, Case Study: Nishapur Plain in Iran**

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Sustainable management of groundwater resources is essential for sustainable agriculture in arid and semiarid regions. Groundwater should be managed to be effective, efficient and robust-balancing changes in demands and supplies over time and space and to ensure that there are no negative long-term irreversible or cumulative impacts on ecosystems. The two important considerations in defining sustainable yield are spatial and time scales. Sustainable yield should be defined on a scale small enough to address important local impacts, but large enough to recognize the ability of aquifer systems to adjust to pumping stress. Sustainable yield must also be defined over a specific time period. Pumping, recharge, and ecological response are all time dependent, changing over varying time scales of days, seasons, and years. So, in order to minimize the adverse impacts, sustainable yield should be defined according to the availability of water in different time scales. In Iran, due to its arid-semiarid climatic condition and limitations of dry farming, groundwater management has an essential role in agriculture as well as drinking water supply. Over the years, the agricultural expansion has resulted in over-exploitation of groundwater resources in almost the whole country. Groundwater depletion has caused many problems such as land subsidence, reduction in base flow of the rivers, destruction of wetlands, increasing the cost of pumping, and salt water intrusion in coastal areas. Studies show that over 90 percent of the groundwater basins in Iran are over-exploited and facing ever-increasing depletion. The purpose of this paper is to optimize the spatial and temporal scales of Nishapur plain in Khorasan Province in north east of Iran, in order to maximize sustainable yield and minimize negative impacts of groundwater withdrawal. Uncontrolled withdrawal of groundwater resources threatening social integrity and security of the region evidently shows the importance and necessity of planning for sustainable groundwater use in the region. Planning for sustainable management of groundwater resources is a complex task due to its long-term nature faced with many uncertainties. Considering the conditions of the Nishapur plain, different management scenarios are analyzed using MODFLOW and the concept of “capture” to determine sustainable groundwater discharge as follow: changing crop pattern, increasing irrigation efficiency, and improving water productivity; changing the temporal distribution of water use; wastewater reuse; surface water resources development projects; and controlling GW pumping. Having determined the sustainable aquifer discharge in each scenario, Game Theory is used to determine the optimal groundwater resources allocation to different consumers. To consider the effect of uncertainty and participation of stakeholders in the sustainable management of groundwater resources, Bayesian Belief Network (BBN) is used. Hugin software is used for the development of BBN network structure based on the conceptual model of the study area. Available information and data and the results of the integrated model of water resources and uses provide the input data to the network. The main results of this study are the estimate of the regional groundwater sustainable yield as well as the required time to achieve groundwater sustainability in different scenarios.

## **Connecting Regional Groundwater Assessments, Agriculture, and Groundwater Governance**

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Regional groundwater assessments provide a venue for understanding groundwater from a systems perspective with agriculture typically a prominent factor. Such assessments, however, can easily become largely an end in them-selves. This presentation focuses on key challenges in making regional groundwater assessments more relevant to agricultural water management and groundwater governance. Topics include integrating water quantity and quality, portraying longer-term effects, addressing multiple scales, the importance of water use data, distinguishing between climatic and direct human influences, and accounting for agricultural effects on groundwater recharge. The importance of a whole water cycle approach is emphasized.



## **Aquifer System Urucuia: Governance and Integrated Water Management in the São Francisco River Basin – Brazil's Northeast**

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The San Francisco River basin has 2.696 km and 638.576 km<sup>2</sup> of drainage basin, which surrounds parts of Alagoas, Bahia, Goiás, Minas Gerais, Pernambuco and Sergipe states, plus the Federal District. Most of water withdrawal of 181 m<sup>3</sup>/s, 63%, is used to irrigation of 500.000 hectares, mainly located in the Middle São Francisco. This region consumes more than half of the flow of irrigation to products fruits and grains (soybeans, cotton and corn) for the foreign market. The region has experienced water stress due to increased demand for water resources, resulting in growing exploitation of groundwater Aquifer System Urucuia (SAU), a regional aquifer which covers an area of 76,000 km<sup>2</sup>, ranging from southern Piauí to northwest of Minas Gerais, majority located in western Bahia. The São Francisco River Basin is an example of water conflict due to multiple and tensioning uses. High rates of extracted flow, water pollution, energy production, navigation, prolonged drought effects and, recently, disputes related to water diversion to ensure water security to Northern Northeast constitute a mix of threats and drivers of conflicts. This aquifer has great potential, in part already exploited, to supply the urban and irrigation demands. At the same time it plays an important role in regulating the river flow, especially in periods of drought, which in the region of Sobradinho, for instance, accounts for 90% of the flow. The Urucuia can be described as an open access aquifer, making it vulnerable to contamination by agricultural chemicals and reduction of natural recharge, product of pores compaction that reduces rainwater infiltration. Furthermore the greater part of this aquifer recharge area coincides with new expansion of agriculture irrigated areas. On the other hand, over-pumping is likely to interfere with its contribution to base flow maintenance to Corrente, Carinhanha and Grande rivers, tributaries of São Francisco River. Between 2003 and 2006 the number of grants of Urucuia water exploitation for irrigation increased by 123%, from 4,500 m<sup>3</sup>/h to 14,340 m<sup>3</sup>/s, increasing in 320% the removal flow. It is worth noting that in Brazil there is a serious problem related to illegal wells in operation; it is estimated that for every given well there are other three not granted. This has consequences for the sustainable management of groundwater resources. On the exposed complexity above and considering the climate change consequences, this article uses the concept of governance related to socio-cultural, economic, ecological and institutional. It aims to analyze public, social and private interests to harmonize the proposals of different users in order to permit a sustainable development and use of water resources. In addition, it will be analyzed how the concept of Integrated Water Resources could enhance governance and water security in this basin.

## **Water Security, Productive Restructuring and Land Use at Sepé Tiaraju Settlement, São Paulo State, Brazil**

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In Brazil, over the past decade, it has been institutionalized a water security policy with special attention to smallholder's farmers. The Decree 7272 (August 25th, 2012) regulated the Organic Law on Food and Nutrition Security and established the National Policy for Food and Nutrition Security (NPFs). It proposes to ensure universal access to quality water with sufficient quantity, establishing a link with the Water Security and prioritizing from the family farmers the families under water insecurity to food production. This paper presents the initial results of a project with smallholders that proposed to expand and ensure their water security by training them when implementing integrated water management practices in a recharge area of the Guarani Aquifer, Ribeirão Preto, São Paulo (SP), Brazil. A partnership of researchers and post-graduation teachers from Territorial Development and Environment Course UNIARA (Araraquara, SP), Groundwater Studies Research Center (CEPAS) of Geoscience Institute-USP, Environment Center from Brazilian Agricultural Research Corporation (Embrapa) (Jaguariúna, SP), and the families of the Sepé Tiaraju settlement located in the municipalities of Serra Azul and Serrana (SP). The settlement, created by the federal government, has 79 families (about 400 persons) and 798 hectares and represents at all more than 10% of the rural population in the municipalities of Serra Azul and Serrana that have an annual precipitation of 1462 mm. In 2004, after the settlement establishment a productive restructuring of land use, occupation and forms and landscape happened. A monoculture sugar cane field adopted until that time was replaced by a less impacting production systems, including agroforestry that promoted recovery of native vegetation and surface water. For social and productive development of families, the federal government provided the drilling of two wells that draw groundwater from the Guarani Aquifer and shared energy costs among the families. The payment share and water use at certain times of day resulted on conflicts especially in the dry seasons. The work had two fronts: a survey and systematization of data information of the area, the families and the needs and uses of water for life and production in the settlement. The second was to empower families to manage the different sources of water provided from: rainwater, spring water and reuse household water. At the current stage, changes towards a historical recovery of land use an occupation and good productive practices can be observed and we would like to know if they are related to groundwater conservation and springs water volume increase.



## **Models to Inform Policy on Agricultural Groundwater Use in the Upper Midwest**

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Groundwater use for agricultural has expanded tremendously in the upper Midwest in the past two decades as a result of longer growing seasons and advances in irrigation technology. As a result, a region that has been always considered water abundant now has conflicts between agricultural, recreational and ecological interests with many talking of water shortages. This has occurred with little legal precedent for managing conflicts and for appropriately dealing with surface-groundwater interactions. This paper will focus on the Central Sands region of Wisconsin where irrigated agriculture for growing potatoes, corn and other vegetable crops has become common in the past decades resulting in lowered lakes levels, with lakefront homes now far from the water, and drying up of headwater streams. The paper will describe the regulatory rules that apply to groundwater use in Wisconsin and how these rules have evolved with time and will discuss the challenges in the near term as sound scientific based rules struggle to keep up with rapidly increasing water use. This paper will describe the author's experience in working on the permitting of large high capacity wells for a number of large agricultural projects in the Central Sands region. For all of these permits, detailed groundwater models were developed to evaluate alternative well locations and pumping rates to select pumping configurations and use that minimized impacts to surface water resources. In the upper Midwest, the effect of irrigation pumping is directly related to the increase in evapotranspiration that results from change land cover from non-irrigated vegetation to irrigated row crops. This paper will describe the difficulties in determining the changes in evapotranspiration that occur and the resultant uncertainty in predictions of the effect of irrigated agriculture on groundwater and surface water resources. This uncertainty is confounded by the fact the climate has been changing and unlike many areas average annual precipitation has increased significantly over the past several decades. The paper will also discuss briefly nutrient management issues related to irrigated agriculture in the Central Sands and the ubiquitous nature of nitrate contamination in shallow aquifers. The use of soil-groundwater models to evaluate nitrate leaching as part of the permitting process and the use of models to select crop rotation and fertilizer application amounts and timing to reduce nitrate leaching will be discussed.

## The Central Valley Dairy Representative Monitoring Program – Insight from 4 Years of Monitoring and Special Studies

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Since 2012, the Central Valley Dairy Representative Monitoring Program (CVDRMP) has been implementing a regulatory compliance groundwater-monitoring program in the Central Valley of California spanning over 600 kilometers from north to south. The climate is semi-arid with hot, dry summers and cool winters with the majority of precipitation occurring between November and March. CVDRMP represents over 1,100 dairies, diverse soil and farming conditions, and collects data in over 430 dedicated monitoring wells adjacent to animal housing, earthen liquid manure storage lagoons, and fields where both liquid and solid manure is applied to fertilize forage crops. The program is tasked to identify farming practices that are protective of groundwater quality and formulate recommendations in 2019. Four years of groundwater monitoring have confirmed impacts to shallow groundwater quality associated with dairy operations. Elevated nitrate concentrations and salinity are ubiquitous and impart a trademark on groundwater similar to other, non-dairy agricultural operations. However, the overall utility of groundwater monitoring has been found to be limited. Regulatory attention was initially focused on lagoons. The program found that groundwater monitoring is not an effective means of investigation in the context of lagoons. Groundwater constituent concentrations do not yield information on concentrations in the leachate, the seepage rate, the overall mass loading rate, or the duration of the loading. To address this issue, CVDRMP conducted a comprehensive field investigation quantifying whole lagoon seepage rates. Seepage rates were small, ranging from zero to 2.2 mm d<sup>-1</sup>, with a mean and median of 1.0 and 0.7 mm d<sup>-1</sup>, respectively (n=16). Lagoons ranged in age from less than 10 to over 50 years, i.e., many of them predated regulations or guidance for lagoon liner design. Subsurface soil textures ranged from sand to silt clay, but seepage rates did not correlate well to soil texture. One lagoon, where exposed gravel strata are suspected, had a seepage rate of 3.9 mm d<sup>-1</sup> when at full capacity. Seepage rates and the mean nitrogen mass-loading rate of 1,172 kg ha<sup>-1</sup> y<sup>-1</sup> were consistent with findings of other research efforts. Complementary soil borings and geophysical methods documented that effects of lagoon seepage on groundwater quality are generally small and remain localized. Based on preliminary land base and unit loading rate estimates from 41 dairies, lagoon contributions were estimated to be 2.3-3.5 percent on a farm scale compared to 96.5-97.7 percent from crop fields (animal housing including corrals not included). The program identified groundwater monitoring as similarly ineffective in the context of assessing farming practices on the crop fields. Improvements in agricultural practices, including improved nutrient use efficiencies, manifest themselves in reduced subsurface nitrogen and salt mass emissions; this reduction is not necessarily observed in concentration decreases at the water table. To address this issue, CVDRMP is carrying out several research studies tackling the difficult task of nutrient management in full-scale production systems that heavily rely on organic sources (i.e., manure) for fertilization.

## **The Exportation of Agricultural Water in California and Other Arid Regions of the US**

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Many of the largest agricultural producers in the United States are located in arid regions that have recently experienced extended droughts. In California, 80% of developed water resources are used in agriculture, but the industry only contributes 2% to the state's gross domestic product. Much of the water used for irrigation is embedded in food products exported from the state. This study estimates the water exported from California and ten other drought-prone states by combining product-level water consumption and national trade data. This research utilized water foot printing methods to estimate total water use for agriculture production. For California, we derived nine unique product water intensities and used spatial analysis to characterize the water sources being used for agriculture. Expanded water foot printing results showed that California (68 TL/yr.), Nebraska (60 TL/yr.), and Texas (56 TL/yr.) were the largest consumers of water for agriculture in 2012 exporting 26%, 50%, and 28% of this water through products, respectively. Agriculture in these arid regions is heavily reliant on groundwater resources, which are being rapidly exhausted in dry periods, compromising sustained production in future droughts. Agricultural drought resilience in these states could be bolstered through alternative water resources, improving water use efficiency, and sustainable groundwater management.

## **Groundwater and Nitrogen Recharge Model for the On-Farm Flood Flow Capture Project in California**

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On-Farm Flood Flow Capture (OFFC) is a method to divert flood flow to agricultural lands for groundwater recharge and downstream flood damage reduction. An OFFC pilot project was conducted at the Terranova Ranch in western Fresno County (36°34'27.18"N, 120°5'39.69"W) in the Central Valley in California on vineyards, which can be ponded in winter without severely damaging the crop. The Terranova Ranch has access to water in the adjacent James Bypass, which retains overflow from the Kings River in wet years. The OFFC experiments were conducted using water in the James Bypass in 2011 to assess its feasibility and cost effectiveness. Groundwater recharges timing and nitrate leaching potential from OFFC likely affects the project benefits and feasibility. Therefore, this study assessed groundwater and nitrate recharge quantities and timings for OFFC using a HYDRUS 1-D model. In addition, the possibility of nitrate capturing soil pores was assessed through field infiltration tests. The modeled results indicated an equilibrium transport without the consideration of soil pore immobilizing affect could predict nitrate transport well. Therefore, an equilibrium transport model was developed for the 60 m vadose zone with multiple OFFC event and irrigation scenarios, using James Bypass's flow and climate data from 1983 to 2002. The model was calibrated with water contents monitored during the OFFC experiments in 2011 for the top 1.8 m soil. The model showed a quick increase (within 1 year) in groundwater recharge at the depth of 60 m when annual infiltration exceeds approximately 3 m, which is equivalent to 45 days of ponding at the project site. Nitrate recharge patterns varied as a function of deep vadose zone flow parameters and water application scenarios, but resulted in at least 70% of initial soil nitrate leached to groundwater by the end of modeling period in all scenarios. The findings indicate that an aquifer is recharged more quickly by applying OFFC to a small field for a longer period than applying it to a large field for a shorter period. Also it is important to select OFFC sites with smaller initial nitrate concentrations since most of the soil nitrate likely leaches to groundwater.



Figure 1 Infiltration Test with a Dual-ring Infiltrimeter and Mariotte Bottles. Pre- and post-nitrate concentrations were measured and plugged into HYDRUS 1D model to assess immobile zone nitrate capturing potential.

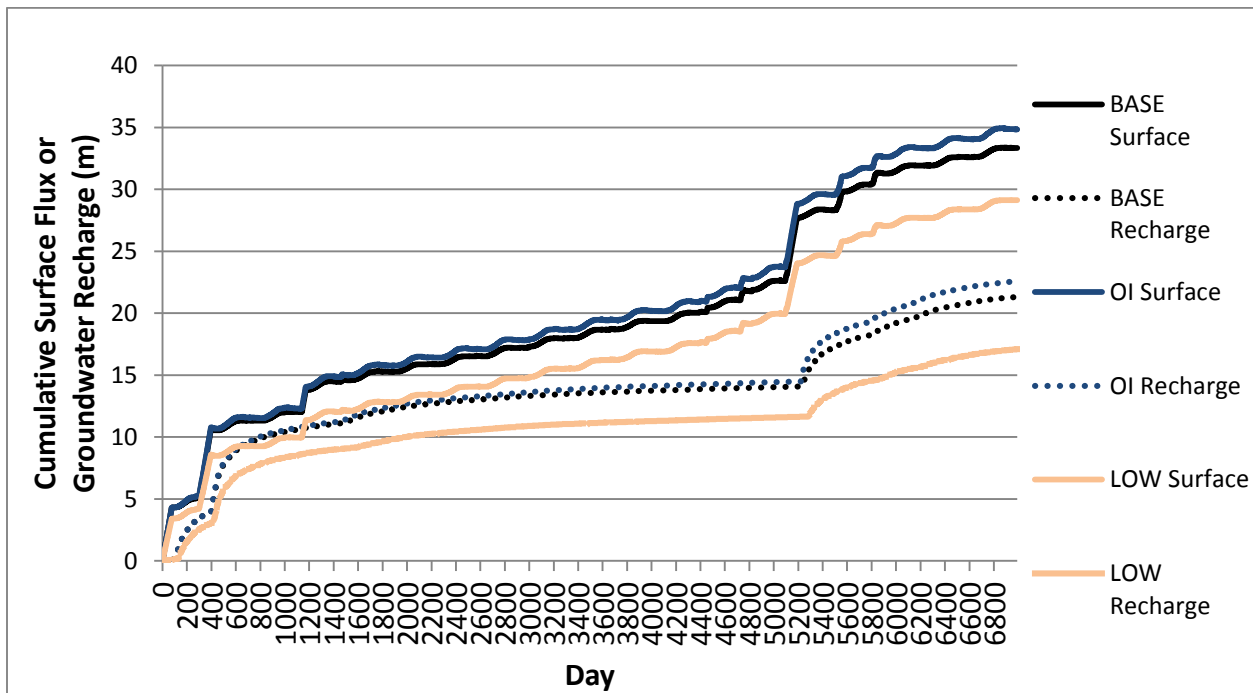


Figure 2. Groundwater Recharge Response to Surface Water Flux. Groundwater recharge increases quickly when surface water flux spike. BASE: Baseline scenario, OI: Over-irrigation scenario, and LOW: lower OFFC application rate scenario.

## Evaluating the Effects of Over Pumping and Drought on Water Supply Well Production Capacities and Pumping Costs

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Pumping more from groundwater basins than they can sustainably supply generally causes significant decreases in groundwater elevations. Such over pumping can be especially pronounced during droughts when surface water supplies are low. The economic impacts caused by over pumping and drought include increased costs for supplying water and lost revenue from inability to meet water demand. In some cases, the combination of decreased groundwater elevation and existing well depth limits well production capacity as wells run dry. Also, decreased groundwater elevation limits well pump operating capacity and increases cost. Water supply wells are constructed to different depths depending upon a variety of factors that include production rate and water quality requirements, local hydrogeology, and projections of future conditions and supply needs. Deeper wells also have been constructed over time as conditions and construction methods have evolved. As a result, the depths of existing water supply wells vary over fairly wide ranges. Overall, shallower wells are more susceptible to impact from decreased groundwater elevations. Likewise, pumps are initially selected and installed in wells based upon specific existing conditions (i.e., desired production rate, standing groundwater elevation and hydraulic performance of the well) and operations are impacted by decreased groundwater elevations. As groundwater elevations decrease, costs may be incurred to move pumps deeper in the wells so the pumps are adequately submerged below pumping water levels. Further elevation decreases may increase production and maintenance costs, as well as decrease production capacity, as pumping levels drop into the screened intervals of wells and cause screen clogging. In more extreme cases, well replacement costs may be incurred as groundwater elevations drop so low that adequate submergence of pumps cannot be maintained and wells become unusable. Additionally, operating points on pump head-capacity curves shift towards lower production rates, efficiencies decrease and operating times to produce required volumes of water increase. All of these effects decrease production capacity and increase operating costs. The potential impacts of decreasing groundwater elevation on well pumping costs were evaluated for a study area located in California's Central Valley (greater vicinity of Tulare, CA). Well constructions were characterized through statistical analysis of the elevations for the tops and bottoms of screened intervals obtained from well construction logs provided by the California Department of Water Resources (DWR). Groundwater elevation time series were obtained from the DWR Water Data Library. Estimated trends in well capacity loss were developed by determining the fraction of wells over time that had standing water levels (minus an estimated pumping drawdown) below 1) the top of the screened interval and 2) the bottom of the screened interval. Changes in pumping cost were evaluated by considering ranges in lift requirements based on the standing groundwater elevations (minus an estimated pumping drawdown) at different points in time. Trends in pumping costs were developed by calculating lift cost based on standard calculations. This presentation summarizes findings of groundwater well production capacities and pumping costs in the study area under sustained drought conditions.



## **The Economic Value of Emergency Groundwater Pumping During drought: The Yakima Basin, Washington State**

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The Yakima basin in south-central Washington is a major contributor to irrigated agricultural production in the state's 40-billion dollar agricultural industry. Climate change forecasts suggest that the snowpack providing water for the basin is expected to diminish in the next decade, bringing more frequent and severe agricultural irrigation water curtailment to several major irrigation districts in the basin. The economic impact of the 2015 drought on Washington State agriculture has been estimated by the state to be around 1-billion dollars, including direct and indirect economic impacts. There are many drought mitigation strategies that can be pursued at either the individual farm or irrigation district level including crop choice, the use of holding ponds, water market leasing, and emergency groundwater use for those who have invested in emergency wells. These wells may only be used with permission from the Washington State Department of Ecology during a formal State-recognized drought emergency. To the extent that these emergency groundwater wells reduce agricultural losses to the farmers using them, they will reduce the aggregate economic impacts. The economic benefits of groundwater use would be attenuated, however, if their use has downstream consequences on other surface water users through surface-groundwater interaction, or through impacts on other groundwater users during the high-demand season of late summer. Several recent studies have estimated the economic impact of drought in the Yakima Basin, but no study to date has estimated the value of emergency groundwater pumping in the basin. The objective of this study is to take a first step toward accurately estimating the value of emergency groundwater pumping in terms of its effect in reducing economic impact of drought. This analysis uses an existing hydrologic model of the Yakima Basin based on RiverWare, agricultural crop distributions and water value data for the major proratable irrigation districts in the Basin, and newly compiled emergency well-log data from these districts for the drought years of 2001, 2005, and 2015. We will also use curtailment histories for the Yakima Basin Project (a U.S. Bureau of Reclamation Irrigation Project) as well as simulated curtailment distributions based on available CMIP3 climate scenarios to estimate the aggregate expected present value of emergency pumping in terms of economic loss reduction. While we are not yet able to estimate the indirect effects of emergency pumping on other users, this model will ultimately be integrated with a groundwater model of the Basin, which will allow us to estimate these effects. We also empirically examine which water rights holders use emergency wells and which do not to assess the importance of spatial location, terrain, soil type, and farm size.

## **The McMullin Project: The justification and Process to Bring On-Farm Flood Capture from Concept to Implementation**

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The McMullin Recharge Project, a \$7 M project funded through a California Department of Water Resources (DWR) Flood Corridor grant, represents the first large-scale implementation of On-Farm Flood Capture as an approach to recharge aquifers and mitigate downstream flood risks. On-Farm Flood Capture leverages large areas of private farmlands for operation under dual purposes: farming and capture of available river flood flows. This concept was first funded through a USDA Natural Resources Conservation Service (NRCS) Conservation Innovation Grant (CIG) feasibility study (2010 – 2012) that tested technical and logistical questions associated with implementing this new approach: i.e., what farm level infrastructure is required, how to integrate flood capture and farming BMPs, which crops are compatible, what infiltration rates are achievable, what are the water quality challenges, what are the costs? These questions were addressed and answered to varying degrees through the CIG grant which identified infrastructure needs, determined anticipated infiltration rates on farmlands, identified compatible crops, estimated costs, and recommended approaches to managing water quality challenges. The CIG project led to the DWR-funded McMullin Recharge Project. Since awarded to the Kings River Conservation District (KRCD) in 2012, and with matching funds from Terranova Ranch, progress has been made with implementing this large-scale On-Farm Flood Capture project with the completion of Hydraulic and Hydrologic (H&H) analyses showing positive economics strictly from flood mitigation benefits; the development of the 30% design identifying design elements for implementation; development of a California Environmental Quality Act (CEQA) Initial Study to identify environmental impacts and recommended mitigation measures; development of a contractual framework for implementation and further expansion to neighboring farms; and beginning the permitting process. After completion of the McMullin Recharge Project Phase 1, the project will be able to divert up to 150 CFS of excess flood flows from the Kings River across over 5000 acres of farmland for monthly recharge total over 9000 ac-ft./month. Under full build out in future phases, the project will cover over three times the acreage and be designed to capture about 30,000 ac-ft./month. This project ultimately seeks to provide a cost-effective means for agricultural communities to participate in creating more sustainable water supplies and for GSAs to comply with the SGMA; and to provide a template for future On-Farm Flood Capture projects, identifying and providing solutions to the technical and regulatory challenges associated with implementing this technology.

## **The Challenges of Integrating Groundwater in a Significant Way Into California's Water Supply Portfolio**

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California's unprecedented drought is very likely a sign of California's water future under climate change: longer drought cycles, less reliable snow pack water supplies, higher temperatures and greater reliance on groundwater. The current drought has accelerated groundwater overdraft throughout the state, increased the cost and value of water for farmers, resulted in farmers moving to high value crops, hardened agricultural water demand despite less reliable water supplies, and perhaps most importantly focused the California public on the looming water challenges in the State. California has begun to take action by passing the Sustainable Groundwater Management Act (SGMA) to protect groundwater resources and by making resources available to address the drought. Nevertheless, in the coming decades California will likely face increased challenges in meeting environmental, urban and agricultural water demand because of a number of factors: climate change will likely increase inter- and intra-annual variability in precipitation and move more precipitation from snow to rain in the Sierra Nevada mountains. Combined with increased temperatures and increased summer crop ET demands these hydro-climatic changes will create greater a synchronicity between water supply and agricultural delivery schedules. These challenges will require a re-imagining and perhaps a re-engineering of California's water system. One potential tool for addressing this challenge is greater reliance on conjunctive use, leveraging private agricultural acreage throughout the Central Valley to capture release flows from reservoirs for storage in groundwater reservoirs. The concept of using agricultural lands to capture excess flood flows has been gaining interest and acceptance in California. Challenges associated with this approach include not only technical challenges associated with developing BMPs, strategies and infrastructure for capturing flood and storm water flows but also challenges associated with integrating flood capture BMPs with farming BMPs to protect crop yields and agricultural profits at economically sustainable levels and with implementing practices in ways that are legally consistent with State water laws, identified beneficial uses and future groundwater sustainability plans developed to comply with SGMA. These questions being currently addressed under several research efforts discussed here are the foundation for a future in which groundwater becomes a more critical and integrated component of California's water portfolio.

## Can Nitrate Leaching from an Orchard Be Accurately Estimated?

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Ground water pollution by fertilizer losses from agriculture land, mainly as nitrogen (N) compounds, is of major concern worldwide. The huge spatial and temporal variability in water flow and N-transport dynamics in an orchard makes it extremely challenging to accurately estimate N losses from such agricultural units. A 2-year study was conducted to explore nitrate (NO<sub>3</sub><sup>-</sup>) leaching below the root zone of an almond orchard. Temporal changes in water content, pore water NO<sub>3</sub><sup>-</sup> concentrations and soil water potential were monitored within and below the root zone to a soil depth of 3 m at eight sites which represented spatial variations in soil layers at the orchard. NO<sub>3</sub><sup>-</sup> concentrations below the root zone ranged from <1 mg L<sup>-1</sup> to more than 2400 mg L<sup>-1</sup> with mean concentrations of 326 mg L<sup>-1</sup>. Within the fertigation cycle, fertilizer injection at the end of an irrigation event generally resulted in lower NO<sub>3</sub><sup>-</sup> losses below the root zone compared with fertilizer injection mid-way through the irrigation. Statistical analysis using principal component analysis, Chi-squared Automatic Interaction Detector and the Artificial Neural Network showed that most of the deep soil NO<sub>3</sub><sup>-</sup> concentration variability could not be explained by irrigation duration, fertigation timing or local variations in soil physical characteristics. In addition coefficients of variation and semivariograms indicated weak (RMSE 220 mg NO<sub>3</sub><sup>-</sup> L<sup>-1</sup>) spatial correlation up to a distance of 60 m. Despite the huge variability in the NO<sub>3</sub><sup>-</sup> concentration, the orchard average annual N-losses estimated based on N-mass balance, water mass balance, flow calculations and HYDRUS modeling were all in the same order of magnitude (80 – 150 kg-N ha<sup>-1</sup> y<sup>-1</sup>). All methods indicated that most of the N losses occur early in the growing season (February – May), when fertilizer is applied to wet soil profiles. The study indicated that simple mass balance (i.e. water and N-load applied minus water and N-load removed) provides a good proxy of the annual N losses and that eight vadose zone monitoring sites can capture the orchard variability. Reduction of N losses at the orchard scale would require alternative fertigation and irrigation practices, including better control of fertigation amounts and irrigation duration.

## Matching Agricultural Freshwater Supply and Demand: Using Industrial and Domestic Treated Wastewater for Sub-Irrigation Purposes

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Agricultural crop yields depend largely on soil moisture conditions in the root zone. Climate change leads to more prolonged drought periods that alternate with more intensive rainfall events. With unaltered water management practices, reduced crop yield due to drought stress will increase. Therefore, both farmers and water management authorities search for opportunities to manage risks of decreasing crop yields. Available groundwater sources for irrigation purposes are increasingly under pressure due to the regional coexistence of land use functions that are critical to groundwater levels or compete for available water. At the same time, treated wastewater from industries and domestic wastewater treatment plants are quickly discharged via surface waters towards sea. Exploitation of these freshwater sources may be an effective strategy to balance regional water supply and agricultural water demand. We present results of two pilot studies in drought sensitive regions in the Netherlands, concerning agricultural water supply through reuse of industrial and domestic treated wastewater. In these pilots, excess wastewater is delivered to the plant root zone through sub-irrigation by drainage systems. Sub-irrigation is a subsurface irrigation method that can be more efficient than classical, aboveground irrigation methods using sprinkler installations. Domestic wastewater treatment plants in the Netherlands produce annually 40-50 mm freshwater. A pilot project has been setup in the eastern part of the Netherlands, in which treated wastewater is applied to a corn field by sub-irrigation during the growing season of 2015, using a climate adaptive drainage system. The chemical composition of treated domestic wastewater is different from rainfall excess water and agricultural drainage water. In the pilot project, specific chemicals in the treated wastewater are used as a tracer to describe water and solute transport in the soil system. Focus of this pilot study is on quantifying potential contamination of both the root zone and the deeper groundwater with pharmaceutical residues. We have installed a field-monitoring network at several locations on the vadose zone and the upper part of the local groundwater system, which enables us to measure vertical solute profiles in the soil water by taking samples. Based on field data obtained during the experiments, combined with SWAP (1D) and Hydrous (2D) model simulations, flow and transport of the sub-irrigated treated wastewater are quantified. In the south of The Netherlands, the Bavaria Beer Brewery discharges treated wastewater to the surface water. Nevertheless, neighboring farmers invest in sprinkler irrigation to maintain their crop production during drought periods. In this region, increasing pressure is put on the regional groundwater and surface water availability. Within a pilot study, a sub-irrigation system has been installed, by using subsurface drains, interconnected through a collector drain, and connected to an inlet control pit for the treated wastewater to enter the drainage system. We combine both process-based modeling of the soil-plant-atmosphere system and field experiments to i) investigate the amount of water that needs to be and that can be sub-irrigated, and ii) quantify the effect on soil moisture availability and herewith reduced needs for aboveground irrigation.

## Sub-Irrigation with Water: A Soil Column Experiment to Foresee and Mitigate Clogging

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The Netherlands hosts a well-developed agricultural sector that largely relies on an almost guaranteed availability of fresh water from surface water or ground water sources. This business strategy is at risk of failure, however, because socio-economic developments and climate change will lead to prolonged periods of water scarcity due to increasing water demand and decreasing water availability. In order to secure sufficient agricultural water supply to maintain current crop yields in future, water managers seek for measures to mitigate water scarcity. In search for these measures, particular interest is exhibited to the implementation of measures for improving regional self-sufficiency in water demand by re-using wastewater as a source for agricultural crop irrigation. Major challenge for implementation of this strategy is the development of a cost-effective infrastructure for equal distribution and supply of wastewater across agricultural fields. In this study, we investigated whether such infrastructure can be provided by sub-irrigation systems. Sub-irrigation is a parcel-scale, subsurface technique for water distribution and supply across agricultural fields. It consists of a network of subsurface drains, interconnected through a collector tube, and connected to an inlet control pit for supply water to enter the drainage system. Sub-irrigation may be more efficient compared to classical, above ground irrigation techniques, as evaporation losses are prevented and vast agricultural fields can be irrigated in equal or manageable amounts. Moreover, when irrigating from wastewater, sub-irrigation prevents crop leaves from being exposed to the wastewater, and its solutes, which can be harmful for the crop itself or lead to public health risks. A possible disadvantage of sub-irrigation with wastewater is that sub-optimal water quality may speed up clogging of drain tubes used to distribute and supply irrigation water equally over the parcel. This would require more regular and intense maintenance, causing additional costs. To foresee and prevent costs associated with clogging of the drain tubes, we employed experimental research on two soil columns that were supplied with wastewater from the Bavaria Beer Brewery. To this purpose, two undisturbed soil columns (1.0 x 0.5 x 0.5 m) were collected from an agricultural field by gently pressing a perforated casing made of stainless steel into the soil. After installing perforated bottom plates, a drain, 6 cm in diameter, was installed along the longitudinal axis of each soil column. The soil columns, cased in perforated stainless steel, were installed in containers filled with coarse-grained sand, and attached to inflow and outflow containers with adjustable water levels. Head differences over and within the soil column and outflow fluxes were measured hourly using pressure sensors. Based on these experimental data and supporting Hydrus 2D simulations we quantify irrigation and clogging rates and translate the results to field scale application. With this poster, we present the method and results of a series of column experiments and seek for discussion about additional experimental research on measures to prevent clogging of sub-irrigation systems when using wastewater.



## Negotiating Agriculture Representation in Decision Making on Groundwater Sustainability

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Recent California law requires local public agencies overlying basins in overdraft conditions to come together to form public agencies to manage groundwater sustainably. This paper will examine challenges that the law presents for agriculture groundwater users to participate in governance decision-making: unifying diverse agricultural interests and representing agricultural groundwater users via existing or by forming new public agencies. The paper will draw on coastal case studies, specifically Sonoma County in Northern California, Ventura County in Southern California, and the Salinas Valley on the Central Coast. Many growers and operators in California agriculture rely heavily, sometimes solely, on groundwater for production. In groundwater basins, growers, processors, and shippers may all rely on a common resource. Agriculture is also likely to be dispersed over a large geographic area within the same groundwater basin with different climatic conditions and crops subject to management and state requirements for sustainability. Growers may have very different cultures, social classes, and water use practices – think orchards, strawberries, vegetable farmers, grape growers, and cattle ranchers. Yet, despite the diversity within agriculture and the necessity of groundwater to support the agriculture (and local) economy, agriculture may be vying for just one seat on a governing body that can levy fees and limit pumping under the new law. This is one significant challenge with implementing groundwater sustainability. The law is designed for public bodies to step up groundwater management. While agriculture relies on irrigation districts that qualify as public bodies to represent agricultural interests in some basins, many have no public entities to fully represent the interests of agriculture. Often representation of diverse agriculture interests falls to county governments and elected officials. Concerns about the ability of government staff to be able to represent agricultural interests are leading agriculture to innovate and organize to form new public bodies. For example, the Sonoma County Farm Bureau has been advocating creation of irrigation districts to secure supply of water for agriculture and contribute to the sustainability of groundwater resources. Two of the three medium-priority basins took an approach to establish an agricultural water district through an election process with the Local Agency Formation Commission while the third basin took a legislative approach. The first group ended up resurrecting an existing dormant district and transforming it to a larger and more representative district to serve on the groundwater agency. The paper will discuss the merits and challenges of these different approaches, looking at both negotiation theory and practical case experience to examine options for representing agricultural interests to support unifying diverse agricultural interests to engage effectively as “one voice” in groundwater management.

## **The Nitrogen Legacy: Emerging Evidence of Nitrogen Accumulation in Anthropogenic Landscapes**

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Watershed and global-scale nitrogen (N) budgets indicate that the majority of anthropogenic N inputs to the landscape do not reach the coastal ocean. While there is general consensus that this “missing” N either exits the landscape via denitrification or is retained within watersheds as nitrate or organic N, the relative magnitudes of these pools and fluxes are subject to considerable uncertainty. Our study, for the first time, provides direct, large-scale evidence of N accumulation in the root zones of agricultural soils that may account for much of the “missing-N” identified in mass balance studies. We analyzed long-term soil data (1957-2010) from sites throughout the Mississippi River Basin to reveal N accumulation in cropland of 25-70 kg ha<sup>-1</sup> y<sup>-1</sup>, a total of 3.8±1.8 Mt/y. We then developed a simple modeling framework to capture N depletion and accumulation dynamics under intensive agriculture. Using the model, we show that the observed accumulation of soil organic N in the MRB over a 30-year period (142 Tg N) would lead to a biogeochemical lag time of 35 years for 99% of legacy soil organic N, even with complete cessation of fertilizer application. By demonstrating that agricultural soils can act as a net N sink, the present work makes a critical contribution towards the closing of global N budgets.

## **Exploring Nitrogen Legacies and Time Lags: A 200-Year Longitudinal Study of the Mississippi and Susquehanna Watersheds**

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Global flows of reactive nitrogen (N) have increased significantly over the last century in response to land-use change, agricultural intensification and elevated levels of atmospheric N. Despite widespread implementation of a range of conservation measures to mitigate the impacts of N-intensive agriculture, N concentrations in surface waters are in many cases remaining steady or continuing to increase. Such time lags to the recovery of surface water quality are increasingly being attributed to the presence of legacy N stores in subsurface reservoirs. It has remained unclear, however, what the magnitude of such stores might be and how they are partitioned between soil and groundwater reservoirs. In the present work, we have synthesized data from numerous sources to develop a comprehensive, 200-year dataset of N inputs to the land surface of the continental United States. We have concurrently developed a parsimonious, process-based model that utilizes this N input trajectory together with a travel time-based approach to simulate biogeochemical transformations of N along subsurface pathways. Model results allow us predict the magnitudes of legacy N in soil and groundwater pools and to predict long-term N loading trajectories over the last century and into the future. We have applied this modeling approach to two major U.S. watersheds, the Mississippi River and Susquehanna River Basins, which are the sources of significant nutrient contamination to the Gulf of Mexico and Chesapeake Bay, respectively. Our results show significant N loading above baseline levels in both watersheds before the widespread use of commercial N fertilizers, largely due to 19<sup>th</sup> century conversion of natural forest and grassland areas to row crop agriculture, although the temporal patterns of this loading differed between the two watersheds due to differences in the trajectories of land-use change. Using the model, we estimate spatiotemporal patterns of N accumulation in both groundwater and soil organic matter in response to increases in N inputs to agricultural soil as well as changes in N residence times across the terrestrial system. Simulations of future scenarios allow us to predict changes in N loading as determined by both ongoing inputs and the existence of biogeochemical and hydrologic N legacies.

## **Soil Leaching in Saline Areas are it the Best Practice for Salinity Management in Agriculture? A Case Study from the Aral Sea Basin, Central Asia**

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Salinization and waterlogging of irrigated agricultural land is a serious threat in Central Asia and especially in the Aral Sea basin. Salinization is coped with by pre-season leaching and excessive irrigations. However, massive water applications cause rising groundwater tables of few decimeters till few meters from the soil surface. Too shallow groundwater can be a barrier for leaching of salts from the soil root zone. A study is conducted in the Khorezm Region of the Aral Sea Basin, where the objective is to assess the efficiency of soil leaching to reduce harmful salts. HYDRUS-1D was used to model vertical soil root-zone moisture and salinity dynamics, accounting for shallow groundwater, which by far prevails over lateral flow. Long term groundwater table and salinity, soil texture and salinity, and other factors that drive soil salinization and waterlogging, have been collected over the period of 2003 – 2014. Simulation covered most crops grown in the province, cotton, winter wheat and vegetables. Inverse modeling was used to calibrate the model for each of the crops. The results show a substantial contribution of moisture from shallow groundwater in the range of 23% – 30 % depending on groundwater levels, to the total crop water requirements. The leaching procedure caused relocation, but not removal, of salts within the 1.5-m profile and maintains the high groundwater table problem. Evaporation, causes the capillary rise and 40 % increase of salts in loamy soils and tripled in sandy soils within the top 80-cm soil layers during the crop growth season. Research results also showed that, improving irrigation and drainage management will lead to alleviation of the land degradation.

## **New Model for Groundwater Management in Rural-Agricultural Basins**

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California's Central Coast Hydrologic Region relies on groundwater for approximately 80 percent of its water supply to serve rural, urban, agricultural, and environmental demands. San Luis Obispo County, one of six counties within this region, has 22 groundwater basins underlying 3,304 square miles of largely rural and agricultural lands. Historically, these groundwater basins have had no requirements to manage groundwater. However in January 2015, the State enacted its first major groundwater law – the Sustainable Groundwater Management Act (SGMA) – that requires local agencies to establish governance structures in order to sustainably manage groundwater resources. Some groundwater basins have adequate existing local agencies capable of this task; others do not. This topic will briefly overview potential management strategies being considered in local basins. Speakers will focus discussion on a unique case study of a governance model developed by stakeholders in the Paso Robles Groundwater Basin (Paso Basin). Stakeholders in this basin worked with Assemblyman Achadjian to introduce AB2453, a bill that created the opportunity to form California's first hybrid water district. The intent was to have a board of directors that reflected the unique demographics of the basin. Instead of a basin comprised solely of agricultural interests, the Paso basin has a diverse mix of rural residential, commercial wineries, irrigated agriculture (vineyards, deciduous fruit, forage crops & vegetables) and livestock. Landowners on a weighted 'one acre-one vote' methodology elect traditional water districts board of directors. AB2453 modifies this practice by instituting a hybrid nine-member board reflective of the various land uses in the Paso Basin. Three members have to be registered voters living within the district boundary, and would be elected by registered voters living within the district boundary. The remaining six seats would be filled by landowners, but broken further into three categories of small (<40 acres), medium (40 – 40 acres) and large (>400 acres) landowners. These members would be elected by an acreage vote, similar to traditional water districts. Creation of the water district is subject to a formation vote by landowners and funding approval under Proposition 218. The water district application was reviewed by the Local Agency Formation Commission in order to establish boundaries and powers, and the landowner formation vote and Proposition 218 funding vote are scheduled for March 2016. At the time of the conference we will know the results of the elections, and will be able to discuss next steps based on those outcomes.

## **The Effects of climate Change on Groundwater Extraction for Agriculture and Land-Use Change**

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The management of groundwater resources is an issue that reaches far and wide; regions around the world are struggling with ways to reign in extraction from aquifers that have been deemed over-exploited, and many of the world's most productive agricultural basins depend almost exclusively on groundwater. The food consumers that eat, the farmers who produce that food, and the local economies supporting that production are all affected by the availability of groundwater. Worldwide, about 60 percent of groundwater withdrawn is used in agriculture, and in some countries, the percent of groundwater extracted for irrigation can be as high as 90 percent. Thus, any investigation into the economics of groundwater must consider the agricultural industry. The proposed research focuses exclusively on the groundwater used for agriculture. Climate change has the potential to impact groundwater availability in several ways. For example, it may cause farmers to change the crops they plant or the amount of water they apply, both of which have implications for water availability. Climate change also affects water availability directly by changes in precipitation and evapotranspiration patterns. In this paper, we analyze the effects of changes in temperature, precipitation, and humidity on groundwater extraction for agriculture using an econometric model of a farmer's irrigation water pumping decision that accounts for both the intensive (water use) and extensive margins (crop acreage). Our research focuses on the groundwater used for agriculture in the High Plains (Ogallala) Aquifer system of the Midwestern United States. We find that changes in climate variables will influence crop selection decisions, crop acreage allocation decisions, technology adoption, and the demand for water by farmers. We also find that such changes in behavior can affect the diversity of crops planted, potentially impacting agricultural biodiversity. According to our preliminary results, water intensity decreases in rainy years. Farmers tend to plant more corn and soybeans after rainy years, as evidenced by a significant positive coefficients a total precipitation over the last 3 years on the crop acreage regressions for these crops. Farmers planting more than one type of crop tend to increase acreage of alfalfa, sorghum and wheat in warmer/dryer years and increase acreage of corn and soybeans in colder/wetter years. High temperatures in March can trigger the installation of central pivots with sprinklers: also true for rain in May/June. We find mixed results for crop acreage and water use in the regressions with monthly variables. Farmers tend to diversify crop acreage in warmer/dryer years. The outcome of this research provides a better understanding of how changes in temperature, precipitation, and humidity affect the availability of groundwater for agricultural use and of how agriculture can adapt to these changes. We are also able to see how such adaptation measures affect crop diversity, one of the main components of agricultural biodiversity.



## **Water Quality Trends in Irrigation Return Flow from a Southern Idaho Watershed.**

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The quality of irrigation return flow in an 82,000 ha watershed in southern Idaho has changed since 1970 when return flow water quality was first measured. Converting from furrow irrigation to sprinkler irrigation and installation of sedimentation ponds has greatly reduced sediment losses. There is now more sediment entering the watershed with irrigation water from the Snake River than returns to the river, compared to a net loss of 460-kg/ha sediment in 1971. The irrigation water has <0.5 mg/L of nitrate-N. Runoff from furrow-irrigated fields does not increase nitrate-N concentrations. Subsurface drainage, however, does contribute nitrate-N from shallow groundwater to irrigation return flow, resulting in 10 to 15 kg/ha of nitrate-N flowing to the Snake River each year. Nitrate-N concentrations in four main return flow streams approximately doubled from 1970 to 2005 to 2-2.5 mg/L. Recent data indicate about a 10% decrease in nitrate-N concentrations from 2005 to 2015. There is more soluble salt flowing into the watershed with irrigation water than returning to the river. While continually adding salts to the soil is not desirable, the overall average sodium adsorption ratio (SAR) in the irrigation water from 2005-2008 was only 0.73 and the average soluble salt concentration was 280 mg/L or 435  $\mu$ S/cm, which are low enough to not impact crop production. Nitrate-N has become a higher natural resource concern in this watershed as sediment losses have been addressed. Continued efforts to improve irrigation and nitrogen management will be needed to reduce nitrate-N concentrations in shallow groundwater which will reduce nitrate-N in irrigation return flow.

## Fate and Persistence of Emerging Contaminants and Multi-Resistant Bacteria in the Continuum Surface Water – Groundwater (The PERSIST Project)

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The PERSIST project aims to increase the knowledge on the behavior of a selection of targeted pharmaceutical products (as EOCs) and antibiotic multi-resistant bacteria (MRB) in both surface water and groundwater bodies, as they represent a growing public health concern. Residual pharmaceutical products in the environment may arise from wastewater effluent outlets and intensive manure application as fertilizers in agricultural areas. MRB are transmitted to ecosystems directly from wastewater or developed in-situ due to the occurrence of residual antibiotics. However, the fate and transfer of EOCs and MRB in both surface water and groundwater bodies are not well known yet; that is, the hydrological processes that govern their migration at a field scale. The study is carried out on two complementary hydrogeological field sites: the Vistrenque basin (SE France) and the Empordà basin (Catalonia, NE Spain). The investigation will be carried out at the catchment scale, in a surface water/groundwater continuum, as well as at the laboratory scale where soil columns will be used to evaluate the transport properties of selected pharmaceuticals. The results will be useful to delineate guidelines for groundwater pollution prevention and aquifer restoration, contributing to the development and implementation of EU directives for EOCs occurrence in water bodies. Preliminary results are presented on the occurrence of EOCs on the Vistrenque and Empordà alluvial aquifers. On the Vistrenque basin, an overall survey including 52 sampling sites, 21 molecules were analyzed including, carbamazepine and its degradation product, 6 betablockers, 11 antibiotics and 1 anti-diabetic molecule. Only 4 of the 21 molecules were not detected in groundwater at all: Flumequine, Ciprofloxacin, Trimethoprim, and Atenolol. The remaining 17 molecules showed detection frequencies varying from 4% to 77%. The most detected molecules, with detection frequencies above 20%, are Carbamazepine (77%) and its degradation product (42%), Erythromicine (70%), Roxithromycin (46%), Sulfamethoxazole (31%), Ofloxacin (31%) and Spiramycin (23%). The mean individual concentrations are on the order of a few ng/L. Carbamazepine reaches tens of ng/L and in a few locations attains a few hundreds of ng/L. On the Empordà basin area, analyzes focused on antibiotics in groundwater (n=47) and surface water (n=7). 11 out of 53 analyzed antibiotics were found in groundwater, corresponding to four different chemical groups: fluoroquinilones, macrolides, quinolones and sulfonamides. The most detected compounds were Ciprofloxacin, Enrofloxacin, Norfloxacin, and Sulfamethoxazole. Sulfamethoxazole was detected in 80% of the groundwater samples with mean concentration of 6.1 ng/L and highest concentration of 28.6 ng/L. Ciprofloxacin was observed in 45% of the samples, with mean concentration of 77.2 ng/L and highest concentration of 298.3 ng/L. In surface water samples, five different antibiotics were quantified, being Sulfamethoxazole and

Ciprofloxacin the most detected ones. To better constrain the sources and transfer processes of these compounds, their occurrence will be correlated to environmental tracers allowing to define the origin and residence time of water sample, and to set the hydrological processes that control their transport. Results from complementary column experiments will provide transport parameters, support field evidences, and allow the results to be up-scaled with the aim to model the fate and migration of EOCs at the catchment scale. Acknowledgements: This study is part of the PERSIST project funded by the EU Water JPI.

## **New MODFLOW's One-Water Hydrologic Flow Model and Application to Conjunctive Use of the Rio Grande River and Trans boundary Aquifers**

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The Palomas, Mesilla, and Conejos-Medanos Basins in New Mexico, Texas, and Mexico comprise a geologically and hydrological complex region. The conjunctive use of surface-water and groundwater takes place under a myriad of legal and operational constraints, including the Rio Grande Compact, an international treaty, and the Bureau of Reclamation's Rio Grande Project. New demands are being placed on the interconnected water system, even as the region is experiencing an extended drought. To better understand the complex hydrogeological flow system and support ongoing resource management decisions, the U.S. Geological Survey in cooperation with the Bureau of Reclamation is developing the Rio Grande Trans-boundary Integrated Hydrologic Model (RGTIHM). This model uses MODFLOW's One-Water Hydrologic Flow Model (MF-OWHM) to build on previous hydrologic modeling efforts. The RGTIHM model is being developed concurrently with the new release of MF-OWHM to take advantage of new features unique to it. The One-Water Hydrologic Flow Model is a MODFLOW-based integrated hydrologic flow model that is the most complete version, to date, of the MODFLOW family of hydrologic simulators needed for the analysis of a broad range of conjunctive-use issues. MF-OWHM fully links the movement and use of groundwater, surface water, and imported water for consumption by agriculture and natural vegetation on the landscape, and for potable and other uses within a supply-and-demand framework. MF-OWHM is based on the Farm Process for MODFLOW-2005 combined with Local Grid Refinement, Stream flow Routing, Surface-water Routing Process, Seawater Intrusion, Riparian Evapotranspiration, and the Newton-Raphson solver. MF-OWHM also includes linkages for deformation-, flow-, and head-dependent flows; additional observation and parameter options for higher-order calibrations; and redesigned code for facilitation of self-updating models and faster simulation run times. The next version of MF-OWHM, currently under development, will include a new surface-water operations module that simulates dynamic reservoir operations, the conduit flow process for karst aquifers and leaky pipe networks, a new subsidence and aquifer compaction package, and additional features and enhancements to enable more integration and cross communication between traditional MODFLOW packages. By retaining and tracking the water within the hydrosphere, MF-OWHM accounts for "all of the water everywhere and all of the time." This philosophy provides more confidence in the water accounting by the scientific community and provides the public a foundation needed to address wider classes of problems such as evaluation of conjunctive-use alternatives and sustainability analysis, including potential adaptation and mitigation strategies, and best management practices. Thus this provides a more complete understanding of the conjunctive use of surface-water and groundwater along the transboundary aquifer of the Lower Rio Grande.

## **Innovations in Agricultural Groundwater Management: Smart Markets for Transferable Pumping Rights**

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While no national policy on groundwater use exists in the United States, local groundwater management is emerging across the country in response to concerns and conflicts over declining well yields, land subsidence, and the depletion of hydro-logically connected surface waters. Management strategies include well drilling moratoria, pumping restrictions, and restrictions on the expansion of irrigated land. To provide flexibility to groundwater users, local regulatory authorities increasingly have begun to allow the transfer of groundwater rights as a cost-effective management tool. Markets can be a versatile risk management tool, helping agricultural communities to cope with scarcity, to meet goals for sustainability, and to grow resilient local economies. For example, active groundwater rights transfers exist in the High Plains region of the United States. Since most groundwater pumped in the High Plains region is used for irrigation, the transfers of use rights are therefore predominantly between agricultural producers. Yet, several barriers to trade exist: high search costs for interested parties, complicated requirements for regulatory compliance, and reluctance to share sensitive financial information. Additionally, groundwater pumping leads to several kinds of spatial and inter-temporal externalities such as stream depletion. Indeed, groundwater management schemes that reallocate water between alternate pumping locations are often explicitly designed to change the distribution and magnitude of pumping externalities. Reallocation may be designed to minimize unwanted impacts on third parties or to encourage trades that reduce the magnitude of externalities. We discuss how “smart” markets can deal with complex biophysical constraints while also encouraging active trading, therefore ensuring local goals for aquifer sustainability while growing local economies. Smart markets address these issues by providing a centralized hub for trading, automating the process of regulatory compliance by only matching buyers and sellers eligible to trade as specified in the regulations, and maintaining anonymous, confidential bidding.

## Evolution and Future of Nitrate Sensing Technology

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With the historic and recent attention to nutrient pollution in aquatic environments worldwide, the need for nutrient-sensing tools becomes increasingly prevalent. Interest has piqued in the sources of pollution and the dynamics of nutrients coming from these sources. Researchers have higher expectations for immediate information than in decades past. Due to instrumentation challenges, agricultural runoff and groundwater dynamics are currently cumbersome to quantify, involving the use of laboratory instrumentation, ion-selective electrodes, or optical in-situ devices. Optical continuous monitoring nutrient sensing devices that are currently available to the market were primarily designed for oceanographic or large water body applications. More recent efforts have been made to adapt such tools to agricultural applications. On the front lines of these efforts have been such groups as the Alliance for Coastal Technology with their Nutrient Sensor Challenge, and Tulane with their Grand Challenge, encouraging developers to progress the market. Scientists are working together with developers to customize sensors to modern studies. Our group at Decagon Devices, Inc. is currently working on a next generation nitrate sensor employing absorption spectroscopy techniques to eliminate the need for reagents and system maintenance. Our focus and interest has been in tile drains as well as edge-of-field measurements by the connection of this sensor to our drain gauge lysimeter. This nitrate sensor uses a small hose and pump for sample delivery to a surface-deployable unit that is low-maintenance, low-cost, and has low power-consumption as compared to its current market counterparts.

## Groundwater Nitrate Concentrations in the Permo-Triassic Aquifer of the Eden Valley, UK

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Groundwater nitrate concentrations in the Permo-Triassic aquifer of the Eden Valley, UK vary from less than 4 mg/l to in excess of 100 mg/l (as NO<sub>3</sub>). The variability is presumed to be due to land use and the main source of the nitrate is believed to be the nitrogen applied to grassland, both as slurry and as inorganic fertilizers. The main aim of this study was to estimate recharge rates and the timescale for water movement through the unsaturated zone and identify possible land use changes to reduce this influx of nitrate. Given the inherent uncertainties and limitations associated with the various methods for estimating recharge, it was proposed to use three different and independent methods and to compare the results obtained. The three methods proposed were: **(i)** to date the pore water profile within the unsaturated zone using the historical tracer tritium **(ii)** to date the pore water profile within the unsaturated zone using nitrate and chloride, released from the soil following the change in land-use from rough grazing to intensive pasture **(iii)** to estimate recharge using a soil moisture water balance approach. The average recharge rate was found to be in the range 424-468 mm/y and the rate of water movement through the unsaturated zone is c. 3.5-3.85 m/y. Based on this estimate of water movement in the unsaturated zone, the travel time for recharge to migrate from the soil to the water table (or the delay imposed by the unsaturated zone) over the highest ground (where unsaturated zone thickness can be in excess of 175m) the travel times could exceed 50 years. However, over large areas of the Eden Valley, the recharge currently arriving at the water table is of post 1990 origin. Thus, an important conclusion is that, over most of the Eden Valley, nitrate concentrations arriving at the water table are unlikely to substantially increase but the effects of any BMPs are unlikely to be seen in the saturated zone for a significant number of years.



## **Decadal-Scale Changes in Uranium and Bicarbonate Concentrations in Groundwater in the U.S.: Effects of Irrigation on the Mobilization of Uranium**

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Uranium has been shown to be mobilized by downward-moving irrigation water in the eastern San Joaquin Valley (SJV) of California (Jurgens and others, 2010). Development of the landscape for crop production has caused increased bicarbonate concentrations in shallow groundwater, and increased rates of recharge. The downward moving, bicarbonate-enriched groundwater mobilizes naturally occurring uranium in the sediments. Consequently, uranium concentrations at depth are increasing with time, and are affecting wells used for drinking water. It is hypothesized that the process observed in the SJV will be operative in other arid and semi-arid areas of the U.S., but not in humid areas. Water-quality data from 1,105 wells from across the U.S. were compiled from the U.S. Geological Survey National Water-Quality Assessment project. Most of the wells were first sampled during 1993-2002 and then subsequently sampled during 2001-2012. Some wells used in the analysis were sampled in 2001-2005 and subsequently sampled during 2012-2014. Uranium concentrations in groundwater were highest in the arid to semi-arid climate zones in the western U.S, where uranium in surficial sediments and rocks are abundant. Sixty-four wells (6 percent) sampled in the second decade were above the U.S. EPA MCL of 30 ug/L; all but one are in the arid west. Areas with low uranium concentrations in surficial rocks and sediments such as the Coastal Plain in the southeastern U.S., the upper Midwest, and northeast parts of Oregon and Washington generally have low concentrations of uranium in groundwater. Large uranium and bicarbonate increases (differences are greater than the uncertainty in concentrations) occur in 109 wells between decade 1 and decade 2. Similarly, large uranium and bicarbonate decreases occur in 76 wells between decade 1 and decade 2. Significantly more wells are concordant (uranium and bicarbonate are both going the same direction) than discordant (uranium and bicarbonate are going opposite directions) ( $p < 0.001$ ; Chi-square test). The largest percent difference in uranium concentrations occur in wells where uranium is increasing and bicarbonate is also increasing. These large differences occur mostly in the arid to semi-arid western U.S., consistent with the process of the mobilization of uranium by the increasing bicarbonate concentrations in irrigated areas. Uranium was not detected in either decade in 53 percent of the wells in the dataset. Ninety percent of these wells with no detections occur in the humid or dry sub-humid climate zones of the eastern U.S. Speciation calculations on water from wells with detection in at least one decade indicate that the uranium in groundwater occurs predominantly in the form of ternary complexes of uranyl carbonate with calcium (94 percent of samples). The concordant change in uranium and bicarbonate concentrations and the dominantly neutral pH ranges (6-8) are consistent with the speciation calculations, and consistent with the processes found by Jurgens and others (2010). References: Jurgens, B.C., Fram, M.S., Belitz, Kenneth, Burow, K.R., and Landon, M.K., 2010, Effects of groundwater development on uranium: Central Valley, California, USA: Ground Water, v. 48, no. 6, pp. 913-928

## What Will It Take To Protect Groundwater Quality Under California Central Valley Dairies?

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There is ample evidence of elevated nitrate concentrations in groundwater under dairies in the Central Valley of California, however solutions to this issue have been elusive. Regulations put in place may have raised awareness among dairy operators, and may have resulted in improved nutrient management, but have not resulted in the level of improvement necessary to protect groundwater quality. Work done in a 10-year study showed that while decreasing the amount of manure applied did result in a decrease in shallow groundwater nitrate concentrations, yields could not be maintained unless the amount of manure and other nitrogen applied exceeded what is now the regulatory limit of 1.4 times crop removal. Many dairy producers now find themselves in the position of being unable to maintain their production levels and still stay within the regulatory limits. Without access to improved nutrient management techniques and technologies, additional education and potentially changes in the regulatory system, dairy operators face the real possibility of being forced to move their dairies out of state or leave the dairy business. Many factors limit a dairy operator's ability to maintain production using only manure nitrogen forms. They include sandy soils with poor ability to retain nutrients, irrigation systems that cannot apply water at rates that minimize leaching of nitrates, fluctuating lagoon nitrogen concentrations, difficulty and complexity of measuring, recording and calculating application rates, uncertainties in predicting and accounting for manure and soil organic nitrogen availability, inadequate land base for the amount of manure generated, and limited economic resources to implement improvements even where proven technology exists. Solutions to these issues will be different for different regions and dairies within regions; there is no one approach that will fit all situations. However, in general, an effective nutrient management system on a dairy would include these essential components:

- Reasonable irrigation efficiency and uniformity to prevent excessive leaching
- Accurate measurements of irrigation water and nutrient inputs, and nutrient harvest removal
- Ability to apply specific amounts of manure nutrients at the target rates and times they are needed
- On-farm record keeping that provides timely in-season computation of application amounts
- Decision support for estimating organic N release, expected leaching losses and other dynamic nitrogen processes throughout the year both to make an application plan and to identify the need for in-season adjustments.

Implementation of each of these components has significant challenges, and in many cases the technology and science are currently inadequate or nonexistent. In addition, our experience is that there are many additional unforeseen issues that will need to be addressed on an individual basis for each dairy. Even when the best technology is implemented to minimize leaching through irrigation improvements, groundwater quality may not improve enough to meet regulatory expectations because some leaching is unavoidable and necessary to prevent salt buildup in the soil, and the nitrate and salt concentration in the reduced amount of leachate would be expected to be high.

## **Evaluation of N Mass Balance and Soil Nitrate as Indicators of N Leaching to Groundwater in a Pacific Northwest Dairy Grass Field**

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Dairy farms in the U.S. are expected to use nitrogen (N) mass balance techniques to determine appropriate agronomic manure application rates for forage crops. In addition, soil nitrate sampling is increasingly used as an indicator of the amount of N available at the end of the growing season for leaching to groundwater. We conducted a 4-1/2-year study that quantified the major N inputs, outputs, and residuals (soil and groundwater) at a commercial dairy field overlying a shallow water table aquifer in the Pacific Northwest. A purpose of the study was to evaluate N mass balance and post-harvest soil nitrate for effectiveness in representing effects on groundwater nitrate. A simple spreadsheet model that takes into account hydrologic characteristics of the site was useful for quantifying the mass of nitrate reaching the water table whether originating from the current year's N application or from internal loading due to past applications. However without groundwater nitrate data for comparison, even 4-5 year means for N mass balance and post-harvest soil nitrate did not correspond with early winter groundwater nitrate, despite intensive sampling of N balance components.

## **Changing California's Groundwater Policies and Implementation Strategies Could Increase Opportunities for Protecting Drinking Water While Improving Dairy Farm Environmental Performance**

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California's water protection policies were not developed with agriculture in mind, and the resulting limitations are becoming increasingly problematic. Existing regulations and permits are based on concepts born from regulation of point sources such as effluent limitations, total maximum daily loads, and others that do not fit well in an agricultural context, particularly for groundwater protection. Meanwhile, regional water quality control plans call for protection of all identified beneficial uses in water bodies, including the protection of drinking water quality. Since in many areas these protective policies extend to all groundwater (not just usable aquifers), this creates a fundamental conflict between contemporary agriculture, which applies nitrogen fertilizers to many crops, and drinking water protection regulations, which set standards for nitrate at very low levels (10 mg/L nitrate as N) even in non-aquifers. This especially challenges dairies whose use of organic nitrogen-rich manure is difficult to manage precisely. For agriculture to maintain compatibility with good water quality, large steps forward in technology and management techniques may be needed, some of which may take decades to achieve. Regulators and farmers, including dairy farmers, have few options when agricultural discharges to groundwater cannot meet water quality objectives. Among these, regulators may disallow the discharges, or only allow discharges to continue under a schedule that requires actions by the discharger expected to result, within a defined time frame, attainment of objectives. Unfortunately, it is not always clear what actions will actually attain this goal, especially in very shallow groundwater directly beneath actively farmed croplands. While dairy farmers have improved nitrogen use's efficiency, and have options for further improvement, it is far from clear when objectives can be met with today's or even future management practices and technology. California should consider policy options that allow for continued farming while pursuing improvement over time, even if those efforts do not immediately or even in the near future meet water quality objectives. Our goal should be continued and responsible farming using economically and environmentally sound practices that move toward attainment of objectives. Meanwhile, policy makers must work with agriculture and other stakeholders to assure safe, affordable drinking water for all Californians. In this manner, agricultural communities can remain viable. Existing regulatory and permitting approaches for implementing the above policies also need improvement. For dairies, regulators require extensive accounting, record-keeping and reporting of nutrient applications, and ongoing groundwater monitoring. This approach is logistically impractical, as it tends to direct resources toward generating records instead of recommendations and actions for improvement. California should instead encourage ongoing professional training for farmers, including education related to using new technologies, funding toward purchases of improved irrigation infrastructure where needed, and research toward continued improvement, refinement and standardization of tools farmers can use to improve economic and environmental performance on farms. Measuring success of these programs should be focused on verifying farmer participation in training efforts, and on broad trends in water quality and nutrient use efficiency, rather than creating overly detailed accounting of outcomes on individual dairy farms.

## **Groundwater Management: Past, Present, and Future in the Upper Kings Basin of the Central Valley, California**

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The San Joaquin Valley covers about 26,000 km<sup>2</sup> and is one of the most productive agricultural regions in California. Because the valley is semi-arid and the availability of surface water varies substantially from year to year and season to season, the agricultural industry developed a reliance on local groundwater for irrigation. Groundwater pumpage caused significant and extensive drawdowns, resulting in land subsidence at rates up to 0.3 meters per year. The completion of state and federal water distribution systems by the early 1970s eased the reliance on local groundwater as dependence shifted to diverted surface water. As a result, groundwater levels recovered and subsidence virtually ceased. In the last 20 years, however, land-use changes and an assortment of restrictions to surface-water availability— including droughts and environmental flows – have resulted in increased pumping and renewed land subsidence. The spatially variable subsidence has changed the land-surface slope in some places and caused operational, maintenance, and construction-design problems for water-delivery and flood-control canals as well as other infrastructure. The location, extent, and magnitude of land subsidence from the 1920s to 2015 were examined using Interferometric Synthetic Aperture Radar (InSAR), geodetic survey (spirit leveling and Global Positioning System surveys), extensometer, and continuous Global Positioning System (CGPS) data to estimate subsidence. Spatially and temporally dense data types are complementary and are needed to understand the mechanisms that underlie the spatial subsidence patterns and improve subsidence simulations. Since InSAR data became available in 1992, the comprehensive spatial coverage it provided has allowed the delineation of the spatial extent of subsidence: Geodetic survey, extensometer, and CGPS measurements show monthly, seasonal, and (or) inter-annual variations in subsidence rates at specific locations. Spirit-leveling surveys between the 1920s and 1970 indicated that more than half of the valley was affected by at least 0.3 m, and a local maximum exceeded 8 m of subsidence. Data from extensometers, combined with geodetic survey or CGPS data, indicated that compaction of sediments below the Corcoran Clay was the primary cause of subsidence. Data from extensometers, combined with other data sources, indicated that beginning around 1970, subsidence during the remainder of the 20th century occurred largely during drought periods. However, data from InSAR, geodetic surveys, extensometers, and CGPS during the 21st century showed subsidence patterns have changed, and in some circumstances, subsidence occurred irrespective of climatic conditions and was tied to land-use changes. Planning for the effects of subsidence in the San Joaquin Valley is important for water managers. As land use and surface-water availability continue to vary; long-term groundwater-level and subsidence monitoring, analysis, and modeling are critical to understanding the dynamics of historical and continued groundwater use resulting in water-level and groundwater-storage changes, and associated subsidence. Modeling tools, such as the USGS Central Valley Hydrologic Model, can be used in the evaluation of management strategies to mitigate adverse impacts due to subsidence while also optimizing water availability. This knowledge will be critical for successful implementation of recent legislation aimed toward sustainable groundwater use.

## **An Index for Evaluating the Risk of Water Contamination by Pesticides: Development and Validation**

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Since the surface and groundwater are strategic and vulnerable environmental compartments, their contamination by pesticides could cause significant damage to man and the ecosystems. The objective of this study was to develop a simple and robust index (ARCA) to estimate the risk of water contamination by pesticides, in different agronomic and environmental settings, and to validate it at the field level. The risk of contamination (R) in the ARCA index is the product of the environmental vulnerability of the site (V) and the contamination potential of the pesticides (Pc). The vulnerability is the product of the clay content of the soil, the distance to the nearest stream, and the type of soil management. The product of the pesticide mobility, persistence, and its toxicity gives the contamination potential to man and fish. An experiment was carried in a soybean field in Brasilia, Brazil, to validate the model. In that field study, the glyphosate concentration on the slope runoff and in the leachate were compared with the pesticide behavior predicted by the index. Furthermore, the glyphosate concentrations in the river downstream were compared with the risk calculated by the index. In both cases, the ARCA index correctly predicted the values and trends obtained in the field study. However, considering the limited scope of the field experiment, it is recommended that additional studies be carried, to better assess the validity of the ARCA index.

## **Balancing of Interests in Polder Dewatering: A Starring Role for an Integrated Groundwater-Surface Water Model**

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The Odra river floodplains at the German/Polish border have been dewatered and used for farming since the 18th century. An extensive system of hundreds of drainage ditches, a dike along the Odra River, and numerous pumping stations is used and maintained till date, ensuring to keep groundwater levels low enough for farming. At the same time, the remaining wetlands and pristine riparian forests in the area are valued increasingly from a conservation perspective, energy and maintenance costs become more important, and regarding the downstream flood risk precipitation is to be retained in the area for as long as possible. To facilitate the balancing of interests between the different stakeholders, such as farmers, different government authorities, and conservation groups, a coupled groundwater/surface water model has been set up for one of the polders. The integrated model developed in FEFLOW (groundwater) and MIKE 11 (surface water) considers the surface-water network with all control structures and pumping stations as well as the groundwater system. The model has been calibrated in detail for a transient period. Target groundwater levels have been defined, considering both a spatial and a temporal component. For example, farmland requires a high depth-to-groundwater especially in summer, while for wetlands water levels close to the ground surface during the bird-breeding period (until end of April/early May) are most crucial. The current drainage system operation has been evaluated based on these target groundwater levels, showing large deviations from an ideal situation. On basis of this reference scenario, an optimization of the management of the drainage system has been conducted, with the goals of (1) maximum water retention in the area and (2) matching the target levels as closely as possible. The adjustments to the system included different water levels at weirs, construction of new weirs and removal of existing ones, construction of new and abandoning of existing drainage ditches, modification of ditch-clearance plans and change of pumping station operation. Overall, a scenario could be developed that had the potential to significantly improve the situation. Not all goals, however, could be fulfilled in parallel. In order to use local knowledge as much as possible and to finally achieve a compromise that is acceptable to all different groups, a comprehensive stakeholder-participation process accompanied the entire project. Nearly all of the proposed measures have finally been accepted – not the least because the modeling tool, which was trusted by all parties involved, provided nonbiased information about benefits and losses for each party in each of the scenarios discussed.



## Groundwater Nitrate Attenuation and Changes in Groundwater Quality Across a California Delta Floodplain

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Groundwater is an essential resource to California residents, agriculture, and industry. Ongoing drought conditions limit aboveground water resources, causing groundwater to become increasingly vital. This study addressed groundwater quality as it relates to a delta floodplain in California's central valley. The objectives were to evaluate the role of riparian buffer zones as well as biogeochemical processes in the mitigation of groundwater nitrate (NO<sub>3</sub><sup>-</sup>) and to estimate the spatial, temporal and restoration related changes seen in groundwater quality. We hypothesized that NO<sub>3</sub><sup>-</sup> would decrease in groundwater (mitigation) after restoration of the floodplain and the wetland riparian ecosystem. The study site was located on the Cosumnes River floodplain approximately 30 miles south of Sacramento. The area has a history of agricultural production, but recently underwent restoration to become a preserve. We used 12 groundwater-monitoring wells located in areas of the floodplain representing various physical hydrological parameters and depths to groundwater. Groundwater and river water quality samples were taken bimonthly to monthly with concurrent measurements of groundwater levels. The groundwater quality samples were analyzed for NO<sub>3</sub><sup>-</sup> and ammonium (NH<sub>4</sub><sup>+</sup>) as well as d15N and d18O of NO<sub>3</sub><sup>-</sup>. Major cation and anion analysis was undertaken to evaluate hydrochemical facies and flow patterns within the aquifer, and pH, DO, and EC were recorded for part of the study to better understand environmental variables that might drive nitrogen transformations. Sediment textures were characterized at each well and soil C and N profiles were available for some locations from a concurrent study. Comparison of all these factors revealed tremendous spatial variability in the floodplain, with some temporal variability. Taking into account the ongoing drought (absence of seasonal flooding) it was difficult to discern any changes related to restoration efforts. Nitrate concentrations in riparian areas were significantly reduced compared to that elsewhere on the floodplain, though it was difficult to assess if this was due to low nitrate river inputs or riparian uptake. Isotopic analysis provided evidence of denitrification occurring in at least one well in a riparian area. We hypothesize that as restoration continues to improve riparian habitat, nitrate removal in the floodplain will continue providing a valuable ecosystem service for this type of restoration.

## Direct Monitoring of Agriculture Impact on Groundwater Quality

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Minimization subsurface pollution is much dependent on the capability to provide real-time information on the chemical and hydrological properties of the percolating water. Today, most monitoring programs are based on observation wells that enable data acquisitions from the saturated part of the subsurface. Unfortunately, identification of pollutants in well water is clear evidence that the contaminants already crossed the entire vadose-zone and accumulated in the aquifer water to detectable concentration. Therefore, effective monitoring programs that aim at protecting groundwater from pollution hazard should include vadose zone monitoring technologies that are capable to provide real-time information on the chemical composition of the percolating water. Obviously, identification of pollution process in the vadose zone may provide an early warning on potential risk to groundwater quality, long before contaminants reach the water-table and accumulate in the aquifers. Since productive agriculture must inherently include down leaching of excess lower quality water, understanding the mechanisms controlling transport and degradation of pollutants in the unsaturated is crucial for water resources management. A vadose-zone monitoring system (VMS), which was specially developed to enable continuous measurements of the hydrological and chemical properties of percolating water, was used to assess the impact of various agricultural setups on groundwater quality, including: (a) intensive organic and conventional greenhouses, (b) citrus orchard and open field crops, and (c) dairy farms. In these applications frequent sampling of vadose zone water for chemical and isotopic analysis along with continuous measurement of water content was used to assess the link between agricultural setups and groundwater pollution potential. Transient data on variation in water content along with solute breakthrough at multiple depths were used to calibrate flow and transport models. These models were then used to assess the long term impact of various agricultural setups on the quantity and quality of groundwater recharge. Relevant publications: Turkeltaub et al., WRR. 2016; Turkeltaub et al., J. Hydrol. 2015; Dahan et al., HESS 2014. Baram et al., J. Hydrol. 2012.

## Historic, Current, and Future Availability of Surface Water for Agricultural Groundwater Banking in the Central Valley, California

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Groundwater banking, the intentional recharge of groundwater from surface water for storage and recovery, is an important conjunctive use strategy for water management in California. A largely unexplored approach to groundwater banking, agricultural groundwater banking (ag-GB), utilizes flood flows and agricultural lands for recharging groundwater. Understanding the availability of excess stream flow (e.g., the magnitude, frequency, timing, and duration of winter flood flows) is fundamental to assessing the feasibility of local-scale implementation of ag-GB. In this study, we estimate the current availability flows based on current and historic daily stream flow records for about 100 stream gauges on tributaries to and streams within the Central Valley, California by quantifying the magnitude, frequency, duration, and timing of winter flood flow events. For each gauge, we consider flows above a stationary 90th percentile as ideal (available) for ag-GB because reservoir operations mitigate flood risk by releasing early winter flood flows. Additionally, we investigate the future availability of flood flows by determining the long-term trends in the magnitude, frequency, duration, and timing of winter flood flow events. Results suggest that on average across all year types, there are 5 million acre-feet of flows above the 90th percentile available from rivers in the Sacramento, San Joaquin, and Tulare basins between December and February. Trend analyses indicate that Sierra watersheds show 1) increasing trends in the average flood flow volume, 2) increasing trends in the average number of days, and 3) increasing trends in the average number of flood peaks above the 90th percentile. These positive trends suggest ongoing climate change effects on snowpack and the progressive shift from snow- to rain-dominated runoff generation. In contrast, CV gauges show predominantly negative trends in all metrics. Finally, we compare the quantified available water to the existing water rights (eWRIMS database from the State Water Resources Control Board) for each station to determine the amount of surface water that could potentially be allocated for groundwater recharge through a temporary water permit.

## **Potential for Managed Aquifer Recharge on Alfalfa Cropland in California.**

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Agricultural groundwater banking (ag-GB) seeks to opportunistically use winter storm flows from surface water sources for the artificial recharge of groundwater by spreading water onto crop land. Among the over 400 crops grown in California alfalfa represents an attractive cropping system to implement ag-GB practices on. Alfalfa is attractive for ag-GB for several reasons: 1) it comprises greater than one million acres in CA (high probability of finding suitable soil types and infrastructure); 2) it requires relatively low N fertilizer and agrochemical inputs compared to other crops (limited environmental impact of flooding); and, 3) it is often flood irrigated using surface water (high capacity conveyance system). In addition, utilizing mature alfalfa fields at or near the end of a rotation (e.g. after 4 years) poses little risk for economically significant crop loss or negative environmental impacts. Preliminary studies of the tolerance of alfalfa to large winter irrigation events conducted during the 2014/2015 recharge season suggest alfalfa is capable of withstanding cumulative applications of water in the order of 4 to 6 feet during the months of January, February and March. Where water was delivered to fields as several pulsed applications, no complications due to excess water were observed. In a treatment where water was continuously applied to dormant alfalfa over a 6-week period, with a cumulative application of 29 feet of water, a statistically significant decline of biomass was observed in the second cutting. Since site specific characteristics influence the subsurface storage capacity, travel times and the recoverability of “banked” water at these preliminary experimental sites more research is necessary to identify the bounds on crop tolerance for different site conditions.

## **Groundwater Challenges Faced by Southeast Asian Smallholder Farmers in Fresno County, California**

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Smallholder farmers in Fresno County and in particular Hmong and other Southeast Asian refugee farmers are facing multiple challenges as a result of reduced groundwater availability during the current drought. As the water table drops, smallholder farmers must make critical production decisions on whether to reduce their crop acreage or irrigate their total acreage in smaller sets due to decreased flow rates. Many smallholder farmers have encountered drastic increases in their operational costs associated with higher electrical bills due to changes in irrigation scheduling. In these cases the pump may be turned on for a longer period of time than usual, either to irrigate several sets one by one, or to completely flood to the end of a row using surface irrigation. Many smallholder farmers face difficulties obtaining financing to deepen their wells or drill a new well. This is especially true for smallholders who do not own their land, as is the case for most Southeast Asian farmers in Fresno County. Minority and refugee farmers in general are at a particular disadvantage in seeking government and non-profit drought relief assistance due to language and cultural barriers. This paper examines how Hmong refugee smallholder farmers are experiencing the drought, and the strategies they are using to respond to the reduction in groundwater availability. It also evaluates the degree to which this group of farmers is able to access drought relief programs. Our data is drawn from 71 telephone interviews with Southeast Asian smallholder farmers in Fresno County. Interview questions included basic information on the grower's irrigation system and any problems with wells or pumps, as well as their knowledge of and participation in governmental or nonprofit drought-relief programs. We present results of this study to demonstrate the unique impact that groundwater challenges are having on the economic viability of smallholder immigrant and ethnic minority farmers in our state, and to identify opportunities for greater outreach and support for these vulnerable farmer populations.

## **A Combined Approach for Understanding Nitrogen Loading to Groundwater from a Field Under Potato Production in Prince Edward Island**

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Agricultural practices associated with potato production, the most important agricultural commodity in Prince Edward Island, have potential impacts on groundwater quality the sole source of drinking water for the province. Groundwater with higher nitrogen loading can also be associated with the increased frequency of anoxic events in down gradient coastal ecosystems. In many cases, soil nitrogen cycling processes, which contribute significantly to the amount and form of nitrogen available for transport to groundwater, are neglected when nitrogen loading from agricultural fields is estimated. In this study, a preliminary model developed in Root Zone Water Quality Model (RZWQM, USDA-ARS) has been initiated for a three-year potato rotation (potato-barley-red clover) implemented on a small field located at AAFC's Harrington Research Farm, located 10 km north of Charlottetown. The nitrogen leached from the soil profile is further compared to nitrogen loading to groundwater derived based on water balance calculations, groundwater level dynamics and direct measurements of nitrogen concentrations in the aquifer. The soil at the study site is about one meter thick and is underlain by a thick (8 m) overburden derived from parental red sandstone bedrock, the dominant consolidated deposit across the province. Hydraulic conductivity in both the unsaturated and saturated zones is relatively high and previous investigations show that both the bedrock and the overburden are fractured, with fracture orientation being predominantly horizontal. The water table is about 16 m below ground and shows annual level amplitudes of 1-2 meters. In soil, the main inputs of nitrogen come from fertilizer application (150 kg N ha<sup>-1</sup> y<sup>-1</sup> for potatoes, 51 kg N ha<sup>-1</sup> y<sup>-1</sup> for barley with no fertilizer applied for clover) and mineralization of soil organic matter, which ranges between 42 and 52 kg N ha<sup>-1</sup> y<sup>-1</sup>, depending on the rotation phase. In terms of nitrogen removal from soil, plant uptake is the most important process (126 kg N ha<sup>-1</sup> y<sup>-1</sup> under potatoes, 83 kg N ha<sup>-1</sup> y<sup>-1</sup> under barley and 23 kg N ha<sup>-1</sup> y<sup>-1</sup> under clover) and is followed by leaching (63.5 kg N ha<sup>-1</sup> y<sup>-1</sup> under potatoes, 50 kg N ha<sup>-1</sup> y<sup>-1</sup> under barley and 29.5 kg N ha<sup>-1</sup> y<sup>-1</sup> under clover), with all other losses being insignificant. The monthly dynamics of the nitrogen leaching is well reflected by the nitrogen loading calculated using a series of monitoring wells located down gradient of the study site. The loadings estimated using nitrate concentrations measured in these wells are 2-3 times lower than the amount of nitrogen leached through the bottom of the soil profile, which could be attributed to the mixing with the lower nitrogen concentrations water from the unconfined regional aquifer. The quick response of groundwater loads confirms that a portion of the nitrogen leaving the bottom of the root zone travel at a fast rate through the overburden.

## The Groundwater Constraint: Responses to Falling Water Tables in India

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The objective of this paper is to examine the trends in groundwater depletion in India and analyze their short-term consequences by studying their impact on area under irrigation. Indian agriculture continues to employ three out of five people in the labor force and its development is crucial for the growth of the entire economy. Efforts to increase the growth rate of agriculture have relied on increasing the intensity of cropping, use of high-yielding variety of seeds, expansion of irrigation facilities and use of fertilizers. On one hand, the modern seed-fertilizer-water technology has catalyzed the entire crop production system, but on the other it has led to deleterious environmental consequences (in terms of ground water depletion). An open question in policy circles now is whether the groundwater constraint is binding or not, and if it is then what is the impact of falling water tables. To study this we present results from a new panel dataset that records groundwater levels in 20,166 wells, four times a year, over 1996-2012. We document two results: firstly, overall trends in groundwater depletion mask important regional and temporal heterogeneity. We can identify three distinct phases: (a) in the first phase - the period of concentration - groundwater is declining in the north and west (excluding Maharashtra); (ii) in the second phase - the period of diffusion - there is a remarkable improvement in the second phase as locii of groundwater extraction shifts to east (though in terms of magnitude the problem is not severe); (iii) in the third phase - the period of resurgence - the erstwhile problem areas from phase 1 make a comeback and the problem intensifies in the new areas that were added in phase 2. Secondly, analyzing the impacts of falling water tables, using over 100,000 observations and high resolution spatial data, we find that a 1 meter fall in November's water table leads to a decline in irrigated area by approximately 0.1 percentage points. To put these numbers in perspective, it is important to remember that gains in area under irrigation are notoriously sluggish and that it has taken India more than 60 years to increase gross irrigated area by 20 percentage points (net irrigated area has increased only by 13 percentage points since independence). Given that the magnitude of the impact we estimate is a third of the average annual gains India has made in irrigation since independence, this implies that the groundwater constraint is strict and binding.



## **Regional Scale Simulations of Nitrate Movement Through the Vadose Zone Using Hydrus 1D**

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Nitrate is recognized as one of California's most widespread groundwater contaminants since it is frequently detected in groundwater systems. Nitrate enters the soils mainly due to excessive application of nitrogen fertilization for agricultural purposes. The fate of nitrate in the soils, along with the risk of reaching the groundwater is a function of very complex processes at various time and spatial scales. In this study we classify agricultural soils in California by their nitrate leaching risk. Risk is here defined through transient flow and nitrate transport simulations for almost 6000 unique soil profiles using the Richards equation. The parameterization of the model was based on the SoilWeb Database, taking into account heterogeneity of the soil hydraulic properties (SHPs) in the z-axis. Overall, over 22,000 soil horizons were used. In a first step, we calculated nitrate transport through the shallow vadose zone for a simple scenario: Nitrate was modelled as a conservative tracer for a constant rainfall/irrigation scenario. In a second step, we included the effect of climate conditions on nitrate transport. The final goal of this study is to evaluate and include key management, physical, and chemical processes that influence nitrate leaching. Preliminary results show, that SHPs influence strongly the movement of nitrate through soils. We present maps for all the agricultural soils in California, helping identify regions in California which may need improved fertilization management. Furthermore, this analysis allows us to estimate drainage rates of water under the root zone at the regional scale, a very important parameter for assessing the risk of groundwater contamination.

## **From Integrated Regional Water Management to the Sustainable Groundwater Management Act: Lessons on Institutionalizing Participation to Achieve the Human Right to Water in California**

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In 2014, more than one million Californians were served water that did not meet safe drinking water standards, violating their right to clean, safe and affordable drinking water recognized in the state since 2012. In the eighth largest economy in the world, small, rural, low-income, communities of color have been systematically excluded from the services most in the state take for granted. Despite increased investment in, and technical assistance for, these communities, California's drinking water crisis has only intensified in the face of record drought and ongoing groundwater contamination. Consequently, it has become increasingly clear that realizing the human right to water in California, beyond investment, also requires long-term, proactive regional planning that addresses small community needs, both in terms of the quantity and quality of their water supply. Tracing the State's Integrated Regional Water Management (IRWM) program, it is clear that the last five years have been characterized by a growing state rhetoric of participation and integration. Policy makers, advocates and bureaucrats alike have seen the engagement of rural communities in regional and state planning as integral in addressing systemic injustices. The Sustainable Groundwater Management Act (SGMA) of 2014 embraces this approach like never before. This hallmark legislation includes explicit mandates to not only to "consider all beneficial uses and users of groundwater", including disadvantaged communities, but also to "encourage the active involvement of diverse social, cultural and economic elements of the population". And because sustainable groundwater management necessitates effective long-term management of a common-pool resource, research indicates that the local results of this law will be highly dependent on how successful they are at accomplishing exactly these mandates. Unfortunately, democratizing water management has proven significantly more difficult in practice. Like with Integrated Regional Water Management, getting communities to the table, let alone meaningfully engaging with the process, is much harder said than done. Much as with IRWM, geographic isolation, language and cultural barriers, limited resources and power inequities have limited the ability of many rural communities to participate in the first year of implementation of the new law. Unlike IRWM, however, SGMA is a regulatory process that not only represents a potential benefit to Disadvantaged Communities, but also represents potential challenges if ongoing barriers cannot be addressed. Drawing from lessons learned from case studies on the first year of SGMA implementation and ongoing IRWM, I identify challenges and lessons learned as to what, realistically, furthering the human right to water through SGMA entails.

## **USDA-NIFA's Water for Agriculture: A Mechanism to Fund a Broader Portfolio in Groundwater Sustainability.**

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NIFA launched a new challenge area, Water for Agriculture, to tackle critical water issues such as availability (quality + quantity) for irrigation and food processing, drought preparedness, excess soil moisture, flooding, nutrient loss and contamination in agricultural, rural and urbanizing areas across the U.S. Continued significant variations from the historical rate of water supply, demand and quality are projected to have major impacts on agricultural, forest, and rangeland production systems making the initiation of this new challenge area particularly timely. Of particular interest is the improvement of NIFA's portfolio of groundwater-focused projects in water stressed regions like the Colorado River Basin (CRB). Population growth and a changing climate are taxing the future reliability of Colorado River water supply. This vulnerability has been witnessed in the first decade of the 21st century due to the recent prolonged dry spell in the western U.S., including the Colorado River Basin (CRB). Freshwater in the CRB is fully appropriated, with agriculture the biggest consumer at about 80%. Growing urban areas are the second largest water demand, expected to increase dramatically by as much as 80% by 2025. Concomitantly, in western North America, the timing of spring snowmelt has shifted to earlier in the year from 1948 to 2000 due to warmer temperatures. These scenarios have implications for the sustainability of irrigated agriculture in the CRB--if innovative new strategies are not forthcoming, water shortage in the CRB will inevitably result in reduced agriculture to feed urban water demands. NASA's GRACE mission showed that demands have outpaced supplies by as much as 30 percent, with groundwater filling the gap. Both the problems and solutions to water scarcity, particularly groundwater sustainability in the CRB lie within agriculture, and because of the complexities involved, an integrated, multi-state, and multi-disciplinary Coordinated Agricultural Project (CAP) offered by Water for Agriculture could help to address water scarcity across the CRB's geographic reach, number of water governance organizations, rapidly changing urban-rural landscape, and the significant presence of federal lands and reclamation projects. Furthermore, the existence of common water issues across the region serves as the basis for regional coordination to efficiently allocate and target personnel and funding resources for problem identification, education, and management, and the resolution of current and emerging surface and groundwater availability problems from regional to local levels. NIFA's funded portfolio must expand to address groundwater loss (70% in the CRB over the last 10 years), if both groundwater and agriculture sustainability are to continue. NIFA's presentation will suggest how the development of innovative management practices, technologies, and tools for farmers, ranchers, forest owners and managers, public decision-makers, public and private managers and citizens could improve groundwater quantity and quality across critical regions of the U.S. NIFA's approach requires the linkage of social, economic, and behavioral sciences with biophysical sciences and engineering to promote science based technology adoption and behavior change and towards true solution of groundwater issues.

## The Irrigation-Groundwater Nexus at the Global Scale

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In many regions of the globe, irrigation affects groundwater recharge and storage. According to simulations with the global water resources and use model WaterGAP, irrigation accounts for about 90% of global consumptive water use, while about 40% of the consumptive water use in irrigation stems from groundwater. Irrigation with surface water leads to an increase of groundwater recharge in e.g. Southeast and Central Asia, while in some semi-arid and arid regions with groundwater irrigation, net groundwater abstractions are so high that even a decline of base flow to zero cannot prevent groundwater depletion, i.e. a steady decline of groundwater storage. Comparing WaterGAP groundwater depletion to independent depletion estimates from local modeling, well observations or GRACE data, we found that depletion is simulated best if we assume that farmers in depletion areas irrigate at 70% of optimal water requirement (Döll et al. 2014). During 2000-2009 about 15% of the globally abstracted groundwater was taken from nonrenewable groundwater. Considering the significant environmental impacts of irrigation, it is noteworthy that according to the Global Crop Water Model, global cereal production would decrease by only 20% if currently irrigated crops were not irrigated (Siebert and Döll 2010). Of course, regional impacts would be much stronger, with losses of 66% in Northern Africa and 45% in Southern Asia.

## **Integrated Modeling of In-Lieu Groundwater Recharge Using Recycled Water for Agriculture-Maximizing Benefits to Groundwater Dependent Ecosystems and Sustainable Groundwater Management**

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The Sacramento Regional County Sanitation District (Regional San) is planning to distribute tertiary treated recycled water to south Sacramento County, which overlies the South American Subbasin, a high-priority basin under the Sustainable Groundwater Management Act. Recycled water will be used by farms in lieu of pumping existing groundwater supplies. The project will result in multiple benefits such as increasing groundwater levels, and improving conditions for adjacent Groundwater Dependent Ecosystems (GDEs) within the Cosumnes River Preserve, increasing in-stream flows for fisheries and improving water supply sustainability. The South Sacramento County Agriculture and Habitat Lands Recycled Water Program proposes reuse of up to 50,000 AFY of recycled water on approximately 16,000 acres. The Sacramento Regional Wastewater Treatment Plant through the EchoWater project, a \$2 billion dollar wastewater treatment plant upgrade, will produce title 22 recycled water. The SacIWRM model shared by all users in the basin evaluated the water budget for multiple scenarios, all involving delivery of recycled water for agricultural uses in-lieu of groundwater pumping. Regional San partnered with The Nature Conservancy (Conservancy), modeling multiple potential scenarios for recycled water distribution and banking, prioritizing benefits for adjacent habitats, under certain groundwater use conditions. Results project groundwater levels increasing as much as 30', with elevation increases extending outside the project limits to support valley oak riparian forest health. Raised levels would also benefit wetlands with listed species and increase in-stream flows for anadromous fisheries. Inclusion of ecosystem benefits in the design of the project provides a model for multi-benefit water supply projects. It also informs how groundwater basins can best identify, protect and even improve Groundwater Dependent Ecosystems with Sustainable Groundwater Management Act implementation. Some supplied water goes to Stone Lakes National Wildlife refuge, a wetland area in the Pacific flyway, benefitting migratory waterfowl and other birds. In another area, a recharge component is being evaluated. It would use winter over-irrigation to create flooded habitat for migratory bird roosting and foraging, while allowing continued farming during the primary growing season. Siting of the recharge farm on looser soils increases project benefits for the water table and in stream flows in the Cosumnes River. 293,000 AF of new groundwater storage is projected over 30 years of project operation, with twice that amount returning to area rivers. The presentation will include maps showing groundwater elevation and in-stream flow benefits, some arriving less than ten years after project implementation. One scenario modeled includes hypothetical extraction of groundwater by municipal users in the driest 30% of years. Modeling of this scenario still shows an overall increase in the water table while allowing for improved regional and statewide water storage options and operational flexibility. Assurances for agricultural and environmental users will need to be developed over the next several years to ensure projected benefits occur when implemented, with resulting sustainable groundwater management benefiting both people and nature.

## **State Implementation of the Sustainable Groundwater Management Act (SGMA)**

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California uses more groundwater annually than any other state in the United States. Yet for over a century, California has not regulated groundwater extractions or required comprehensive groundwater management. The Sustainable Groundwater Management Act (SGMA) was signed into law in September 2014, marking the first significant groundwater management law enacted in California in more than 100 years. SGMA will result in profound changes in how groundwater is used and managed in California. Local agencies must now define when and how groundwater extractions cause significant and unreasonable undesirable results, where an undesirable result is defined in statute as chronic lowering of groundwater levels, reduction of storage, seawater intrusion, degraded water quality, subsidence, and depletions of interconnected surface water. When local efforts are unsuccessful, SGMA authorizes the State Water Resources Control Board (State Water Board) to directly intervene and develop interim groundwater management strategies. The State Water Board faces numerous challenges in setting up and implementing a groundwater management strategy. The presentation will focus on planning efforts currently underway to prepare the state for intervention, including development of regulations, future data needs, data management, and socio/economic drivers. Specific highlights will include development of a State Water Board database to collect and record groundwater extractions from individual wells, remote sensing capabilities and how remote sensing evapotranspiration data could be used for enforcement, how the State Water Board will develop water budgets and verify water budgets developed at the local level, and how State Water Board actions must comply with existing water rights laws and priorities. Additional topics will focus on how state management will differ from locally developed plans, with particular focus on metering programs, fees, and mandated pumping reductions. Lastly, challenges to local management and state intervention will drive planning elements and will influence local definitions of sustainability. The presentation will highlight these challenges and discuss how intervention will need to incorporate local values and needs.

## **Evolution of Groundwater Law in Arizona and Jordan – Legal Dimension of the Groundwater Revolution and Implications for the Groundwater Crisis of the 21st Century**

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The year 1904 marks the beginning of modern groundwater law in Arizona. *Howard v. Perrin* was the first decision of the Supreme Court of what was the Territory of Arizona at the time in a conflict over the use of groundwater: Perrin used two wells on a piece of land that Howard claimed for himself. About 100 years later – in 1999 – the Jordan Paper and Cardboard Factories sued the Water Authority of Jordan at the Court of Cassation, the highest appellate court of the country. The Water Authority charged fees for the withdrawal from the wells the company used on its premises, but the company refused to pay. The two examples mark instances in the development of groundwater law in Arizona and Jordan. Within the 100 years between the decisions of two high courts the judges in both countries took a number of further decisions. They revoked earlier rulings and modified the legal concepts. In the second half of the 20th century laws and regulations were promulgated and replaced the court decisions as the main source of groundwater law. This paper takes the legal development in Arizona and Jordan as case studies for the evolution of groundwater law in arid regions. The paper aims at identifying the contribution of legal concepts to what has been termed the “groundwater revolution” of the 20th and their capability as a policing instrument in the groundwater crisis of the 21st century. The paper takes its starting point in a common denominator of groundwater use in Arizona and Jordan: Judges, lawmakers and water administrators in both countries have been confronted with aridity and scarcity of water resources from early on. This played out in specific conflicts between groundwater users. When groundwater use was still mainly an agricultural phenomenon farmers fought over neighboring wells. The conflicts escalated to a higher level when urban water companies started to reach out into rural areas to supply their customers from resources that had hitherto been tapped by agricultural users. The paper discusses how legal concepts have evolved under the conditions of aridity and scarcity. The major challenges to sustainable groundwater use – dwindling supplies and the redistribution of groundwater use from agriculture to urban and other uses – are closely reflected in the legal systems in both Arizona and Jordan. There are significant differences in how the legal systems have actually been effective with regard to distribution of groundwater. This is where the second level of comparison comes in: The political and social framework in Arizona and Jordan could not be more different. Arizona has managed to reverse the previously disastrous overexploitation of its resources through the complex and long-term regulative framework of the Groundwater Management Act of 1980. The political economy of groundwater use in Jordan is equally challenging. Confidence in the legal system as a factor of change is far less developed however. The paper takes Jordan as an example of legal regulation of groundwater use under autocratic rule and rentier state conditions – political conditions that are reality in many of the most drought-struck regions around the globe.



## **Watershed Modeling to Evaluate the Impact of Irrigated Agriculture on Surface Water – Groundwater Interactions**

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We examine the impacts of irrigation and associated surface water (SW) diversions and groundwater (GW) pumping on stream flow, GW recharge and SW-GW interactions using a watershed-scale coupled SW-GW flow model. The U.S. Geological Survey (USGS) model GSFLOW (Markstrom et al., 2008), an integration of the USGS Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW), is being utilized for this effort. Processes represented in the model include daily rain, snowfall, snowmelt, stream flow, surface runoff, interflow, infiltration, soil-zone evapotranspiration (ET), and subsurface unsaturated and saturated GW flow and ET. We use the upper Smith River watershed, an important agricultural and recreational area in west-central Montana, as the basis for watershed climate, topography, hydrography, vegetation, and soil properties as well as for scenarios of irrigation and associated practices. The 640 square kilometer watershed area has been discretized into coincident 200 m by 200 m hydrologic response units (for climate and soil zone flow processes) and grid blocks (for unsaturated zone and GW flow processes). The subsurface GW system is discretized into 6 layers representing Quaternary alluvium, Tertiary sediments and bedrock. The model is used to compare stream flow, GW recharge and SW-GW interactions in the watershed under natural, pre-irrigation conditions; current irrigation conditions; and a scenario of future increased irrigation. Model results reproduce observed hydrologic responses to both natural climate variability and irrigation practices. Current irrigation practices have decreased stream flow out of the watershed relative to pre-irrigation conditions as result of SW diversion. Irrigation has increased GW recharge below irrigated areas. Despite these local increases in GW recharge, more widespread lowering of the water table by GW pumping for irrigation decreases GW ET in lowlands with shallow water tables, decreases GW discharge to streams, and induces SW infiltration from streams. Irrigation practices cause SW-GW interactions to become more temporally and spatially variable. Flood irrigation in riparian zones increases GW flow to the stream, whereas, GW pumping for irrigation can cause naturally gaining stream reaches to become losing stream reaches. These changes in SW-GW interactions could influence stream ecology.

## **Enhancing Groundwater Management Capabilities in California's Central Valley - Generating High-Resolution Groundwater Maps from GRACE and in Situ Data**

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Groundwater is a critical component of the local, regional and global water cycle. It constitutes an important storage of water, often relied upon in times of drought and in arid environments. Sustainable planning and management of groundwater resources requires accurate information about trends in groundwater water levels and quantities. In much of the globe, however, this data is limited. The Gravity Recovery and Climate Experiment (GRACE) have already proven to be a powerful data source for regional groundwater assessments in many areas around the world. However, the applicability of this data product to more localized studies and its utility to water management authorities has been constrained by its limited spatial resolution (~150,000 km<sup>2</sup>). Researchers have begun to address these shortcomings with data assimilation approaches that integrate GRACE total water storage estimates into complex regional models, producing higher-resolution hydrologic results (~4,000 km<sup>2</sup>). The present study takes these approaches one-step further by developing an empirically based model capable of downscaling GRACE data to a high-resolution (~16 km<sup>2</sup>) dataset of groundwater storage changes. The model utilizes an artificial neural network (ANN) to generate a series of maps of groundwater level change over the GRACE time period (2002-present) using GRACE estimates of variations in total water storage and a series of publicly available hydrologic variables. The San Joaquin Valley Groundwater Basin in California's Central Valley serves as the initial case study. Overall, the present study achieves two main goals: 1) it integrates robust numerical methods from the field of systems analysis with geodesy and hydrology; and most importantly 2) it also represents an important application of GRACE data to a local-scale water management study, illustrating how widely available remote sensing data can be utilized by management authorities.

## **Potatoes and Trout: Groundwater Model Optimization to Balance Agricultural and Ecosystem Stakeholder Needs in the Little Plover River Basin, Wisconsin**

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The well-drained sandy soil in the Wisconsin Central Sands is ideal for growing potatoes, corn, and other vegetables. A shallow sand and gravel aquifer provides abundant water for agricultural irrigation but also supplies critical base flows to cold-water trout streams. These needs compete with one another, and stakeholders from various perspectives are collaborating to seek solutions. Stakeholders were engaged in providing and verifying data to guide construction of a groundwater flow model which was used with linear and sequential linear programming to evaluate optimal tradeoffs between agricultural pumping and ecologically based minimum base flow values. The connection between individual irrigation wells as well as industrial and municipal supply and stream flow depletion can be evaluated using the model. Rather than addressing 1000s of wells individually, a variety of well management groups were established through k-means clustering. These groups are based on location, potential impact, water-use categories, depletion potential, and other factors. Through optimization, pumping rates were reduced to attain mandated minimum base flows. This formalization enables exploration of possible solutions for the stakeholders, and provides a tool, which is transparent and forms a basis for discussion and negotiation.

## **Storm Water Runoff Analysis for Placement of Managed Aquifer Recharge Projects in Santa Cruz and Northern Monterey Counties, California**

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We apply a USGS surface hydrology model, Precipitation-Runoff Modeling System (PRMS), to analyze storm water runoff in Santa Cruz and northern Monterey Counties, CA with the goal of identifying catchments (generally 100-1000 acres) from which hill slope runoff can be collected and infiltrated for managed aquifer recharge (MAR). Under the combined threats of multi-year drought and excess withdrawals, this region's aquifers face numerous sustainability challenges, including seawater intrusion and degradation of water quality. The CA Department of Water Resources classifies four of the region's eight groundwater basins as medium or high priority, and two of these are critically over drafted. We address the supply side of this resource challenge by investigating the spatial and temporal dynamics of storm water runoff, which could be used to replenish aquifers via MAR projects that use infiltration basins, drywells, and flooding of agricultural fields or flood plains. Ensuring the effectiveness of MAR using storm water requires a thorough understanding of runoff distribution at the sub-watershed scale, as well as site-specific surface and subsurface aquifer conditions. In this study we use a geographic information system (GIS) and a high-resolution digital elevation model (DEM) to divide the region's four primary watersheds into Hydrologic Response Units (HRUs), or topographic sub-basins, that serve as discretized input cells for PRMS. To facilitate evaluation of hill slope runoff at a fine scale, we create a high-resolution HRU grid (using 0.1-1.0 km<sup>2</sup> cells) and spatial and density-weighted averaging schemes to assign topographic, vegetation, and soil characteristics. Additionally, we couple high temporal resolution with high-spatial-resolution climate data to generate input precipitation catalogs that drive the model, allowing analyses of a variety of climate regimes. To gain an understanding of how surface hydrology has responded to agricultural and urban development, we develop input datasets to represent both pre- and post-development conditions. Combined with a concurrent surface and subsurface analysis, our model results help screen for suitable locations of future MAR projects. Additionally, our results improve our understanding of how changes in climate and land use impact runoff and recharge.

## Nitrogen Cycling and Water Quality Improvement During Managed Aquifer Recharge: Experiments Using Reactive Barrier Technology

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Aquifers throughout California are experiencing chronic overdraft. Accordingly, aquifer replenishment techniques such as managed aquifer recharge (MAR) are increasingly important for sustaining groundwater supply for agricultural, municipal, industrial, and environmental benefit. MAR can involve collecting excess surface water and infiltrating it into the subsurface where there are appropriate soil and aquifer conditions. Infiltrating water is subject to many microbial, chemical, and physical processes that affect water quality and aquifer health. As a greater variety of water sources—including hillslope runoff, recycled water, and excess channel flows—are used to supply MAR systems, there is a growing need to better understand how infiltration properties and processes affect water quality. Under some conditions, MAR has been shown to improve water quality by reducing nitrate (NO<sub>3</sub><sup>-</sup>) concentrations via microbial denitrification in the shallow subsurface. Denitrification during MAR is spatially and temporally heterogeneous, and is often limited by the amount of available carbon and/or soil redox conditions. In an effort to better understand fundamental mechanisms and controls on water quality during infiltration, especially those involving the nitrogen cycle, we ran a series of field experiments, explicitly linking hydrologic conditions, subsurface nitrogen cycling, and microbial activity. Nitrate-rich water was continuously applied to experimental plots at measured rates during four two-week tests. Replicate plots were constructed with native soil and with a carbon-rich permeable reactive barrier (PRB) in the form of redwood chips. We collected surface and subsurface fluid samples daily and measured NO<sub>3</sub><sup>-</sup>, NO<sub>2</sub><sup>-</sup>, NH<sub>4</sub><sup>+</sup>, and DOC for each sample. Our water chemistry results and high vertical infiltration rates (=1-2 m/day) illustrate that rapid infiltration can inhibit the formation of redox conditions favorable for net denitrification. However, comparison of experimental results for native soil and PRB plots shows that the PRB drives dynamic variations in fluid geochemistry and increases nitrogen cycling in the subsurface. Soil samples collected before and immediately after each experiment are being tested for total C/N and the presence of microbiological genes associated with denitrification. Initial microbiology results indicate that microbial populations shifted significantly in response to infiltration. In addition, nitrate isotopic work is underway in an effort to characterize nitrate reduction pathways and elucidate nitrogen cycling dynamics. These experiments provide a foundation for a more comprehensive examination of factors that impact changes to water quality during infiltration. Gaining a better understanding of these relationships is crucial to designing MAR systems that can achieve simultaneous water supply and water quality improvement goals, contributing to sustainable groundwater management.

## The Case for Subsurface Storage of Water in Agricultural Basins

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For most of human history, water supplies have come predominantly from existing surface water bodies, and in more recent decades, from engineered reservoirs. As population and hence demand for water grew, more and bigger surface storage projects were constructed, including conveyance structures for wheeling water long distances. As the Green Revolution and the associated large increase in food production ramped up during the middle part of the 20th century, the irrigation water needed for the revolution came initially from surface storage systems, but in the second half of the century groundwater development was increasingly used to satisfy demand. This system, with managed water storage being done mainly with surface reservoirs, and groundwater being used to supplement increasingly larger fractions of the water supply, is becoming increasingly unreliable because of groundwater overdraft and groundwater quality degradation. Furthermore, in many agricultural basins, the irrigation and urban water demands are no longer being met by the existing water stores, with simultaneous, severe depletion of both the surface and subsurface stores of water during droughts. Even moderate amounts of groundwater production have caused significant reductions in lakes, rivers and wetlands that were previously sustained by groundwater discharge, while also in effect converting many basins into closed hydrologic basins in which most of the water exits by evapotranspiration of applied irrigation water. In these newly closed hydrologic basins, just as in other closed basins such as Death Valley and the Great Salt Lake, groundwater salinization is inevitable. Resolving the storage problem and water security in the face of drought can be accomplished by long-term planning and alternative land management that produces much greater groundwater recharge during wet years and a greater emphasis on subsurface storage instead of the traditional emphasis on surface storage. In turn, such a reimagining of our water storage systems is the only path toward (1) reversing the ongoing declines in regional groundwater quality caused by non-point source contamination from irrigation water and hydrologic basin closure, and (2) recovering some the ecosystem functions that were formerly supported by the underlying groundwater systems being sufficiently 'full' of water to discharge to the surface. In short, neither the quantity nor the quality of groundwater in many agricultural basins is sustainable unless those basins are used much more proactively for subsurface storage, which would in turn have significant benefits for the surface ecology and environmental quality.

## Exploring Relationship Between Evapotranspiration and Groundwater Level Fluctuations in Different Land Covers

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Groundwater is often the most reliable source of water in arid and semiarid regions. In order to achieve sustainable groundwater management, specifically in the agricultural sector, a more detailed accounting of water balance terms in space and time should be investigated. While the impact of evapotranspiration (ET) on stream flow has been discussed in many studies, the relationship between ET and groundwater levels has yet to be sufficiently explored. One of the largest concerns of water resource planners in groundwater conservation is water loss through ET. Some planners believe that by controlling deep-rooted plants or replacing them with shallower rooted plants would reduce groundwater losses through ET processes and potentially provide greater water resources for human consumption. In this paper, we investigated the relationship between ET and groundwater level fluctuation in 3 different land covers across a 1.2 km gradient in central Nebraska: cottonwood, wetland, and grassland areas. Groundwater observation data obtained from monitoring wells in the different land cover areas at the study site were used to measure the groundwater level fluctuations. In addition, a Mapping Evapotranspiration at high Resolution and with Internalized Calibration (METRIC) model, a satellite-based image-processing model, was used to estimate actual ET at ~30 m spatial resolution. We used eight Landsat 8 images from the study site to estimate actual ET for each well location from May to July 2014. The results reveal that while there was a strong relationship between hourly actual ET and hourly groundwater level fluctuations in the cottonwood area for most of the days during the study period, ET did not directly affect the groundwater level in the wetland and grassland areas. The results here indicate the diurnal influence that the deep-rooted plants have on localized water table elevations and ET fluxes. When combined with detailed groundwater and surface water flow models, the results of this work can be used in aiding decisions for water managers in water-limited environments.



## Use of Early Warning Monitoring Systems for Groundwater Protection in a Policy Decision Context

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A recent comparison of monitoring networks showed that sampling methodology strongly affects the measured nitrate concentrations in soil moisture in the vadose zone, affecting the evaluation of Dutch manure policies. The European Nitrates Directive aims at the reduction of nitrate pollution by agriculture. It obliges Member States to abate and prevent groundwater and surface water pollution and to monitor the effectiveness of the actions carried out to comply with the Directive. To ensure that these obligations are met, different early warning monitoring systems have been developed during the last decade. To ensure equal compliance among Dutch soils with large differences in hydro geochemical properties all these systems focus on the assessment of nitrates in soil moisture leaching the rooting zone. The Loess region, in the southern part of the Netherlands, is the smallest of the four soil type regions. Groundwater levels are often deep (>>5 m below surface level) and, therefore, soil moisture is extracted from the soil layer below the root zone to monitor nitrate leaching. Within this region, the national authority (RIVM), the Province of Limburg and the Water Supply Company Limburg (WML) have their own early warning-monitoring network. RIVM carries out on-farm monitoring within the entire Loess region as part of the national Minerals Policy Monitoring Program (LMM). The Province of Limburg carries out a comparable monitoring program called the 'Soil Moisture Monitoring' (BVM). BVM focuses at agricultural fields on the so-called plateaus. These plateaus (higher areas) cover about two-third of the LMM Loess region. The Water Supply Company Limburg is responsible for the project 'Sustainable Clean Groundwater' (DSG). DSG aims to ensure the protection of groundwater resources. This project is carried out in co-operation with farmers within the groundwater protection zones. At the beginning of 2014 questions were raised in the agrarian press and the Dutch Parliament about the LMM monitoring protocol for the Loess region. An exploratory research of WML had shown that the WML protocol resulted in 30-40% lower measured nitrate concentrations. As nitrate concentrations in soil moisture are currently not much above the standard of 50 mg/l in the Loess region, this difference between protocols may lead to opposite conclusions. In case of the WML protocol, the conclusion is that almost no additional measures are required, while in case of the LMM protocol; one concludes that still additional measures are needed. WML, the Province of Limburg and RIVM are currently carrying out research – together with other relevant organizations – to determine the extent and cause of this difference. From 2014 onwards, farmers in the Loess region are confronted with additional measures that limit both the use of animal manure and of artificial nitrogen fertilizer to a greater extent than in some other regions. Therefore, the outcome of this research is relevant for farmers in this region. This paper will discuss the scientific, managerial and political dimensions of this research.

## Evaluating the Influence of Tile Drainage Management on Shallow Groundwater Resources

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Tile drainage management is considered a beneficial management practice (BMP) for reducing nutrient loads in surface water. Previous research has shown that controlling tile discharge via control structures with adjustable stop gates can be very effective for reducing tile discharge volume, and that on an annualized basis there is often a reduction in nitrate loads that is proportional to the reduction in discharge. However, the influence of controlled drainage on groundwater resources is rarely considered. In this presentation we will discuss tile drainage experiments that were conducted in Ontario, Canada, that were designed to assess the influence of drainage management on the movement of nutrients and rhodamine WT to surface water and groundwater under controlled (CD) and free drainage (FD) tile management. We will also present results from 2-dimensional dual permeability modeling that was conducted to help develop a better understanding of the flow and transport processes within the soil profile and shallow groundwater system under different drainage management scenarios. Results from the modeling demonstrate that dominant flow and transport characteristics at the field site were successfully replicated, including higher, more continuous tile discharge and lower peak rhodamine concentrations in FD tile effluent; as compared to CD, where discharge was intermittent, peak rhodamine concentrations higher, and mass exchange from macropores into the soil matrix greater. Explicit representation of preferential flow in the modeling framework was essential, as macropores were shown to transmit > 98 % of surface infiltration, tile flow, and tile solute loads for both FD and CD. Incorporating an active 3rd type boundary across the bottom of the model domain in order to facilitate shallow groundwater outflow was imperative for simulating CD, as the higher (relative to FD) water table facilitated greater water and soluble nutrient movement from the soil profile into deeper groundwater. Scenario analysis revealed that in conditions where slight upwards hydraulic gradients exist in tile drained settings, groundwater upwelling can dilute the concentration of surface derived solutes under FD conditions; whereas the higher and flatter water table associated with CD can act to reduce groundwater upwelling. Results show that while CD can reduce tile discharge, and soluble nutrient loads and concentrations in tile effluent and hence surface water receptors, it can promote NO<sub>3</sub> loading into groundwater.

## Summary of Managed Aquifer Recharge Concepts and Planning Methods

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Managed aquifer recharge (MAR), also known as water banking, consists of water management methods and techniques - using treated or non-treated water - to recharge an aquifer, or water bearing zone of sediments, using either surface or subsurface (i.e., via wells) recharge methods. The stored water is available for use in dry years when surface water supplies may be low. Other possible benefits of a properly managed water bank may include making water available for sale, lease, or exchange with other water users for regional water supply sustainability and/or mutual benefit. Surface recharge systems are more likely to work in situations where soils are permeable from the ground surface to the water table, and where adequate land area is available at reasonable cost to accommodate the recharge facilities. Solids that accumulate at the surface are periodically removed following a series of wet-dry cycles to maintain the long-term infiltration rate. Where low permeability soils are present between ground surface and the water table, or where land availability at reasonable cost is limited, surface recharge may not be viable (Pyne, 2005). It must be realized that a MAR system is an engineered system requiring technical inputs from multiple disciplines. Mechanical and process engineering is just as important as water quality modeling and hydro-geologic conceptual modeling inputs for successful design and operations of MAR technology. MAR technology has evolved and supported projects in California for over 40 years, with several long-running projects still in existence and serving as industry standards. Several examples of these long-running successful projects are the Water Replenishment District of Southern California, Orange County Water District, Kern County facilities, and the Santa Clara Valley Water District operations. These successful projects are presented in this paper as examples of surface water-applied aquifer recharge and groundwater-applied aquifer recharge methods as the mechanisms to deliver, store or bank, and extract applied water using a groundwater system. When developing a MAR project, experience has proven that well-researched and planned projects that have well-defined objectives, a solid conceptual model, and proper levels of pilot testing have the best chance of achieving a successful, long-term operation. A project's conceptual model should include at a minimum a thorough understanding of the site's hydrology, hydrogeology, mixing water geochemistry, and engineering geologic factors such as soil mechanics and land surface expressions of aquifer response to inflation or deflation. Other technical issues involve the aboveground water delivery system, and logic control systems that run the designed system, including flow control valve technologies that regulate injection and extraction rates. Plugging or clogging is a reality of any system, but a well-defined and executed asset management program can alleviate the severity and frequency of these realities and protect the asset's investments. Regulatory issues must be confronted and incorporated into project planning. Historical experience has provided some key lessons learned, which are worth incorporating in pre-project planning and design to ensure successful MAR operations. A well-planned public outreach program that informs and engages the community to be served by the MAR project is necessary to the success of such projects; economic considerations can be part of this effort to show the long-term benefit to the community. Recent legislation in California has moved the State toward a more strict and comprehensive policy regarding groundwater management. These new regulations and laws will have particular impact on groundwater basins that have been defined by the California Department of Water Resources as medium or high priority basins. The legislation, signed into law in 2014, creates a framework for sustainable local groundwater management, and allows local agencies to modify groundwater plans to their regional needs. As more counties and local agencies have to comprehensively manage large multi-jurisdictional groundwater basins, more opportunities for MAR/groundwater banking projects should emerge. These projects will have to be planned, designed, and operated by well-trained, experienced, multi-disciplinary teams of professionals.

## **Managing Groundwater in a Time of Increasing Demand and Changing Climate**

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A changing climate, population growth and other factors are placing greater demands on water resources, particularly groundwater and straining the institutions and laws that govern it. California has faced these challenges for more than half a century, and while California has had some notable and well-publicized groundwater management problems, some groundwater management efforts in Southern California have been very successful. Indeed they have been so successful that some experts have cited them as examples of some of the best managed common pool resources in the world. This presentation will explore the local, self-governing management structures that have functioned within California's extremely complex water rights system that are responsible for this water management success. The presentation will discuss the key elements that have made these management structures successful and why, ultimately, most successful, if not all, groundwater management must be local. In California these management structures have largely been implemented through adjudications. This presentation will explore several adjudications, specifically those in the Raymond, Los Angeles, Santa Maria and Antelope Valley basins. It will discuss how water rights and priorities factored in to the physical solutions and the role of the Constitutional doctrine of reasonable use in reaching an allocation of water. It will also briefly discuss the impact of the recently adopted Sustainable Groundwater Management Act on physical solutions and future adjudications. Importantly, the water law concept of reasonable utilization, which is conceptually similar to California's reasonable use doctrine, is present in water law regimes throughout the world. Although many countries lack the strong rule of law present in California, I will discuss how these structures may possibly be employed effectively around the world and specifically how their adaptive management aspects are essential to adapting water law regimes to climate change. The presentation will cite some specific examples at the international level, from Central and South America and Africa, where the elements that have led to successful physical solutions and groundwater management in California are present.

## Combined Analysis of Time-Varying Sensitivity and Identifiability Indices to Diagnose the Response of Complex Environmental Models

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The problem of parameter non-uniqueness in complex hydrological models limits their potential applications for decision making. While it takes a long time to estimate the values of a larger number of unknown parameters, their predictive capabilities may be reduced due to non-identifiability. Sensitivity and identifiability analyses are common diagnostic tools to address these limitations, although combined application of the two methods is rarely reported and discussed in the literature. In this study, we employed an integrated and physically-based hydrologic model to: i) perform a temporal sensitivity analysis (TSA) using the global and variance-based method of Sobol (2001), to study how the uncertainty in the model output can be apportioned to different inputs, ii) perform a temporal identifiability analysis (TIA) of model parameters, using the dynamic identifiability method of DYNIA (dynamic identifiability analysis) to extract the maximum information content from available observations, and iii) discuss the relationship between TSA and TIA results. The study was performed in the framework of a weighing lysimeter where HydroGeoSphere was used to build a hydrologic model to simulate daily actual evapotranspiration, water content, and discharge from the bottom of the lysimeter. We then performed a TSA of model parameters for each individual output to highlight: 1) the most contributing parameters to the uncertainty of the model outputs based on their individual effects (main effect) 2) the parameters affecting model output through their interactions with other parameters (interaction effect) and 3) the dominant processes based on the contribution of relevant parameters to the output uncertainty over the course of the simulation. Consequently, we performed a TIA to find out time periods that gave the maximum information about model parameters for each output. Contrary to the TSA which showed that sensitivity of parameters to different outputs of the model was not the same, TIA indicated a consistent response to different outputs, meaning that the most identifiable parameters remained the same, independent of the output. Exploring the relation between the two analyses revealed that both Sobol indices (main and interaction effects) are required to be considered in addition to the identifiability for a proper evaluation of uncertainty reduction in the model output. We also found that identifiability is a necessary but not sufficient condition for a parameter to reduce the uncertainty in the model output. Furthermore, we underlined how hydrologic conditions, represented by average water content in our study, can affect the two requirements for uncertainty reduction. Overall, the study highlights the problem of model over-parameterization, as many of the parameters did not meet the two requirements, considering the available observations.

## **From Open Access to Institutional Management: Spring Water Use in Hindukush Himalayan Region**

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In the Hindukush Himalaya (HKH) region springs play an important role in the daily lives of thousands of communities in the hills and mountains regions. However, in many parts of the Himalayas, springs as an outlet for underground aquifers are now drying up, presenting rural communities and women in particular, with new challenges. In most of the countries in HKH, agriculture is mainly for subsistence, on small farm plots, and with spring water being the only source of irrigation wherever it is available. Springs being a natural resource, they are often open access and rarely is the water-use managed. But with increasing population and with that more demand for water, change in cropping pattern that may require more water for irrigation, and more importantly with several natural disasters impacting springheads – reduction of water released, complete drying of springs – there is increasing need for institutionalizing spring water use. Watershed development, customary management, and traditions of water use are not new concepts; history shows that the people in the Himalayas have adapted by either living along river banks or by harvesting, storing, and managing rainfall, runoff, and stream flows. Our study based in Nepal and India shows that water has been managed in mountain regions at the community level, relying upon diverse, imaginative, and effective methods for harvesting rainwater in tanks, water rationing in arid regions, and small underground storage structures in the hills.

Governments in the region have supported various programs on traditional water management that focus on micro-watersheds as the basis of planning and interventions. However, due to the lack of understanding about the nature and extent of springs and groundwater as a resource, private holdings and enclosing water are serious concerns related to water security and water use rights in the Himalayan context. In most customary traditions on land and water use, the right to use water has been dependent on the use or ownership of land. With increasing conflicts due to increasing competitive use of spring water, need for setting up of institutions is felt throughout HKH region and there is evidence of it growing. There is a need to look into issues of equity, demand and supply, rights of landless people, community participation, and the sustainable use of water. A number of good examples exist for managing natural resources at the local level such as ‘community forestry user groups’ in Nepal and ‘van panchayats’ in India. Similar models could be adopted to regulate springs and groundwater use through institutional provisions such as ‘spring water user groups’. This could also empower communities to establish rights over the water they manage and address the issues of efficiency, equity, and sustainability.

## **Evaluating NRCS Water Conservation Practice Impacts Over the Ogallala Aquifer**

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The Ogallala Aquifer Initiative (OAI) is a multi-state effort designed to reduce the quantity of water withdrawn from the Ogallala aquifer and to reduce nitrate leaching to the aquifer. OAI is an Initiative funded through the Environmental Quality Incentives Program administered by NRCS. The OAI objectives are accomplished through implementation of improved cropping systems and conservation practices. These conservation practices are geared towards improved irrigation water management, crop residue and tillage management, nutrient and pesticide management, brush management, proper grazing systems and playa wetland and associated watershed restorations. This presentation will describe the effectiveness of practices implemented through the OAI and compare them to practices implemented through general conservation programs. It will compare the physical effectiveness of OAI and general conservation practices in reducing the quantity of water withdrawn from the aquifer. Information on practice implementation cost, both Federal and estimated total, will be included to determine the cost effectiveness of the practices deployed. The presentation will outline the methods used to determine the reductions in water withdrawn from the Ogallala Aquifer and how effective the improved cropping systems and conservation practices are when meeting the objectives of this initiative. The analysis is based on modeled water use, local implementation expertise, and program administrative data from the U.S. Department of Agriculture, Natural Resource Conservation Service. The administrative data will be used to discuss trends in financial assistance/technical assistance to address agricultural water conservation concerns and the associated practices implemented. These results will be of interest to anyone who is interested in reducing agricultural water withdrawals, especially in Ogallala Aquifer region.



## Development of Sustainability Strategies in the Agri-Food System-Regional Nitrogen Management

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Nitrogen (N) is necessary and fundamental to the global food and biomass production, and at the same time, the intensification of agriculture has resulted in excess use- and losses of N, which impairs water quality in streams, lakes, coastal waters, and contributes to groundwater pollution. Denmark's agricultural production is intense and farmland covers more than 60% of the land, which have resulted in local N water pollution problems. These unintended consequences of agricultural production in Denmark have raised awareness among citizens, NGOs, politicians and research to deal with the problem. However, regional N management is contested by farm and agricultural interests, why solutions call for stakeholders to collaborate, that the agri-environmental policies are targeted, accepted and legitimized to and by stakeholders and that research highlight best practice examples of how sustainability can be achieved through interdisciplinary studies. Finding the right suit of measures to reduce N pollution in Denmark is difficult and needs a comprehensive view on the agri-food system. In this presentation, results from the Danish Nitrogen Mitigation Assessment: Research and Know-how for a sustainable, low-nitrogen food production ([www.dnmark.org](http://www.dnmark.org)) are presented. Different strategies - consumer driven, integrated practice and policy solutions – are presented to achieve N source control and mitigation of the unintended consequences of excess N. Specifically, the indirect link between human (over) consumption of proteins and agri-environmental problems is investigated by looking at how building awareness about protein consumption and N-footprint can contribute to a changed consumption behavior towards a more sustainable pathway in the Danish agri-food system, beneficial toward sustainable groundwater in agriculture.

## Efficient Data-Driven Estimation of Nitrate Transport and Reactions in Groundwater Using a Vertical Flux Model

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Nitrate contamination in shallow groundwater extends across large regions of agricultural land around the world. Predictions of vertical nitrate migration are difficult because the effects of input histories can appear similar to the effects of reactions. Furthermore, nitrate reactive transport at large scales can be difficult to capture with detailed numerical models. Towards addressing these issues, we developed a simple modeling framework called the Vertical Flux Model (VFM) to analyze nitrate input histories and future concentrations in groundwater based on well information and measured tracer concentrations including dissolved oxygen, nitrate, atmospheric tracers of groundwater age, and dissolved gases. Application of the method yielded information about reaction rates and eventual depth of migration of nitrate at 14 detailed study sites across the US. Under the current N application rates and hydro-geochemical conditions, downward migration of the nitrate front will continue at seven sites with low denitrification rates (zero order rate constant less than 0.2 mg/L/yr). Comparison of results among the 14 sites suggests that rates of oxygen reduction and denitrification are correlated, and that denitrification rates tend to exceed oxygen reduction rates on an electron equivalent basis. Preliminary results from regional VFMs in California and Wisconsin confirm the correlation of rates, suggesting that oxygen reduction rates, which are relatively easy to obtain, can serve as a proxy for denitrification rates in some regional studies. The applications of the VFM indicate that the method gives an efficient and flexible means of characterizing current and future nitrate fate and vertical transport in groundwater.

## Challenging a Trickle-Down View of Climate Change on Agriculture and Groundwater

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Global climate change is largely viewed as affecting eco-hydrology of the Earth's surface, but various studies are showing deeper effects on groundwater. Agricultural systems may be studied at the land surface and into the root zone with deeper effects of water and chemical movement to groundwater. Traditionally, this has been literally a top-down approach, where climate and weather patterns drive plant and soil-water responses that trickle down to groundwater. In this view, feedbacks of groundwater to the surface are mainly given by pumping and irrigation, which are managed to meet the evaporative (evaporation plus transpiration) demands of cropping systems. Full coupling of climate with agriculture and groundwater remains a challenge due to complex biophysical, engineering infrastructure and policy interactions and constraints. For example, crop water management under limited water scenarios should include the possibly compensating effects of rising temperature and atmospheric CO<sub>2</sub> on plant transpiration, along with regional water policies that may consider historical groundwater recharge to be a "return flow" requirement. Such factors impact the potential for water marketing and related agricultural decision making. This talk will provide an overview and examples of the issues faced by different stakeholders and researchers investigating the interconnections of climate change, food security and environmental sustainability of agricultural lands. International collaboration and frameworks for cooperation will also be highlighted.

## **Managing Freshwater Resources: Insights from New Zealand's Policy Experience with Managing the Impacts of Agricultural Non-Point Sources**

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Water quality and availability, both surface and groundwater, are key natural resource management concerns in New Zealand. There has been a growing recognition around the nation of the greater scarcity of water resources primarily related to agricultural non-point sources of contamination and the intensification of agricultural production and its subsequent demand for water. This was increasingly leading to highly conflicted and contentious policy and planning processes around how best to manage these resources. Most of this conflict is between different agricultural sectors, between community and agricultural aspirations for the health of these resources and to a lesser degree between urban vs rural users. In response, New Zealand has dramatically changed the operating paradigm for managing freshwater resources over the last 10 years including: new policy and planning processes and tools, improved approaches to science, and its delivery and the use of more collaborative processes to engage communities and affected stakeholders. The National Policy Statement for Freshwater Management (2011 and 2014 amendments), which is driving much of this change, decrees there will be mandatory limits set for water quality and water takes for all water bodies, including groundwater, in the country. This is affecting rural land uses through their direct impacts on water quality and abstraction of water or through constraints on land use change and intensification. More recently legislative change has formalized the use of collaborative processes as the preferred approach to setting these mandatory limits. The transfer of the responsibility to identify and set freshwater limits to communities is not without its challenges, particularly around the processes to set policy, the difficulties with making trade-offs between different uses and aspirations/values for water, and interpretation and use of science to inform decisions. We will outline some of the experiences of operating within the new policy and collaborative planning paradigms being used in New Zealand to manage freshwater resources and some of the more controversial policy issues that are arising, such as the allocation of water resources. An accompanying presentation outlines the challenges of and approaches to the type of science and its delivery to support collaborative decision-making.

## What Policies to Manage Groundwater Use in Agriculture? Lessons from a Study of OECD Countries

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Groundwater is increasingly used to support agricultural irrigation. In OECD countries, groundwater irrigation covers 23 million hectares of cropland in key agricultural production regions. There, it serves as a reliable water source for irrigation, providing water on demand, while being largely unaffected by short-term hydrological variations. In many regions, however, the expansion of such irrigation has led to groundwater overdraft, in some cases with significant negative economic and environmental impact. Managing these externalities is a critical challenge for irrigated agriculture in these regions. Past experience show that policies have a role to play, but that the design and combination of approaches matters critically to ensure sustainable outcomes. The presentation draws on a 2015 study that studied a wide range of national and subnational management instruments in over twenty OECD countries with very different agriculture and hydrogeological contexts. A wide diversity of policies applied to manage groundwater use in agriculture. Policies are founded on different legal systems; they focus on the demand side, supply side or both, and use direct or indirect approaches to regulatory, economic or collective management. While there is no visible link between the scope of management and the intensity of constraints, economic and supply-side approaches are more prevalent in areas under higher agricultural groundwater stress. These policies are then compared with a grid of necessary conditions for successful groundwater management, relying in particular on a tripod combination of regulatory, economic and collective-action approaches to cope with intensive groundwater use. Survey results indicate that these recommendations have not been uniformly applied in OECD countries or regions that use groundwater intensively for agriculture. In particular, there seems to be a relatively low level of knowledge on groundwater resources and use. Most OECD countries or regions in the survey sample have also applied incomplete management schemes, missing part of the recommended approaches.

## **Groundwater Salinization Due to Hydraulic Closure in Tulare Basin Over a Long Term Time Scale**

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Population growth and the expansion of agriculture, coupled with climate uncertainties, have accelerated groundwater pumping and overdraft in alluvial aquifers worldwide. The low rate of replenishment is far exceeded by the rate of groundwater pumping in overdrafted aquifers, which results in the substantial water table declines and contributes to the formation of a “closed” basin. Moreover, in past decades, extreme weather conditions (i.e., severe drought in California for the past five years) have resulted in unsustainable surface water storage. This increases demand for groundwater to supplement low surface water supplies, and consequently, drives groundwater overdraft. Groundwater salinity increases in these closed basins as evaporation and groundwater pumping become the dominant exits for water. Irrigated agricultural basins are particularly at risk to groundwater salinization, as naturally occurring (i.e., sodium, potassium, chloride) and anthropogenic (i.e., nitrate fertilizers) salts leaches back to water table through the root zone, while a large portion of pumped groundwater leaves the system as it is evapotranspired by crops. In this study, the water balance and salt balance in Tulare Basin, California were computed. Groundwater degradation under current, overdrafted conditions was further investigated applying a solute transport model, and the time scales under which groundwater salinity may pose a threat to societies was estimated. Lastly, and most importantly, management strategies to mitigate groundwater salinization will be proposed.

## Scale Dependence of Controls on Groundwater Vulnerability to Non-Point-Source Nitrate Contamination, California Coastal Basin Aquifer System

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Understanding the controls on nonpoint-source (NPS) nitrate (NO<sub>3</sub><sup>-</sup>) contamination in groundwater is motivated by the widespread detection of NO<sub>3</sub><sup>-</sup>, implications for human health and aquatic ecosystems, groundwater sustainability, and a growing realization that such understanding across spatial scales promotes management and policy choices that optimize the Water-Energy-Food (WEF) Nexus. In the Coastal California basin aquifer system (CCB), the conflicts in the WEF Nexus are apparent because of intensive agricultural practices that have contributed to chronic NO<sub>3</sub><sup>-</sup> loading to groundwater. Here we evaluate the scale-dependent relations among source, transport, and attenuation (STA) factors that control NPS NO<sub>3</sub><sup>-</sup> contamination in recently recharged CCB groundwater. We present univariate and multivariate logistic regression models for two spatial scales common to management and policy decisions: sub-regional scale (the north, central, and south CCB sub-regions) and regional scale (the entire CCB region). Here we define STA scale dependence if such factors are statistically significant in either sub-regional or regional models and STA scale invariance if such factors are statistically significant in both sub-regional and regional models. We find that dissolved oxygen (DO) (attenuation) in groundwater is often the most significant STA factor in all model domains, indicating that DO is an important, scale-invariant factor controlling NPS NO<sub>3</sub><sup>-</sup> contamination. During the collection of water quality data for this study, we found that DO is not regularly collected during routine groundwater sampling. Considering the importance of DO on denitrification and the relative inexpensive tools used to measure it, DO should be regularly monitored. Farm fertilizer (source) is also a significant scale-invariant factor, while many of the transport factors are scale-dependent factors. We present vulnerability maps that illustrate the spatial patterns of predicted probability of detected elevated NO<sub>3</sub><sup>-</sup>. Findings here improve knowledge about the scale dependence of STA factors, which help decision makers develop best management strategies and policies that advances groundwater sustainability and optimizes the WEF Nexus.



## Approach to Reduce Drought in California

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Drought has been projected as the biggest threat from climate change and its impacts are global. Drought occurs in all continents of the world including Africa, Australia, Asia, and North America. A drought can be defined in various ways. A meteorological drought, for example, is when the rains fail. A hydrological drought is when the lack of rainfall goes on long enough to empty rivers and lower water tables. Agricultural drought begins when the lack of water starts killing crops and livestock. And after that, people may start dying too as a result of insufficient food and water supply. Droughts have significant economic, environmental, direct and indirect social impacts. Beyond direct economic impacts, drought can threaten drinking water supplies and ecosystems, and often contributes to increased food costs. Within the last decade, drought conditions have hit the Southeastern U.S, the Midwest, and the Western U.S. In 2013, California had the driest year on record. The 2011 U.S. drought covered the southern states where Texas, Oklahoma and New Mexico were most adversely affected. Drought also affected parts of Arizona, Kansas, Arkansas, Georgia, Florida, Mississippi, Alabama, South and North Carolina. Now is the time to find some approach that might mitigate the drought issue in California. FDB is now initiated several research efforts to evaluate use of recycled water from several sources to provide new insight and timely solutions for amelioration of projected irrigation water deficits in California agriculture. Recycled water has the added benefit of high nutrient content and has the potential of being both a good resource for irrigation and soil nutrient supplementation. Although recycled water is potentially a good resource, it may also have possible negative impacts on food crops and public health due to microbial and heavy metal contamination. The new FDB studies are intended to identify and categorize these public health risks. The greatest concern is that recycled water may be contaminated with human pathogens, which could be absorbed by food plants irrigated with recycled water. These pathogens, if present in the edible parts of the vegetables, have the potential to cause human and animal illness when consumed. Research and epidemiological follow-up has detected *Escherichia coli*, other fecal coliforms, fecal streptococci, and *Salmonella* spp. and helminth eggs in vegetables irrigated with tertiary-treated municipal wastewater. Lonigro et. al. 2015, reported that *Escherichia coli* and *Salmonella* were found, at harvesting time, on edible parts of crops like cucumber, lettuce and melon irrigated with treated municipal wastewater. Rai and Tripathi, 2007, reported that vegetables irrigated with partially treated wastewater had coliform counts higher than the recommended standards, with highest amounts detected in spinach and cabbage. Consumption of such contaminated vegetables has been epidemiologically linked to disease outbreaks with associated serious health risks to vulnerable human populations. In summary, our studies will contribute significant and timely data evaluating the use of recycled water from organic waste for irrigation of leafy greens.

## **Tools for Monitoring and Evaluating Potential Sources of Nitrates to Groundwater, Eastern Idaho**

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Ground water is the primary source of drinking water for more than 95% of Idaho residents including public water systems and private wells. Agricultural and domestic fertilizer applications, animal feeding operations and dairies, septic and onsite waste water treatment systems, and industrial wastewater sources are potential sources of nitrate in ground water. Idaho Department of Environmental Quality (IDEQ) has a leading role in monitoring to identify areas of degraded ground water, understanding potential nitrate sources, and evaluating best management practices to address those sources. Understandings gained by IDEQ studies at the regional and local level is aimed at protecting public and private drinking water sources, aiding groups such as local soil and water conservation districts to protect ground water quality through improving agricultural land use practices, and helping to restore degraded ground water. The following suggested tools are based on IDEQ-led investigations of ground water in eastern Idaho and are meant to be used as a resource for other IDEQ regional offices or other decision makers to understand potential regional sources of nitrates to ground water. In this study, monitoring wells are identified within randomly selected square-mile sections for regional-scale (100's of square miles) characterization. Smaller scale monitoring networks are also identified for subareas sharing similar hydrogeology and land use. Well selection criteria favors newer wells producing from the shallow-most aquifer. The number of sites selected for the subareas is based on the mean and variance of existing nitrate data which estimates the bounds of confidence and prediction intervals for future sampling. Data collected from each site include: field parameters (pH, temperature, conductivity, dissolved oxygen), bacteria (total coliform, E. coli), nutrients (nitrite + nitrate, ammonia), major anions and cations (Ca, Mg, Na, K, total alkalinity, Cl, SO<sub>4</sub>, F), nitrogen isotopes (d<sup>15</sup>NNO<sub>3</sub>, d<sup>18</sup>ONO<sub>3</sub>), characteristic tracers (Br, B), isotopes of water (d<sup>18</sup>OH<sub>2</sub>O, d<sup>2</sup>HH<sub>2</sub>O), and tritium. Data analysis includes the following: 1) Review field parameters to establish the general chemistry and to identify if conditions are oxidizing or reducing, and to confirm that the water sampled is representative of the aquifer, 2) Review bacteria concentrations, specifically E. coli, as a direct indication of human or animal wastes, 3) Plot characteristic ratios of major ions and mixing plots of major ions, tracers, and nitrate or nitrogen isotopes to confirm recharge and nitrate source mixing and to identify signatures of potential nitrate sources, 4) Prepare piper trilinear diagrams in order to show mixing between major recharge and contamination sources, 5) Plot characteristic ratios of major ions, nitrates, tracers, and nitrogen isotopes to provide signatures of potential recharge nitrate sources, 6) Employ mixing plots to identify significant indicators and mixing between both recharge and contaminant sources, 7) Dual isotope plots of nitrogen and oxygen of nitrates are used to identify original nitrate sources and distinguish nitrification and denitrification, 8) Isotopes of oxygen and hydrogen in water are used to confirm timing and source of recharge, and 9) Tritium age dating provides the age of recharge.

## Using High Frequency Pump Monitoring to Reduce Energy Consumption

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In California, the financial cost of pumping irrigation water has seen significant increase in recent years. This is due in large part to the long-term drought, which has forced a shift in water sourcing from surface water to groundwater aquifers. Groundwater is generally more expensive to produce, due to the high-energy cost of pumping water from underground and amortization costs of constructing wells. Agricultural users have responded to price pressure in several ways: reducing water consumption with improvements in irrigation technique and equipment, improvements in pumping equipment, higher levels of monitoring of pump equipment condition, and shifting energy consumption to take advantage of time-of-use (TOU) rate structures. In regards to energy efficiency, there has been a significant shift to utilize variable-frequency drives (VFDs) to control irrigation pumps, many of which have been subsidized by a wide range of state and utility grant programs. Many users also utilize pump efficiency tests more often, which are often subsidized or provided free of charge by local utilities. While VFDs and efficiency tests certainly aid in reducing energy consumption and improving pump efficiency, they may offer misleading results for many systems. In particular, operations where the irrigation load varies significantly, and/or where there are multiple pumps connected to a single pressurized distribution system can see significant deviations from the nominal efficiency indicated by standard efficiency tests. Our approach seeks to use high-resolution monitoring of pump operational parameters (water flow, water pressure, energy consumption, pumping depth, VFD parameters) to more accurately assess true pump efficiency and pumping cost. More accurate information enables pump operators to better optimize their irrigation systems to reduce energy consumption (by optimizing which pumps to run and at what speed) based on segmented irrigation loads. Providing easy visibility to pricing information may encourage shifting irrigation operations to off-peak energy hours. Presently, this information is invisible to operators except in the form of long-term energy and water flow comparisons. To date, we have installed monitoring systems on three large-scale irrigation systems in California. Preliminary results indicate that real pump efficiency varies significantly from nominal tested values. Pumping costs often change by 20% with common variations in irrigation load. Future observations will show if providing this information to operators can impact irrigation practices and improve energy efficiency and/or lower average water pumping costs.

## **Managing the Groundwater-Surface Water Interface Under California's New Groundwater Law**

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The California 2014 Sustainable Groundwater Management Act (SGMA), for the first time in the state's history, protects beneficial uses of surface water from significant and undesirable impacts due to groundwater pumping. The law also explicitly protects groundwater dependent ecosystems. Under SGMA, local groundwater sustainability agencies (GSAs) must define monitoring networks, minimum thresholds, and measurable objectives to sustain the groundwater-surface water connection and groundwater-dependent ecosystems. Regulations spell out some minimum monitoring requirements, but provide flexibility in how to plan and implement sustainable groundwater-surface water connections. Among the groundwater sustainability objectives prescribed by SGMA, achieving sustainable groundwater-surface water and groundwater-dependent ecosystem objectives may be among the most challenging: California groundwater basins with some of the least prior groundwater management activities are most affected; the dynamics of the interface may cause long and hidden delays in impacts; and management of groundwater-surface water connectivity is uncommon, hence there are no ready-made toolboxes to look for. Instruments available to GSAs to assess groundwater-surface water connections and the potential impact from groundwater use and management activities can be broadly categorized into: water level data, water budget information, streamflow data, analytical modeling tools, numerical modeling tools, and statistical tools.

**Mohsen Mehran**, Rubicon Engineering Corporation: Sustainable Application of Recycled Water Nitrate in Agriculture

## Field Scale Groundwater Nitrate Loading Model for the Central Valley, California, 1945-Current

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Anthropogenic groundwater nitrate contamination in the Central Valley aquifer system, California, is widespread, with over 40% of domestic wells in some counties exceeding drinking water standards. Sources of groundwater nitrate include leaky municipal wastewater systems, municipal wastewater recharge, onsite wastewater treatment (septic) systems, atmospheric nitrogen deposition, animal farming, application of organic waste materials (sludge, bio-solids, animal manure) to agricultural lands, and synthetic fertilizer. At the site or field scale, nitrogen inputs to the landscape are balanced by plant nitrogen uptake and harvest, atmospheric nitrogen losses, surface runoff of nitrogen, soil nitrogen storage changes, and leaching to groundwater. Irrigated agriculture is a dominant player in the Central Valley nitrogen cycle: The largest nitrogen fluxes are synthetic fertilizer and animal manure applications to cropland, crop nitrogen uptake, and groundwater nitrogen losses. We construct a historic field/parcel scale groundwater nitrogen-loading model distinguishing urban and residential areas, individual animal farming areas, leaky wastewater lagoons, and approximately 50 different categories of agricultural crops. For non-agricultural land uses, groundwater nitrate loading is based on reported leaching values, animal population, and human population. For cropland, groundwater nitrate loading is computed from mass balance, taking into account diverse and historically changing management practices between different crops. Groundwater nitrate loading is estimated for 1945 to current. Significant increases in groundwater nitrate loading are associated with the expansion of synthetic fertilizer use in the 1950s to 1970s. Nitrate loading from synthetic fertilizer use has stagnated over the past 20 years due to improvements in nutrient use efficiency. However, an unbroken 60-year exponential increase in dairy production until the late 2000s has significantly impacted the nitrogen imbalance and is a significant threat to future groundwater quality in the Central Valley system. The model provides the basis for evaluating future planning scenarios to develop and assess long-term solutions for sustainable groundwater quality management.

## **The Impacts of Piped Water on Water Quality, Sanitation, Hygiene and Health in Rural Households of Northwestern Bangladesh – a Quasi-Experimental Analysis**

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We investigate the impacts of piped water on water quality, sanitation, hygiene and health outcomes in marginalized rural households of northwestern Bangladesh, using a quasi-experimental analysis. A government organization – the Barindra Multipurpose Development Authority (BMDA) – established a piped water network to provide improved water to these rural households, for whom potable water is scarce. Using propensity score matching, the study compares a treated and a control group of households to identify gains in the water-sanitation, hygiene and health outcomes. We find that the BMDA piped water infrastructure generates a positive impact on improved water access and reduces the distance and time for collecting drinking water significantly. However, we find no improvement of the drinking water quality, measured as the extent of faecal contamination (count of pathogen bacteria *E. coli* per 100 ml of water) at the point of use. The hygiene status of the food utensils is also not improved, as they were tested positive to *E. coli* contamination in control and treatment households alike. The clear benefit of the BMDA intervention is on the hygiene behavior: hand washing with soap before feeding children is higher among treated households. Similarly, these households possess bigger water containers. We deduct from this that the intervention has a clear impact on the quantity of water used for household purposes. However, we do not find evidence of immediate health benefits, such as decreased prevalence of diarrhea for under-five children, though longer-term health impacts of access to piped water are observed in child anthropometrics. In particular, weight-for-age and weight-for-height z-scores of under-five children are improved. We also provide evidence that the percentage of underweighted children is reduced significantly due to piped water use.

## Selective Groundwater Extraction for Agricultural Yield Optimization

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Subsurface quality grading of the groundwater supply throughout California began in earnest about a decade ago through miniaturization of down-hole flow and water chemistry measurement technologies as applied to municipal water supply wells. However, there has been a growing push in the agricultural sector for Selective Groundwater Extraction (SGE) – at least within California. SGE means that municipal groundwater producers and a growing number of agricultural concerns that use large quantities of groundwater now have the ability to pick and choose which subsurface layers of earth they extract groundwater from based in-well, down-hole, water quality grading. Many times, these new miniaturized technologies can be deployed in existing production wells without removing the pump from the well – such that an agricultural production well is catheterized in similar fashion to a patient receiving cardiac assist balloon pumping and angioplasty. In this sense the well is the patient. The line shaft turbine is the heart, the casing is the aorta, the well screen and surrounding formational stratigraphic units the complex of veins feeding groundwater to the well in different amounts and varying quality; where it is all mixed and blended in the casing before reaching the surface. In other cases, the farmer's primary pump is removed and then reinstalled with small diameter access pipe (1" to 1.25" ID) to allow safe passage of the miniaturized tooling into the well and past the pump bowls and intake. In either case, the cost savings of using miniaturized technologies to diagnose flow and water quality contribution along the screens (perforations) of wells are significant in both the short and long term. Standard alternative approaches to dealing with water quality problems in agriculture are expensive and stem from not knowing how groundwater from the different stratigraphic horizons are blended inside the well before reaching the surface. The typical response for vineyards that experience difficulty with second plantings due to buildup of boron and sodium in the soil as well as walnut, almond and pistachio growers is to use expensive treatment and/or resort to building new wells. This presentation will explain the concept behind SGE including use of manipulated in-well hydraulics and engineered down-hole blending to achieve the desired water quality result through use of miniaturized diagnostic technologies. In one case, arsenic contribution will be examined, which is of particular concern for ag-facilities delivering potable drinking water to their employees. In another case, subsurface boron distribution will be explained.



## **Designing Production Wells to Optimize Performance and Efficiency**

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There has never been a more critical time to design, operate, and maintain ground water production wells in the most cost efficient manner possible. This presentation will highlight the critical components of the well construction process; material selection, formation sampling, gravel pack selection, screen slot size selection, and well development. Proper application of these design and construction techniques can maximize the well's production potential and service life. Additional topics will include the definition of well efficiency and a discussion on the hydraulic losses that contribute to drawdown in the well. The primary goal for designing and constructing an efficient well is to minimize the hydraulic losses which will reduce the drawdown in the well, thereby resulting in lower pumping costs for the well owner.

## Utilizing Natural Nitrogen Reduction in National Regulation

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Since the mid-1980s a suite of different nitrogen measures have been imposed in different action plans in Denmark. These measures have been successful in reducing the N surplus by 30-50% and reversing an upward trend in nitrate groundwater concentrations in large parts of the country as well as nearly halving the nitrogen loads to estuaries. However, shallow toxic groundwater aquifers, covering approximately 45% of the area in Denmark, still experience nitrate concentrations above the groundwater and drinking water standards of 50mg l<sup>-1</sup>. Similarly, assessments of the ecological status of marine water-bodies indicates that further reductions in nitrogen loadings are required in some water-bodies to obtain a good ecological status according to the European Water Framework Directive. Past and current regulations have primarily relied on a general approach, applying same restrictions for all areas independent on drainage schemes, hydrogeochemical conditions in the subsurface and retention in surface waters. Although, significant reductions have been achieved this way, general measures are not cost-effective, as nitrogen retention (primarily as denitrification) varies significantly depending on the physical and biogeochemical conditions. If areas with high and low retention can be identified, regulation can be targeted allowing less strict regulation in some areas and focus stronger regulation and mitigation measures in areas, where nitrate leaching is high and nitrogen retention is low. The Danish Commission recognized this on Nature and Agriculture, who recommended new regulation principles based on a spatially differentiated and targeted nitrogen regulation. As a first step in exploring how a differentiated approach can be integrated in national regulation, a national nitrogen model has been developed for Denmark. The model is constructed by linking existing models describing nitrate leaching from the root zone, groundwater transport and reduction as well as surface water retention models. The models are coupled at sub-catchment scale dividing the country into topographic catchments with a mean size of 15km<sup>2</sup>, which constitutes the computational units in the national model. Model development, calibration and validation have been performed on measurements of nitrogen transport from 340 streams gauging stations covering approximately half of the total area in Denmark. The national nitrogen model was initially designed to compute the nitrogen loads to coastal areas and compute national maps displaying the estimated nitrogen retention in groundwater, surface water and the total retention from the field to the sea. Further developments are focusing on extending the model to describe also nitrogen loads to the 402-groundwater bodies (consisting of 2771 groundwater aquifers) delineated in Denmark. Currently, new regulation principles utilizing new and more spatially targeted nitrogen measures are implemented in Denmark. The national nitrogen model and the associated retention maps have been important building blocks in the dimensioning of new mitigation measures required to meet the environmental goals, while at the same time optimizing agricultural production.

## Markets, Groundwater and Law: Water Reform Lessons from Australia

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The regulation of non-urban groundwater extraction in Australia has undergone major policy reform over the last 15 years. In this regard, the clear policy ‘winner’ has been the adoption of a top-down policy approach that relies on caps (based on sustainable yield) and the market-based trading of groundwater permits (decoupled from land title). This paper uses survey and interview data collected from landholders and policy makers in the Murray Darling Basin in New South Wales, Australia, to explore three potential shortcomings of this approach for managing groundwater, and then considers policy alternatives for future reform. The first shortcoming is structural impediments to optimal trading. In an ideal market, there are few impediments. However, the practical experience in Australia reveals problems in trading between groundwater and surface water sources; difficulties in trading between discrete groundwater aquifers; and the presence of ‘sleeper’ groundwater licenses. The second issue is deficiencies in the regulatory tools that support market trading. In essence, market trading is a hybrid policy instrument – it relies on the effective security of value of the permits being trading. And yet there is reason to doubt this security due to inadequate compliance and enforcement by water regulators, who have tended to focus on surface water issues, together with a slow embrace of transformative technologies like real-time, remote metering. The third issue is the ‘crowding out’ of other policy/regulatory options. The use of market trading of water can be incompatible with other regulatory approaches that undermine the purity of the market. There has been little exploration of alternatives, particularly the use of bottom-up, collaborative governance approaches that engage local communities, build ownership and provide tailored solutions. Having identified these three problems, the paper canvasses possible groundwater policy reforms, in particular, whether or not such reforms can be conceived within an exclusively top-down, market based approach, as presently exists.

## Regulating Water Bore Drillers: Lessons from Australia

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Drillers of water bores are vital but rarely examined actors in water law and regulation. They carry out drilling, bore construction, and other work on bores on behalf of landholders to supply groundwater for stock, domestic, agricultural/irrigation and town water supply purposes. The quality of drilling practices can have significant impacts on groundwater misuse, wastage and degradation, and the location, size and use of bores can impact on the sustainability of groundwater resources. As such, Australia licenses and regulates their activities to ensure the protection of groundwater resources and the long-term economic production of groundwater. Beyond the need to regulate the drilling industry, drillers themselves play a unique role in providing information to agricultural landholders. Because landholders will typically engage a driller to access groundwater, drillers may be the first points of contact about the landholder's obligations under water management legislation (e.g. to obtain necessary approvals). This role means that drillers have the potential to be a key party that assist or undermine agricultural water user compliance with their obligations under water management legislation. Given the limited examination of the regulation of drillers to date, and their potential lynchpin role in ensuring landholder compliance, this paper examines and assesses the operation of drilling regulation in New South Wales, Australia. Drawing on approximately 45 interviews with drillers and government officers, it provides insights into the effectiveness of these regulations. Its findings reveal some success, but suggest regulation remains confounded by a lack of inspectoral oversight due to geography, resourcing and driller mobility, and current administrative and training arrangements. The paper canvasses options for addressing these challenges, and argues that more effective regulation requires utilizing remote monitoring technology and engaging drillers in the regulatory process through a best practice accreditation approach.

## Nitrogen Surplus Key Factor in Relation Between Farm Practices and Water Quality

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The effects of the EU Nitrates Directive Action Program are monitored in The Netherlands via standard programs for groundwater and surface water, and a special program known as the Dutch Minerals Policy Monitoring Program (LMM) based on a national network for measuring the effects of the Manure Policy. LMM uses an effect monitoring approach to assess the contribution of nitrate from agriculture to receiving waters and the effects of changing agricultural practice on these losses. LMM monitors therefore both water quality and the farm management that might influence this quality. LMM data on water quality and farm management showed the importance of N-surplus on the soil as an indicator for water quality. Therefore within the LMM-program there is a strong focus on farm management factors that affects N-surplus. For this a solid method is needed in order to assess comparable N-surpluses for different farm types and soils. This contribution describes the assessment of N-surplus based on a soil balance method. Furthermore it presents the relation between N-surplus and water quality and the relation with the Dutch policy on manure and the amount of N-fertilization for the period 1991-2013. The surplus on the farm gate balance is first calculated by determining the total annual input (for instance inorganic fertilizer, feedstuffs) and output (for instance animal products, crops and other plant products) of nutrients as registered in the farm records. Stock changes are taken into account when calculating this surplus. The calculated nitrogen surplus on the farm gate balance is then corrected to account for input and output items on the soil surface balance. Allowance is made for net mineralization of organic substances in the soil, nitrogen fixation by leguminous plants, ammonia emission and atmospheric deposition. The phosphate surplus on the soil surface balance is equal to the surplus on the farm gate balance. A state of equilibrium is assumed when calculating nutrient surpluses on the soil surface balance, except for peat soils. On Dutch peat soils a net mineralization occurs. For different farm types the method and data is useful to calculate the nutrient surplus on the soil balance. Comparisons can be made between farm types and within one type between regions. For dairy farms the soil surpluses for nitrogen and phosphate amount to 181 kg of N and 12 kg of P<sub>2</sub>O<sub>5</sub> per hectare (Figure 1, phosphate is not shown). The nitrogen surplus has remained at the same level for the past few years, while the phosphate surplus is still decreasing as a result of the Usage Standard System. The soil surpluses for nitrogen and phosphate at arable farms amounted to 110 kg of N and 19 kg of P<sub>2</sub>O<sub>5</sub> per hectare (Figure 1, phosphate is not shown). The nitrogen surplus has more or less stabilized since 2008, while the phosphate surplus continues to decrease. N-surpluses as well as nitrate concentrations differ between farm types and between regions (not shown). Dry-matter yields of grass are hardly changed despite a lower fertilization level, due to better farm management. Figure 1-Nitrogen applied (kg/ha) and Nitrogen surplus (kg/ha) for Dutch dairy and arable farms in the 1991-2013 periods.

## **Towards Understanding the Role of Social Capital Within Adoption Decision Processes: An Application to Adoption of Irrigation Technology**

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Recently, social capital has gained in importance in explaining technology adoption decisions by farmers. In this paper, we examined the impact of social capital on irrigation technology and scheduling adoption among wine producers in Central Chile. Within this context, we defined seven different components of social capital: general trust, trust in institutions, trust in water communities, norms, formal networks, informal networks, and size of networks. Using a partial least square model, we estimated the impact of these seven factors along with indicators of physical and human capital. As expected, physical and human capital have a positive and significant relationship with adoption, and regarding social capital variables the most relevant were formal networks and the size of network. Importantly, the model results also allowed for determining the impact of human capital and trust as key variables for the building of networks. Thus, human capital and general trust have also an indirect impact on the decision to adopt. It can be argued that in social capital the main catalyst are networks, which in turn are fed by, trust and human capital, hence extension efforts should consider social networks in promoting agricultural innovations, and not just economic or individual level predictors.

## **Towards Development of a Complete Landsat Evapotranspiration and Energy Balance Archive to Support Agricultural Consumptive Water use Reporting and Prediction in the Central Valley, CA**

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Mapping evapotranspiration (ET) from agricultural areas in California's Central Valley is critical for understanding historical consumptive use of surface and groundwater. In addition, long histories of ET maps provide valuable training information for predictive studies of surface and groundwater demands. During times of drought, groundwater is commonly pumped to supplement reduced surface water supplies in the Central Valley. Due to the limited data on historic groundwater pumping, using satellite imagery to map evapotranspiration is an efficient and robust way for estimating agricultural consumptive use and assessing drought impacts. To this end, we have developed and implemented an algorithm for automated calibration of the METRIC remotely sensed surface energy balance model on NASA's Earth Exchange (NEX) to estimate ET at the field scale. Using automated calibration techniques on the NEX has allowed for the creation of spatially explicit historical ET estimates for the Landsat archive dating from 1984 to the near present. Further, our use of spatial NLDAS and CIMIS weather data, and spatial soil water balance simulations within the NEX METRIC workflow, has helped overcome challenges of time integration between satellite image dates. This historical and near present time archive of agricultural water consumption for the Central Valley will be extremely useful dataset for water use and drought impact reporting, and predictive analyses of groundwater demands.



## **Quantifying the Impact of Human activities on Water Sustainability and Crop Yields across the High Plains Aquifer using Process-Based Models**

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Water use for agriculture across the High Plains Aquifer (HPA) greatly expanded since the early to mid-1900s. There have also been significant advances in the efficiency of irrigation technologies over the last several decades from flood irrigation, to center pivot, then to Low Energy Precision Application (LEPA) systems. We present a synthesis of monitoring and modeling methods across the HPA region to investigate changes in water availability across this vast region that is dominated by agriculture. The integrated Landscape Hydrology Model (LHM) was used to quantify hydrologic fluxes including evapotranspiration and groundwater recharge across a range of observed climate conditions including the recent drought across the region. The LHM simulations are coupled to groundwater models to investigate the sustainability of recent water use practices and the quantify impacts of aquifer depletion on water levels and stream-flows. Simulations are compared to measured water levels that have been synthesized across the region from pre-settlement to today, and with remotely sensed estimates from the GRACE satellite. We also present simulations that quantify the likely impacts of projected climate changes from the CMIP5 forecasts of global climate. Finally, we explore the likely impacts of projected changes in climate on crop yields under a range of agricultural management choices using the SALUS crop model.

## **Incorporating Land-Atmospheric-Vegetation Feedbacks into Subsurface Models used for Agriculture Water Management.**

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The need for new technologies and improved management strategies for the efficient agricultural water use and sustainability has become imperative due to increasing demand for food due to global population growth as well as climate change driven stresses. Groundwater is a critical resource in the water-energy-food nexus. The problems and challenges associated with groundwater are not only limited to the semi-arid west but also many parts of the world facing with water shortages. Numerical models of both subsurface flow and transport play a central role in assessing the impacts of over water withdrawal and water quality degradation, developing strategies for efficient use and conservation, and management during droughts. In traditional models used in these applications, only the flow processes in the surface water systems, and the unsaturated and saturated zones are simulated. The conditions that determine the mass and energy fluxes at the land surface are incorporated as external boundary conditions. These types of models where the land-atmospheric interactions are decoupled do not allow for the accurate representation of the feedback processes occurring between the soils, plants and the atmosphere. In agriculture applications, such models should capture the boundary layer interactions with the surface topography that is modified by land preparation, vegetation density and distribution on bare soil surfaces and soil structure affected by macroporosity. This paper discusses the knowledge gaps that need to be filled to develop better conceptual and numerical models. Many challenges exist in developing and validation of such models. First the models need to couple drastically different flow dynamics in the boundary layer and the shallow soil in the unsaturated zone. The models also need to capture simultaneously occurring heat and mass fluxes across interfaces. How to parameterize these coupling processes at different scales associated with the soil heterogeneity, micro-topography of land surface and vegetation distribution is not well understood. Validation of these types of models in the field is not practical due to lack of control of the climate conditions. A validation methodology at the intermediate scale using a unique coupled porous media/climate wind tunnel facility is presented.

## **Investigating Livestock Manure Storage Facility Impacts on Groundwater in Alberta, Canada**

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In January 2002, the Alberta Government assumed responsibility for the regulation of confined feeding operations (CFOs) when the Agricultural Operation Practices Act (AOPA) was amended. The Natural Resources Conservation Board (NRCB), the Provincial agency responsible for the administration of the AOPA, and Alberta Agriculture and Forestry (AF) are concerned that some manure storage facilities and associated activities, such as land application of manure, may be releasing manure constituents into shallow groundwater resources. An integral part of the administration of the AOPA is determining environmental risk, as outlined in a provincially adopted Risk Management Framework policy. This has led to the development and use of a risk-screening tool and risk based compliance initiative, both currently focused towards groundwater. Although the environmental risk based policy being implemented utilizes the best available, current, and relevant science, limited Alberta-specific information exists on the impacts of manure storage and handling on groundwater quality, leading to uncertainty in the actual extent and risk that these activities pose to groundwater. As Alberta is home to almost 50% of Canada's beef cattle population, as well as a significant proportion of the national dairy, pork, and poultry populations, Alberta-specific understanding is important to the overall knowledge base. A multi-year groundwater research program was conducted through the establishment and instrumentation of field-scale CFO pilot study sites to improve the understanding of impacts from manure handling and storage on groundwater quality in Alberta and the fate and transport of various manure constituents in groundwater beneath CFOs. Long-term study sites were identified through site characterization, geological investigations, and monitoring well installation, and represent the primary typical hydrogeological conditions in Alberta affected by manure storage and handling activities. Activities were focused at specific earthen manure storage (EMS) facilities at site specific CFOs, and were also designed to examine the effects of manure land application and on a regional scale on Alberta's groundwater. Research program activities included characterization of the contaminant (i.e., aqueous) source, characterization of the hydrogeological and physical controls on the transport of contaminants, characterization of the background aqueous and solids chemistry, characterization of aqueous and solids chemistry within the contaminant plume, and quantification of the geochemical controls on the fate of contaminants. Results and findings will be presented. By improving the scientific and practical understanding of the fate and transport of manure constituents in the groundwater in typical Alberta CFO settings, improved management, policy, regulation, and protection of the groundwater and environment can be achieved. The results also provide insights and understanding into the impacts of other point- and non-point-sources of manure-associated contamination, particularly land application of inorganic and organic fertilizers and disposal of human waste, on Alberta groundwater. Instrumentation installed may also provide the opportunity to investigate the fate and transport of other emerging contaminants (e.g., pharmaceuticals, viruses, etc.) and thus assess their impact on groundwater.

## **The Relative Influence of Groundwater Versus Surface Irrigation Sources for Agricultural Production in India**

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India is a hotspot for food security issues over the upcoming decades, due to increasing population, groundwater depletion, and climate change. Investing in additional irrigation infrastructure may bolster food security; however, the relative influence of different types of irrigation (e.g. groundwater versus canal) on agricultural production remains unclear. We assess the relative impact of groundwater (i.e. dug, shallow, and deep wells) and canal irrigation (i.e. surface lift and flow canals) on winter cropped area and its sensitivity to rainfall across India at the village-scale from 2000 to 2012 using high-resolution cropped area maps produced using a novel algorithm applied to MODIS satellite data. We find that deep well irrigation is both associated with the greatest amount of winter cropped area, and is also the least sensitive to monsoon and winter rainfall variability. However, the effectiveness of deep well irrigation varies across India, with the greatest benefits seen in the regions that are most at risk for losing groundwater as a possible source of irrigation over the upcoming decades (e.g. Northwest India). This work highlights the need to develop ways to use remaining groundwater more efficiently (e.g. drip irrigation, less water-intensive crops) given that canal irrigation is not an adequate substitute for India's groundwater.

## Assessing the Effects of Buckwheat as a Wireworm Control Crop on Groundwater Quality

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Potato production plays a significant role in the economy in Prince Edward Island (PEI), Canada. However, high levels of nitrogen leaching losses from the potato production systems have been linked to the contamination of groundwater and associated surface water. While the industry is facing unprecedented pressure to mitigate these environmental impacts and maintaining its market competitiveness, it is also being threatened by increased wireworm damages on potatoes. Rotating potato with buckwheat has been promoted for wireworm control as potato tuber damage by wireworm is significantly reduced following a buckwheat crop. A study is being conducted to evaluate the effects of growing buckwheat in rotation with potato on groundwater quality. Five three-year potato rotations were initiated in 2014, including two current industry standards: barley under-seeded with red clover-red clover-potato (T1), and barley under-seeded with timothy-timothy-potato (T2), which are compared to buckwheat-based cropping systems, each consisting of two years of buckwheat but with different buckwheat plant termination methods; buckwheat-buckwheat-potato with buckwheat terminated midseason through mowing (T3), buckwheat-buckwheat-potato, with buckwheat terminated through disking (T4) and buckwheat-buckwheat-potato with buckwheat grown for grain (T5). The experiment of random blocked design was implemented at Harrington Research Farm of Agriculture and Agri-Food Canada (PEI) with each treatment replicated three times on an experimental unit of 6 by 8 m. A stainless steel suction lysimeter (manufactured by Soil Moisture Systems, SW-071-260) was installed in each plot at a depth of 80 cm for collecting soil water samples. Soil water was sampled weekly using a pressure-vacuum hand pump with gauge when the soil was saturated or/and after each rain event for measuring nitrate, nitrite, and ammonium. Anion Exchange Membranes (AEMs) were deployed in each plot at depths of 10 to 15 cm and replaced monthly to track soil nitrate. Composite soil samples were collected from each plot at depths of 0-15, 15-30, and 30-45 cm, respectively, before planting and harvesting every year. The soil samples were analyzed for nitrate, ammonium, total C, and N. Two soil moisture and temperature probes (Hobo, S-SMA-M005) were deployed at depths 0.2 and 0.3 m for measuring soil moisture and temperature in two selected plots. Preliminary soil water nitrate measurements from 2014 showed higher time-averaged concentrations in T4 (11.4 mg N/L,  $\pm 6.1$ ) and lower in T5 (3.8 mg N/L,  $\pm 1.7$ ). AEMs data showed a similar trend towards lower nitrate under T5 with 0.28 mg N/cm<sup>2</sup> /d. This study will show if growing buckwheat in potato rotation can reduce nitrate leaching compared to the industry standard potato rotations.

## **Building Capacity for Regional Sustainability with SGMA**

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While California has vast infrastructure to store winter flows and deliver water hundreds of miles to where it is needed, the majority of water infrastructure and related investment is at the local and regional level. Over the past decade, the State has provided technical services and over \$990 million in financial assistance, matched over 4:1 by local agencies, to implement more than 700 regional multi-benefit projects to improve water sustainability in regions across the State. The prolonged drought, reduction of water supply due to reduced rainfall and snowpack, and compliance with various biological opinions, coupled with increases in permanent crops and increases in urban population, have all taken a toll on regional water supply reliability and sustainability. In many areas, imbalance between water availability and demand has increased groundwater pumping and resulted in over-drafting of groundwater basins. This, in turn, has caused drinking and agricultural water wells to go dry and alarming evidence of subsidence, especially in California's Central Valley. The most significant piece of legislation was the State's passage of the Sustainable Groundwater Management Act (SGMA) in 2014. For the first time in history, the State must manage groundwater use in a sustainable manner. The landmark law requires water and land use agencies to come together in governance, and develop plans to manage groundwater – in the context of an overall regional water balance – sustainably. The State will provide financial incentives, technical tools, and enforcement to ensure implementation of the legislation, but the key to success lies with the local agencies and their ability to balance regional supply and demand in a more sustainable fashion. The Governor's 2014 Action Plan has been instrumental in focusing the State's water leaders on a common set of goals and priority actions, and it has leveraged general obligation bond revenues with existing agency budgets and other funding sources. But, full implementation of the Action Plan, and related actions like SGMA to improve water sustainability, will require investments above the current baseline budgets of State, federal, tribal, and local governments. Multiple and more stable, funding sources will be needed. A key challenge is overcoming regulatory hurdles, including surface water rights and federal and State environmental regulations. Here again, close cooperation between federal, State and local stakeholders will be required for success.

## **Drought Governance and Response Strategies including Mission Kakatiya in Telangana, India**

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Telangana, formed as the 29th state in India about two years ago is struggling to sort its issues concerning agriculture, which contributes to only 12.8% to the State Gross Domestic Product (GSDP) but supports 55.49 % of population. Farming in the state is mainly rain fed (60%) and is often prone to droughts due to climate change. The state is in its third year of successive droughts and is currently in the midst of one of the most severe droughts in its history with 22% of rainfall below normal. Considering the geography and climate of the region, huge number of tanks were constructed that helped to manage droughts for centuries. Water levels in major reservoirs under Godavari and Krishna basins have gone down to an all-time low during the last decade. The ground water table has been reducing and the state government has declared 231 mandals out of 443 rural mandals as drought affected. This warrants governance of drought with response strategies like in other natural hazards comprising, a system of early warning, a system of government preparedness and an enabling system that provides support and assistance to imperiled communities. Based on the proven drought planning mechanisms elsewhere, a drought governance framework is developed for the state of Telangana with suitable modifications. Several drought management strategies like conservation agriculture, integrated farming systems, managing water resources, drought management practices like selection of drought resistant varieties, early maturing varieties, crop specific agronomic recommendations suitable to the state have been identified and proposed. Historically tanks have been a part of the irrigation landscape of Deccan Plateau of India for centuries. Due to topography, Kakatiya rulers constructed thousands of tanks for drinking and as well as irrigation in Telangana. However, their use has been declining over a period of time mainly due to government attention and lack of community involvement in tank management and Maintenance, inadequate and unreliable water supply to the tank resulting in actual decline in the area irrigated by tanks. Tank irrigation which peaked to 5, 30,565 ha from 1956 to 1957 has declined to 2, 18, 124 ha by 2009. Due to impending crisis of groundwater irrigation, there is a renewed attention for restoration of all minor numbering 46,531 irrigation tanks under Mission Kakatiya (Mana Ooru – Mana Cheruvu meaning “our village, our tank”) in a decentralized manner through community involvement. The objective of Mission Kakatiya is to enhance the development of Minor Irrigation infrastructure, strengthening community based irrigation management, adopting a comprehensive program for restoration of tanks. The mission activities began, needed rules have been framed and efforts are being made to ensure proper execution of stipulated procedures. The tanks restoration as a major response to combat drought is expected in the coming years. The program will be implemented in a phased manner in the next five years, the inputs to make the program successful, progress and impacts will be reported.



## **Impact of Community Based Tank Management in Andhra Pradesh (AP) and Telangana states in India**

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The study entitled “Impact of Community Based Tank Management in AP and Telangana states in India” was carried out in the states of Andhra Pradesh and Telangana in India. The results of Final Evaluation of Project Impact Assessment (FEPIA) carried out in 2014 with regard to agricultural productivity and community approach in managing tanks with key outcome indicators are presented. Crop Productivity Paddy productivity has improved by 8.68 q/ha (33%) over BL, 6.14 q/ha over MTR, and 3.5 q/ha over FIA in project tanks, but only by 2.82 q/ha (11%) over BL in control tanks. Paddy, grown in about 84 percent of tank-irrigated farms, thus has achieved about 32 percent higher productivity over the final project target of 25 percent increased productivity (33.3 q/ha). Community management of tanks has enhanced maize productivity from 32.8 q/ha to 38.0 q/ha. The net increase in groundnut productivity was 4.58 q/ha (51.9%) over baseline period in command area of tanks under community management who made use of demonstrations on ICM, trainings and Kisan Mela at project tanks. The increase was by 2.9 q/ha over and above the target set by the funding agency. Cropping Intensity: There was a net increase of 19.8% in cropping intensity under command area of tanks managed by community against target of 15%. Fish Productivity: An increase of 3.05 q/ha EWSA in project tanks was recorded due to community management of tanks at FEPIA. There was an increase of 204.8 percent over base line in project tanks. Milk Productivity: The net gain was 2.02 l/day/animal with an increase of 82.2% due to community initiatives on project with tuning of gopal mitras to project activities, organization of health camps, trainings etc. The milk productivity achieved was higher than the project target of 4.9 l/day/animal by 0.1 l/day/animal. Water distribution in Command Area the project achieved increased value of crop output per unit of water (ha.m) of Rs.35, 142 per ha.m from base value of Rs.28,708 (during 2011-12) recording an increase of 22.4 per cent against end project target 25%. Improvement in adoption of cultural practices of 47.3% over baseline was achieved. Extent of area under Non-paddy: During MTR and FIA there has been decrease in area under non-paddy by 4.5 and 10.3 percent respectively over the non-paddy area collected at baseline survey for project tanks. However, this did not achieve the target of non-paddy (34%) because more tank water was available during FEPIA period and farmers preferred to cultivate rice in more area. The community approach of managing tanks has achieved desired results in improving crop productivity and managing tanks for sustainability. The project is subsequently extended for further two years to end in 2016.

## Control of Topology of Water Fluxes in Arid Agriculture: Amalgamation of Subsurface Irrigation, Managed Aquifer Recharge and Engineered Soil Substrate

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Arid zone agriculture in Oman consumes more than 80% of national fresh water resources and relies on shallow unconfined aquifers with an emerging dependence on sewage treated water of quality different from groundwater. A superjacent coarse-textured vadose zone and top soil host plants' roots subject to harsh conditions of moisture deficit and heat stress that calls for improvements of the conjunctive water use efficiency. Mitigation of adverse ambient conditions impeding the plant growth and causing secondary salinization of topsoil is proposed by innovative agro-engineering techniques. We present the results of field-, farm- observations and experiments, as well as mathematical modeling of optimal control of descending, ascending and lateral water fluxes (viz., evapotranspiration, infiltration, seepage from/to subsurface emitters/drains, losses/gains from/to a deeper confined aquifer commingled via a leaky layer with the irrigated one, and water uptake by roots). We consider two main scenarios of moistening the root zone: by furrows and linear/point sources (subsurface emitters/ leaky pipes) over the soil substrate designed as a tessellation (double-porous medium with a cascade of silt-sand capillary barriers at the interfaces between blocks and fractures). In the first case, two flow regimes are studied: a) with intensive infiltration and phreatic surface mound commanding the periodic surface channels (typical for crop fields with drainage trenches in Holland) and aquitard transmitting groundwater upward from the subjacent aquifer, and b) with intensive evapotranspiration (typical in Oman) when surface water in furrows commands the phreatic surface trough caused by evapotranspiration and groundwater recharged through a leaky layer. The Emikh-Rybakova and Boussinesq-Cherepanov models and analytical solutions are used for quantification of managed aquifer recharge and recovery by controlling the furrow spacing, accretion to the water table and water level in the furrows. In the second scenario, the emitter depth-intensity and hydraulic properties (saturated hydraulic conductivity and capillarity) of the two porous elements and the tessellation geometry determine the tension-saturated perched flow. J.R.Philip, Kirkham-Brock, and Riesenkauf-Vedernikov models are used for predicting the following: a) how much water is "adsorbed" by blocks for further gradual interception by roots, b) how much is winding through the fractures to the next level of the substrate cascade, and c) how much is eventually percolated to the "natural" subsoil and recharges groundwater. Modeled flow nets, isochrones, isotachs, and lines of equal force acting on saturated soil REV (important for structural stability of the designed heterogeneity) are computed by computer algebra routines. Plant characteristics (biomass, number-size of leafs, roots' architecture) are found in field experiments for various tessellations and irrigation schedules. Both physical and mathematical models prove the efficiency of the proposed optimization of irrigation water fluxes.

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## Nitrate Sensitive Salinity Management

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The majority of growers in California have adopted their irrigation system to micro-irrigation systems (drip and micro-spray) in response to the need for improving the management practices for both irrigation and fertigation toward a sustainable agricultural practice. Whereas providing water and nutrient to plants through micro-irrigation system offer a great opportunity to move toward Best Management Practices by reducing the water and nutrient loss through runoff and deep percolation, leaching is an undeniable part of irrigated agricultural practices, since salt accumulation in the root zone adversely affects crop growth and yield. Irrigation strategies, fertigation management, nitrate leaching and salinity management are therefore linked and strategies must be developed that optimize productivity while minimizing nitrate leaching and avoiding salt-induced stress. Perennial species and micro-irrigation impose unique challenges for salinity management and strategies developed for annual crops are not optimized for tree crops. Specifically, 1) for salt sensitive crops (e.g., almond) as water quality diminishes greater leaching volumes will be required, 2) micro-irrigation results in local salt deposition at the lateral and vertical margin of the wetting pattern, and thus water and nitrate within this high salt margin will not be available for uptake, 3) if not conducted properly, strategies that optimize salt leaching to the periphery of the rooted zone will simultaneously leach nitrate. Given the complexity of solute management under micro-irrigation and the lack of information on crop response to salinity and the lack of information on the effects of salinity on root distribution and nitrate uptake it is virtually impossible for growers to make informed irrigation management decisions that satisfy the dual goal of minimizing root zone salinity while simultaneously minimizing nitrate leaching. Therefore, proper irrigation/fertigation management guidelines for grower require a more detailed understanding of patterns of root growth and N uptake in response to non-uniform water and salt distribution. The application of irrigation water and fertigated nutrients, as well as root distribution, and nutrient and water uptake all clearly interact with soil properties and fertilizer source in a complex manner that cannot easily be resolved with 'experience' or experimentation alone. we aim to employ an existing and widely used modeling platform, HYDRUS, to conduct numerical simulation for different scenarios for a variety of almond cultivar, soil types, and different level of salinity and combine it with data obtained field/lysimeter experiments to be used as an integrated water and nitrate management tool. This will provide a means to transfer outcome of the treatments and findings of this project to other orchards with other soil types, tree root systems, crop salinity threshold, etc.

## Groundwater, Bioenergy and Soil Health – Is the Nexus Sustainable?

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Human demand for food, feed, fiber, and fuel resources will continue to increase as our global population climbs steadily towards 9.5 billion or more. Our objective for this presentation is to review potential biofuel production impacts on U.S. groundwater availability and quality by examining interactions affecting the groundwater – bioenergy – soil health nexus. Currently, irrigation supports 40% of global food production, but it occupies only about 18% of the agricultural landscape. Groundwater resources, being used for critical, irrigated food production in several regions of the world, are being depleted because their recharge rates are well below extraction rates. Therefore, without significant improvements in irrigated water management, the life expectancy for many irrigation aquifers, including several in the United States, is projected to be decades or even less. Soil degradation is an equally important problem caused by many factors that can only be addressed by adopting sustainable agricultural and land management practices. Soil and water resources are intimately linked. Addressing the nexus is the only way to ensure solutions for one problem do not induce unintended consequences for the other. Furthermore, to ensure consensus, acceptance, and implementation, it will be essential to embrace multi-Agency/institution, non-government organization (NGO), and private-sector inputs and perspectives using integrated systems approaches. The water analysis tool for energy resources (WATER) developed by Department of Energy (DOE) engineers, land use and cropping systems changes as well as enhanced irrigation water management strategies being developed by ARS scientists and engineers, and policy changes being recommended by several university Water Resource Institutes will be discussed. Our hypothesis is that all of these tools and many more will be needed to address this wicked problem, and thus ensure our fragile, groundwater, energy, and soil health requirements are met within a truly sustainable nexus.

## **Incorporating a Dynamic Irrigation Demand Module into an Integrated Groundwater/Surface Water Model to Assess Drought Sustainability**

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Understanding the cumulative effects of pumping, irrigation, drought and groundwater/surface water interaction is central to the agricultural water management problem. Assessing all of these complex processes within a single modeling framework is optimal, but difficult because of the dynamic interaction between climate, soil moisture and irrigation patterns. The USGS has developed, in parallel, two important model codes to study these processes. The USGS GSFLOW code combines the PRMS hydrologic model with the MODFLOW-NWT groundwater model into a fully integrated model that is ideal for studying groundwater and surface water interaction under drought and climate change conditions. Meanwhile, the USGS MODFLOW-OWHM model includes the Farm Process module that represents dynamic farm pumping, irrigation and return flows as a function of soil water demand. Earthfx has created a unified tool to address this challenge by modifying the GSFLOW code to incorporate the approaches and features of the Farm Process module. This evolution of the integrated GSFLOW model can simulate daily irrigation water use based on dynamic soil moisture conditions. Water is applied to the farms by adding the pumped volume to either daily precipitation or through flow (after interception) based on irrigation method. Return flows are estimated directly by PRMS as overland runoff or interflow and routed to streams. Additional modifications were added to PRMS to account for discharge to tile-drains under saturated soil conditions. Thresholds and other irrigation model parameters are dynamically applied to match water takings for each crop type and sub watershed under average and dry year conditions. While the primary benefit is a fully integrated approach, components of the Farm Package are also improved through integration with the more complete PRMS soil zone hydrology code. This extended version of GSFLOW has been tested in the Whiteman Creek watershed in southwestern Ontario, Canada. Whiteman Creek drains an area of approximately 400 km<sup>2</sup> (150 square miles), with actively cultivated agricultural fields comprising 60% of the watershed. The upper portion of the watershed is extensively tile drained, while the central and lower portions of the watershed contain significant wetlands and groundwater supported fish habitat. Total permitted takings, primarily from drought sensitive shallow sand aquifers in the lower watershed, exceed 80,000 m<sup>3</sup>/d. The model simulates groundwater heads, stream flow, and wetland stage on a daily basis under current conditions, along with future climate, drought and development scenarios. The effect of agricultural demand-driven pumping on specific sensitive stream reaches is fully represented. Detailed breakdowns of water budget components, aggregated on a monthly and annual basis, provide insight into future development scenarios. Results of the model will be utilized in the future to better manage water allocation under drought conditions.

## **Quantifying the Impacts of Irrigation Technology Adoption on Water Resources in the High Plains Aquifer**

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Producers in key agricultural regions worldwide are contending with increasing demand while simultaneously managing declining water resources. The High Plains Aquifer (HPA) is the largest aquifer system in the United States, and supplied most of the water to irrigate 6 million hectares in 2012. Water levels in the central and southern sections of the aquifer have steadily declined, as groundwater recharge in this semi-arid region is insufficient to meet water demands. Individual irrigators have responded to these declines by moving from less efficient irrigation technologies to those that apply water more precisely. Yet, these newer technologies have also allowed for water to be pumped from lower-yielding wells, thus extending the life of any given well and allowing drawdown to continue. Here we use a dataset of the annual irrigation technology choices from every irrigator in the state of Kansas, located in the Central High Plains. This irrigation data, along with remotely sensed Leaf Area Index, crop choice, and irrigated area, drives a coupled surface/groundwater simulation created using the Landscape Hydrology Model (LHM) to examine the impacts of changing irrigation technology on the regional water cycle, and water levels in the HPA. This application of a coupled surface and groundwater model with unprecedented detail of input land cover characteristics and irrigation water use offers new insights into water resources of this complex and vast aquifer system. For instance, the model is applied to simulate cases in which no irrigation technology change had occurred, and complete adoption of newer technologies to better understand impacts of management choices on regional water resources, and how technologies may be developed or adopted to help adapt to global change.



## Remotely Sensed Crop Mapping Applications for Water Resource Management and Decision Support

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Accurate and current information on constantly changing agricultural acreage and distribution of crops is critical for environmental, economic and resource management applications. Land use, resource optimization, and economic models and planning significantly depend on accurate spatial land use data, specifically crop type and change. It is important to understand the impacts of crop type and distribution, crop change, acreage, permanent crop age and associated production practices on resource issues such as water quality, water supply, groundwater depletion/recharge, and economic factors. Conversely, environmental factors, such as climate change and sensitive habitats, increasingly influence how much and where these crops are grown. For these purposes, as well as many others, a current spatial mapping base layer is integral for effective resource analysis and decision-making. Past efforts to categorize and/or spatially map land use (specifically field by field agricultural production) throughout the Central Valley of California has either been: • accurate, but intermittent and not spatially contiguous (e.g. CA Department of Water Resources crop mapping)• frequent and spatially contiguous, but with marginal accuracy (e.g. USDA Crop Data Layer)• spatially contiguous, but lacking in specific crop granularity (e.g. CA Department of Conservation Farmland Mapping)• detailed, but incomplete and not spatial (e.g. grower surveys)As a result, there is currently no highly accurate, spatially contiguous, field scale agricultural land use mapping product. In response to this need, detailed crop mapping has been completed across the state of California. Methods have been developed to accurately and efficiently map field-scale crop coverage with remotely sensing techniques. Field-scale information is important because it accurately characterizes acreage irrigated and it captures variability in crop production within parcels or operations. The result is an accurate spatial database of individual crops throughout the state of California with accuracies exceeding 95%. These data are being used to inform decisions on water resource management, support and greatly refine models, evaluate groundwater recharge suitability, and better assess the role of agriculture in management and sustainability of surface and groundwater resources. These data are also integral to the assessments that will be needed as future Groundwater Sustainability Agencies respond to the Sustainable Groundwater Management Act requirements. Growers, industry, regulators, government agencies, and commodity groups also benefit from applying spatial data for land use change, crop type, location, permanent crop age, and density for management of environmental resources and proximity to sensitive areas of water quality, air quality, disease/pest vectors, etc. Collectively, remotely sensed crop mapping data are valuable for: • Surface & groundwater modeling and assessments of groundwater pumping• Groundwater Recharge Enhancement • Evapotranspiration estimations and models (remotely sensed and conventional)• Permanent crop age determination to further refine water use assessments • Permanent (“hard” water requirements) vs. annual crops and locations• Economic & land use trend analysis• Drought and climate change impact analysis• Following trends and locations• Water use efficiency & water infrastructure planning.

## Model Based Estimation of Turmeric Yield Response to Saline Groundwater Irrigation

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Field studies were conducted in Berambadi watershed of Kabin River, South India to assess the impact of irrigation water salinity on soil salinity and turmeric (*curcuma longa*) crop yield. The area is a defined Semi Arid one prone to salinization resulting from continued use of groundwater of marginal quality. The groundwater quality, with respect to salinity, at farm level was unknown although farmers had used it for irrigation for over ten years. The study was therefore preceded with watershed mapping of groundwater salinity levels using water samples from 95 randomly selected tube wells. Twelve sites with varying groundwater salinity levels were selected for the study. STICS crop model calibrated for the local conditions was used for prediction of potential turmeric yields under no nitrogen and salinity stress conditions. Soil and irrigation water chemistry was assessed through sample analysis using standard methods. Relative yield was calculated as a ratio of observed yield to simulated yield per plot and its interaction with soil salinity was evaluated. At the watershed level, salinity in the groundwater ranged between 0.5 dS/m and 2.3dS/m with mean of 1.2 dS/m (0.34). Results indicated significant ( $p=0.05$ ) interaction between irrigation water and soil salinity and between relative yield and soil salinity. Predicted yield across plots was on average 7.5t/ha (0.474) and the expected yield according to the area horticulture office was reported as 7.2t/ha. Simulated yield was very significantly ( $p=0.005$ ) higher than observed yield with exploitable yield gaps ranging between 2.1 t/ha (29% reduction) where salinity level was lowest at  $E_{c_e}$  0.84 dS/m to 5.7t/ha (73% reduction) where soil salinity was  $E_{c_e}$  2.1 dS/m. We recommend groundwater quality mapping to aid decision making in control of irrigation related salinisation. The basis of characterizing water as safe for agriculture in a given location should be specific about crop and soil type to which the safety standard applies.

## **Nitrogen Fertilization in Central Valley Crops: Answering the Question “Are we Doing it Right?”**

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Nitrate is a major contaminant in Central Valley groundwater and elevated levels are attributed primarily to leaching of nitrogen fertilizers past the root zone. Growers who belong to Central Valley Water Quality Coalitions (CV Coalitions) are under new requirements per the Irrigated Lands Regulatory Program to keep “on farm” a Nitrogen Management Plan (NMP) to track nitrogen fertilizer applications. A key component of the NMP is reporting nitrogen consumption during the growing season with the assumption that the remaining nitrogen is lost to groundwater. Determining crop consumption is one of several requirements of the Management Practices Evaluation Program (MPEP) that five CV Coalitions are cooperatively implementing (East San Joaquin Water Quality Coalition, Westside San Joaquin River Watershed Coalition; San Joaquin County and Delta Water Quality Coalition; Sacramento Valley Water Quality Coalition; Wetlands Water Quality Coalition). The MPEP has specific objectives including identifying management practices that are protective of groundwater quality, determining whether newly implemented management practices are improving or may result in improving groundwater quality, developing an estimate of the effect of grower’s discharge of nitrate on groundwater quality and utilizing the results to determine whether practices need to be improved. There are data gaps in understanding the effectiveness of management practices on reducing the amount of nitrate transported through the root zone of walnuts. Numerous research projects are about to get under way in 2016 that will document the amount of nitrogen applied and the movement and distribution of nitrate from the point of application through the root zone in multiple fields planted to either annual or perennial crops. The projects will evaluate the movement of nitrogen through the root zone during rain and irrigation events over a two to three year period. Fields will be identified with the assistance of the cooperating CV Coalitions and commodity organizations. Management practices implemented by growers will include split fertilizer applications (based crop load and UC/industry expertise on optimal timing), and testing of soils/irrigation water/petiole-leaf to better understand crop nitrogen need and the amount of nitrogen and nutrients needed for optimal production. Measurements will be collected over two to three years (two storm seasons and two irrigation seasons). Additional management practices beyond those listed will be determined once cooperators have been identified. The BMPs will be implemented for at least two years allowing for changes in yields as a result of the BMPs and full evaluation of leaching potential. Management practices for nitrogen fertilizer applications and irrigation timing will be identified for fields prior to the implementation of the study. Throughout the two to three year studies, practices performed by the grower such as nitrogen applications and irrigation events will be recorded. Total yield and root zone nitrate results will be compared over the two years to account for the effect of the implemented BMPs on the amount of nitrate leaching and changes (if any) in yield.

## Regional Management of a Stock Pollutant: Agricultural Drain Sater

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The paper addresses long-run drainage problems in San Joaquin valley irrigated agriculture. The region slopes downward from west to east. Several hundred feet below the land surface is the Corcoran clay layer, which is relatively impervious to water and results in a perched, shallow water table aquifer. Irrigation water is typically applied in excess of crop ET resulting in water percolation below the root zone. Some deep percolation is necessary to flush salts from the root zone, however the bulk is generally due to non-uniform irrigation and infiltration. Deep percolation flows can cause the shallow water table to build up over time with consequent yield losses. Several management strategies are available: Deep percolation can be reduced by alternate irrigation systems, crop switching, moisture-stressing, and reduction of cropped area, and water can be withdrawn from the shallow water table aquifer and disposed in evaporation ponds. Producers have some incentive to adapt water conservation and drainage disposal measures when the water table begins to encroach their own land. Beyond this they have minimal incentive to reduce deep percolation flows in the absence of regulation since, with many users, the bulk of the damages will occur elsewhere. Regional drain water management is considered here using a dynamic stock pollutant model with spatial variability. The analysis integrates an economic model of agricultural production with a hydrologic (finite-difference) model of groundwater flows. Both the value and the cost of reduced emissions are endogenous and can vary over both space and time. The first main issue addressed is long-run sustainability of the resource under common property usage: can a high level of agricultural production be maintained in the basin even in the absence of regulation? The results suggest yes provided growers have access to evaporation ponds or other disposal mechanisms. The second main issue relates to efficient management and specifically the extent to which upslope growers should mitigate emissions to reduce downslope damages. The results suggest both timing and spatial considerations. In particular, the results establish that drainage management should begin before explicit drainage problems occur. This delays – and may even – prevent drainage problems. Considerable spatial variation in efficient source control is also found even with what appears at first glance to be a minimal level of exogenous spatial variability in the underlying system. Conceptual reasoning as well as computational experiments suggests that this result arises as a combination of land slope, finite hydraulic conductivity, and discounting. This suggests a second critical dimension of managing agricultural drain water beyond the timing dimension analyzed in the early stock pollutant studies. The implications of efficient management for regulatory policy are also considered. The results demonstrate how marginal user cost (future impacts) varies temporally and spatially, and demonstrate that efficiency implies a high degree of spatial variability in contrast to SJVDP proposed (uniform) regulatory standards. Efficiency-inducing policy instruments in both quantity form and price form are developed for both input-side regulation and output-side regulation.

## **Sustainability Economics of Groundwater Usage and Management: A Perspective from Environmental Macroeconomics**

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The paper develops a sustainability model for groundwater economics utilizing concepts from macroeconomics. Sustainability is defined as inter-temporal efficiency (Pareto optimality), and intergenerational equity (non-declining utility). The standard groundwater model maximizes present value of net benefits subject to an equation of motion for the resource stock. This model cannot be used as is for sustainability analysis since it is reporting income flows from aquifer usage, while sustainability is defined over consumption streams. Accordingly, the standard model is extended here to include household utility over consumption, a budget constraint, and investment in a human-generated capital stock. The subsequent analysis is conducted utilizing theoretical derivations and a computational model. Normative sustainability conditions are first derived. These include an investment allocation condition analogous to Hotelling's rule to guarantee efficiency in the economy, as well as sufficient aggregate investment in the economy to maintain intergenerational equity. These normative conditions are then applied to the behavioral regimes of common property, present value optimality and sustainability. Common property is not sustainable due to externalities; however, it can be equitable depending on the household discount rate. Utility present value optimization corrects the externality but does not necessarily result in an equitable solution. The sustainability regime optimizes present value of utility subject to a non-declining utility constraint, thereby ensuring efficiency and equity. Several qualitative conclusions and general insights follow from this setup. First, declining resource stocks can be entirely consistent with sustainability; they are not necessarily indicators of non-sustainability. In fact, resource rents greater than the steady state may be necessary for sustainability since they provide additional income for investment in capital stocks. Second, common property (unregulated usage) is not the only – or even necessarily the main – cause of non-sustainability, as externality correction alone does not guarantee intergenerational equity. In particular, for the empirical study here, the inefficiency is relatively small, and so sustainability is driven more by rent investment than resource management. Additional policy implications such as sustainability shadow values, extension to uncertainty, and the Hartwick-Solow rule are also investigated.

## Irrigation Impacts in the Northern Great Lake States

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Irrigated agriculture is expanding rapidly into the humid and traditionally non-irrigated eastern US, bringing fresh environmental challenges that have yet to be assessed and needs for management frameworks that have yet to be constructed. The northern great lake states region of Minnesota, Wisconsin, and Michigan is one part of the eastern US where irrigation expansion is rapid, rising from negligibility in the 1950s to 290,000 ha by 1978 and to 639,000 ha in 2013. Irrigation in the northern great lake states is mostly groundwater-sourced and commonly occurs in areas containing coarse-grained glacial sediments, droughty soils, and productive aquifers. Unlike much of the arid US west, irrigation in the northern lake states is “supplemental.” By augmenting rainfall, periods when soil moisture might be limiting are bridged, allowing high water demand agriculture and greater profitability. In contrast with the west, where irrigation water is often supplied by surface water, aquifers poorly connected to local hydrologic processes, or the valley aquifers of large rivers, lake states irrigation source water is predominantly locally-recharged groundwater with strong connections to local lakes and streams. We characterized the impacts of groundwater irrigation in the northern lake states in the Wisconsin central sands, a 6500 km<sup>2</sup> region composed of 30-60 m of coarse glacial sediments overlying less permeable bedrock. The area receives about 800 mm y<sup>-1</sup> of precipitation of which about 250 mm y<sup>-1</sup> recharges groundwater. Groundwater feeds numerous lakes, wetlands, and nearly 1000 km of headwater streams that support cold water ecosystems. Over 2,000 high capacity wells tap the same groundwater to irrigate field corn, potato, sweet corn, and other processing vegetables. Irrigation effects on central sands surface waters have been substantial and include complete drying of some lakes and streams. Commonly, base flows are reduced by a third or more in stream headwaters and water levels are reduced in aquifers and lakes by more than a meter. Observed flow and stage reductions can be explained by an increase of 45 to 142 mm y<sup>-1</sup> in evapotranspiration on irrigated land compared with pre-irrigated land cover. We conclude that irrigation water availability in the northern lake states and other regions with strong groundwater-surface water connections is tied to concerns for surface water health. Thus a management framework will require a focus on the upper few meters of aquifers on which surface waters depend rather than the consume ability of the aquifer.

## **Napa County Groundwater Resources: A Comprehensive Program to Ensure Sustainability**

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Groundwater and surface water are highly important natural resources in Napa County. Together, the County and other municipalities, water districts, the agricultural community, commercial and industrial operations, and the general public are stewards of the available water resources. Everyone living and working in Napa County has a stake in protecting the county's groundwater resources, including groundwater supplies, quality, and associated watersheds and ecosystems. Without sustainable groundwater resources, the character of the County would be significantly different in terms of its economy, communities, rural character, ecology, housing, lifestyles, and especially its worldwide acclaim for its vineyards and wines. Similar to other areas in California, businesses and residents of Napa County face many water-related challenges, including sustaining the availability, reliability, and quality of water supplies; preparedness for resources management during drought conditions; and changes in long-term availability due to climate change. In 2009, Napa County embarked on a comprehensive, multi-faceted groundwater program to develop a sound understanding of groundwater conditions through development of an updated hydro-geologic conceptualization and an expanded groundwater monitoring, including designated facilities to assess surface water/groundwater interaction. The program provides the foundation for future coordinated, integrated water resources planning and dissemination of water resources information. In 2011, the Napa County Board of Supervisors adopted a resolution to establish a Groundwater Resources Advisory Committee (GRAC). The County Board of Supervisors appointed 15 residents to the GRAC, which represented diverse interests, including environmental, agricultural, development, and community interests. The GRAC was created to assist County staff and technical consultants with recommendations, including synthesis of existing information and identification of critical data needs; development and implementation of an ongoing groundwater monitoring program; development of groundwater sustainability objectives; and building community support for these activities and next steps. Monitoring provides the metrics that support the larger goal of sustainability. Key objectives of the Napa County Groundwater Monitoring Plan (2013) include addressing data gaps, regular evaluation of groundwater level and/or quality and surface water level and quality trends and factors that warrant further examination to ensure sustainable water resources, and public dissemination. The Napa County monitoring program relies on both publicly owned and volunteered private wells. To fulfill its mission and garner community interest and support, the GRAC developed an outreach brochure and a series of fact sheets on specific topics, designed to implement the Monitoring Plan through voluntary participation. Ensuring groundwater sustainability is an adaptive process that maintains the ability of future generations to make choices about how they use groundwater resources. Monitoring is one of many steps in a larger adaptive cycle, along with evaluating progress toward meeting objectives, learning from whole systems data evaluation, revising objectives and activities, developing and implementing best management practices (BMPs), and adjusting BMPs as needed. This presentation describes the approaches that Napa County undertook to integrate water resources sustainability into County policies and programs in advance of California's 2014 Sustainable Groundwater Management Act (SGMA). The County has developed an important foundation upon which to respond to SGMA requirements with community involvement and support.



## **A Flow and Transport Model Developed as a Salt and Nitrate Management Analysis Tool for a Management Zone in California's Eastern Kings Subbasin**

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For the purposes of Salt and Nitrate Management Plans (SNMP), management zones (MZ) are created that cover a spatial area within which salt and nitrate can be managed by one or more entity. As an archetype for the Central Valley SNMP, an MZ was defined for Alta Irrigation District (AID), located in the eastern portion of the Kings Subbasin. Groundwater quality data are used to estimate the salt and nitrate occurrence for different zones of the saturated subsurface. Separately modeled loading of surface recharge (mass and volume) allows the assessment of the effects of various management regimes on groundwater quality (e.g., changes in irrigation efficiency and fertilization rates, artificial recharge projects, improving POTW effluent quality, etc.). A groundwater flow and transport model was developed using MODFLOW and MT3D to investigate the effects of different management practices on underlying groundwater over time. Extracting a portion of the Kings Subbasin from the USGS's large-scale Central Valley Hydrologic Model (CVHM) (Faunt et al., 2009) developed a local AID model. Several transformations occurred to adapt the CVHM parent model into the smaller-scale local AID MZ Model. Previous efforts using CVHM for salt and nitrate movement assessments concluded that transient flow simulation durations were not sufficient to evaluate the impacts of management regimes on groundwater used for municipal drinking water purposes. Therefore, the AID MZ model was converted into a steady state model using averaged hydrologic conditions over a selected baseline hydrologic period for model inputs, including initial heads, general head boundaries on model edges, stream flow and stage data, diversion data, pumping data, and recharge data. Increasing the vertical and horizontal discretization further refined the local steady-state AID MZ model. The baseline groundwater flow model was calibrated using water levels in monitored wells and contour maps of groundwater elevation. Management conditions were developed to represent ongoing shifts in land and water management. The Baseline condition involved historical surface application of N fertilizers and surface irrigation (i.e., before current regulatory program); Scenario 1 involved increased irrigation efficiency and artificial recharge projects; Scenario 2 involved lower fertilization rates in response to regulatory programs; and Scenario 3 combines the changes from Scenario 1 and 2. MT3D transport (transient) modeling included assignment of initial salt and nitrate concentrations to all cells, boundaries, and streams. Simulated recharge concentrations were provided on a cell-by-cell basis for the entire model area for each surface management condition. Transport modeling was run forward in time for 100 years to assess the effects of surface loading changes on different zones in the saturated subsurface.

## **Sustainable Groundwater Management – Special Considerations for Agricultural Water Agencies in California**

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In 2014, the State of California passed legislation that requires groundwater resources is managed for long-term sustainability. Adapting to this legislation will require different efforts from agricultural water agencies, urban water agencies and private well owners. Special considerations for agricultural water agencies are evaluated related to groundwater management infrastructure, funding, customer expectations, conservation opportunities, reliance on groundwater as a backup supply, and others. A comparison of the legislation's impact on agricultural agencies versus urban agencies is also provided. Lastly, special groundwater programs that can help agricultural water agencies manage and optimize groundwater are highlighted.

## **The Influence of the Recent California Drought on Water Table Levels in the Sacramento Valley**

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Rice (*Oryza sativa*) covers more area worldwide than any other crop and irrigated rice accounts for over 75% of all rice production. Rice is unique from other agronomic crops in that it is typically cultivated under flooded conditions, which may allow for both groundwater withdrawals for irrigation and groundwater recharge from deep percolation. Despite the importance of irrigation to rice production and the fact that many important rice growing areas rely on groundwater for irrigation, the relationship between groundwater and rice systems is poorly characterized. Rice production in California, which accounts for approximately 25% of all U.S. production, typically relies on surface water for irrigation. While the water table is usually at or near the surface throughout much of California's principal rice growing region, this area experienced declining groundwater levels during the recent drought along with the rest of the state. Anecdotal evidence has revealed that rice field water budgets changed significantly during the drought, with increased water input requirements per land area, likely due to dropping groundwater levels (and thus more deep percolation) and less rice acreage under flooded cultivation (and thus more lateral seepage). Here we characterize the changes in groundwater levels in the Sacramento Valley (the state's principal rice growing region) during the drought. Our subsequent research will analyze the relationship between groundwater levels during the drought and landscape-level water management associated with rice cultivation, including water inputs to rice fields and the land area flooded for rice cultivation or winter fallow. The goal of this work is to understand the reciprocal interaction between groundwater levels and water input requirements to rice fields, under both normal and drought conditions, in order to inform policy and management decisions associated with California rice production.

## **Institutional Approaches to Manage Groundwater in California: Evaluating Special Act Districts and Court Adjudications**

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Groundwater in California is managed by four general institutional arrangements: 1) local groundwater management districts with limited regulatory powers; 2) special act districts that are provided with enhanced authority to establish rules for groundwater management; 3) court adjudications, where the court is generally focused on the assignment of private property rights to users; and, 4) city and county ordinances. The 2014 Sustainable Groundwater Management Act (SGMA) enabled special act districts to exercise extra authority as needed to comply with SGMA, but exempted all 26 of the state's adjudicated groundwater basins from the Act. Adjudicated groundwater basins and special act districts underlie large areas of Southern California and parts of the Central Coast including major agricultural regions. Working with the State Water Resources Control Board, our research provided two extensive reports that evaluated the history and current condition of all of California's adjudicated basins and special act districts, along with potential future improvements that would better align these institutional management arrangements with SGMA goals for the sustainable management of groundwater. The presentation will provide a summary of our findings and highlight and compare the successes and challenges both special act districts and adjudicated basins face to achieve long-term sustainable groundwater management. It will include a review of: whether groundwater extractions are at or near a basins' designated safe yield; whether overdraft conditions are reduced or eliminated over the long term; and the degree of collaboration and inclusion of community stakeholders in determining how the basin is managed. In addition to this overview, the presentation will highlight 4-6 basins with a significant agricultural presence and particularly interesting management challenges and solutions. For these basins, key issues that will be highlighted include: 1) the problem that precipitated the need for court adjudication or the formation of a special act district; 2) the management structure and current strategies to manage the basin, including how costs and benefits are distributed in the basin; 3) how safe yield and overdraft are defined and determined; and, 4) how well management is aligned with SGMA goals for sustainable management.

## **Veterinary Antibiotic, Pathogen, and Antibiotic Resistance Genes in Tile Effluent and Shallow Groundwater Following Manure Application: Influence of Controlled Tile Drainage**

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Chlortetracycline, tylosin, and tetracycline (plus transformation products), and DNA-based *Campylobacter* spp. and tetracycline antibiotic resistant gene (*tet(O)*) in tile drainage and shallow (1.2 to 2m depth) groundwater were examined following a autumn liquid swine manure application on clay loam plots under controlled (CD) and free (FD) tile drainage. The chlorotetracycline transformation product iso-chlortetracycline was the most persistent veterinary antibiotic (VA) analyte in water. Rhodamine WT (RWT) tracer was mixed with manure and monitored in tile and groundwater. RWT and VA concentrations were strongly correlated in water. While CD reduced tile discharge and eliminated application-induced VA movement to tile drains, total VA mass loading from tile was not affected significantly by CD. At CD and FD test plots, the biggest 'flush' of VA mass and highest VA concentrations occurred in response to precipitation received 2d after application, which strongly influenced the flow abatement capacity of CD on account of highly elevated water levels in field initiating overflow drainage for CD systems (when water level <0.3m below surface). VA concentrations in tile and groundwater became very low within 10 d following application. Both *Campylobacter* spp. and *tet(O)* genes were present in groundwater and soil prior to application, and increased thereafter. Unlike the VA compounds, *Campylobacter* spp. and *tet(O)* gene loads in tile drainage were reduced by CD, in relation to FD; which was consistent with how CD mitigated loading of fecal indicator bacteria over the study period.

## **Characterization and Treatability Assessment of Abattoir Wastewater Using Elephant Grass Stalks as Filter Media**

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Wastewater generated and discharged by abattoirs are categorized as high strength with restricted pollutants exceeding standards set by regulating authorities. To avoid environmental degradation, these effluents requires pretreatment prior to their discharge into water bodies or alternative application (wastewater irrigation) as commonly practiced in some developing countries. The study was performed using three lab scale column reactors with elephant grass (*Pennisetum purpureum*) stalks as filter media in treating abattoir wastewater. The reactors (50cm height, 10cm diameter and a supportive gravel of 5cm depth at the bottom) with individual volume of 3.5L and working volume of 3.1L were constructed using polyvinyl chloride (PVC) pipes. Elephant grass stalks were collected, pre-treated, characterized and cut to average length of 20mm-40mm. The reactors were fed with substrate at a constant flow rate of 0.00024m<sup>3</sup>/hr. with hydraulic retention times of 15hours, 30hours, 40hours and 60hours. The results obtained indicated a maximum average removal efficiency of 43.03% for BOD, 35.94% for soluble COD, 62.42% for protein and 63.33% for NH<sub>4</sub><sup>+</sup> after 60 hours. The results revealed an increasing removal efficiency with time for all the parameters investigated except for pH with a slight improvement from an acidic value of 5.6 to a value of 6.1. The column reactors with elephant grass (*Pennisetum purpureum*) media achieved an increasingly stable performance; however, further research is recommended to investigate its long term application to determine its optimum life span and potential application in other wastewater stabilization. Key words: Degradation, Abattoir, Wastewater, and Irrigation.

## **Decadal Changes in Agricultural Contaminants in Groundwater in the United States, 1988-2015**

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The U.S. Geological Survey, National Water-Quality Assessment (NAWQA) Project has been evaluating groundwater quality with respect to agricultural and other contaminants for more than 25 years. A key element of these studies has been resampling of networks of wells to evaluate changes in water quality on a decadal scale. Results from the period of 1988 to 2000 are compared to results from the period of 2000 to 2012. An interactive web-based mapping tool has been developed to illustrate these changes. This tool allows the user to display the statistical results for groundwater networks for 24 constituents, including agricultural contaminants such as nitrate, phosphorus, and several pesticide compounds. In addition to the comparison of data between the first and second decade of sampling, data from a third decade of sampling are available for those networks that have been sampled from 2013 to 2015. Highlights of the findings from the comparison of the first 2 decades include significant increases in concentrations of nitrate and the atrazine degraded deethylatrazine in about 21% and 25% of the 67 networks, respectively. Dissolved solids and chloride concentrations also increased in a large percentage of networks but have many sources in addition to agricultural activity. Other sampling and analysis has been done to enhance the understanding of the decadal-scale changes. Biennial sampling took place for a 10-year period on a subset of wells in each network, and can be used to help determine whether the decadal changes are part of a long-term trend, or to illustrate the timing of a trend reversal. Groundwater age-dating and flow modeling also provide perspective on the time frame in which changes might be expected, given a change in source inputs. The NAWQA project has also implemented continuous (daily) monitoring at a subset of wells across the country in order to understand changes that take place on a time scale that is less than a decade. In addition, wells are being sampled along a vertical profile in selected areas to help understand changes that take place on a time scale greater than a decade.



## **The California Nitrogen Assessment: Implications for the Future of Groundwater Resources**

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Nitrogen (N) plays a vital role in sustaining the agricultural economy of California, as well as the global food supply. However, environmental losses of reactive N also have adverse impacts on other important ecosystem services by diminishing water and air quality and contributing to climate change. Despite the important benefits and tradeoffs of N in humans and ecological systems, there remains a paucity of quantitative knowledge on the interrelationships between California's N flows and the various ecosystem services that contribute to the public good. To fill this knowledge gap the Agricultural Sustainability Institute at UC Davis conducted a comprehensive integrated assessment of N in California to establish a baseline of credible information on the sources, sinks and flows of N into, out of, and within the state. This is the first comprehensive accounting of nitrogen flows, practices, and policies for California agriculture at the statewide level. We present an overview of results of a statewide N mass balance, focusing particular attention on losses of NO<sub>3</sub> to groundwater. Leaching of NO<sub>3</sub> to groundwater is a large flow of N within the state, accounting for roughly 16% of total N imports, with approximately 90% of the NO<sub>3</sub> originating from crop and livestock production. Because N emissions from agricultural sources are geographically dispersed, cannot be easily observed, and are difficult to precisely control, this problem presents unique challenges for effective policy design. A suite of integrated practice and policy solutions may be needed to achieve both adequate source control and mitigation of the existing N contamination within reasonable time frames. We provide an overview of available policy instruments for nonpoint source pollution control and examine specific outcomes when these mechanisms have been implemented to control nitrogen pollution in practice. Policy characteristics are then organized into a coherent methodology for assessing candidate policies for controlling nitrogen emissions from agricultural sources in California.

## Trends in Extreme Droughts and their Impact on Grain Yield in China Over the Past 50 Years

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Climate change and climate extremes and their impacts on agriculture, water resources, and ecosystems have become hot issues globally. Agricultural sustainability and food security are facing unprecedented challenges due to the increasing occurrence of extreme climatic events, including notably, extreme droughts in recent years in China. In this study, an agricultural drought index was developed by combining meteorological and crop planting pattern data in different regions and water demand data in different growing seasons. An inverse probability distribution function was derived based on the relationship between CDWEP (consecutive days without effective precipitation, the agricultural drought index) and their corresponding occurrence frequencies. Furthermore, a threshold model of extreme droughts of China was developed. Based on that model, changes in the frequencies and intensities of the extreme droughts in China and their corresponding relationships with the climatic grain yields in rain-fed regions were analyzed over the past 50 years. The whole China was divided into six regions, i.e. Northeast China, North China, Southeast China, Southwest China, Northwest China and Qinghai-Tibet Plateau. The results were as follows: (1) The threshold value of the extreme droughts increased gradually from the southeast to the northwest; the highest value was located in the deserts in the northwest arid areas where the CDWEP was more than 60 days, while the lowest value was in the middle reaches of the Yangzi River, where the CDWEP was less than 16 days; the value in North China was between 20–40 days, while Southeast China had a value of less than 20 days. (2) The frequencies and intensities of the extreme droughts increased in most regions of China except in Northwest China and Qinghai-Xizang Plateau. Stations in North China and in Southwest China showed the two strongest positive trends; the relative change rates in frequency and intensity per station were, respectively, 11.3% and 2.2% for North China, and 9.3% and 2.7% for Southwest China; for Southeast China, the relative change rates in frequency and intensity per station were, respectively, 7.1% and 1.8%; and for Northeast China, that of 5.7% and 0.7%, respectively. (3) A case study in Yushe in North China, Bijie in Southwest China and Meixian in Southeast China indicated that the per unit area climatic grain yields of the rain-fed region had an anti-phase relationship with the frequencies and intensities of extreme droughts. (4) A case study in Shijiazhuang of North China showed that the groundwater depth was on a significant downward trend, with an annual mean change rate of 0.82 m since the 1970s, which was mainly attributed to water exploitation mostly due to agricultural irrigation. After removing the impacts of the exploitation trend on groundwater depth variation, the results indicated that the natural groundwater level depth variation had a positive phase relationship with the annual precipitation and the annual frequencies and intensities of the extreme precipitations but had no evident relationship with the annual frequencies and intensities of the extreme droughts.

## **Safe Yield of Large and Small Aquifers in Agricultural Regions**

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The safe yield is perhaps the most important management variable of an aquifer: it describes the maximum amount of groundwater that can be extracted from an aquifer without causing adverse effects. This paper compares four traditional methods and one novel method to estimate the safe yield in aquifers supporting agriculture. The paper also stresses the importance of adjusting groundwater extraction to protracted decline in recharge caused by drought. This is essential to protect against adverse impacts such as seawater intrusion in coastal aquifers and against land subsidence in layered aquifers with compressible aquitards. Two examples are presented illustrating this paper's methodology. One involves a 15 square mile aquifer supporting agriculture in the Carpinteria Valley, Santa Barbara, and County. The other example concerns the 15000 square mile regional Edwards aquifer in south central Texas, which serves agricultural, aquatic, and urban functions. Both aquifers have detailed water-balance data for nearly one century, providing strong statistical reliability for the estimates of safe yield.

## Working Toward Sustainable Groundwater Resources in an Uncertain Future

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Groundwater overdraft and seawater intrusion are two serious threats to the sustainability of groundwater resources in the Pajaro Valley. Located adjacent to the Monterey Bay in Central California, the Pajaro Valley is home to some of the most productive agricultural land in the country, producing more than \$900 million/year of high value fruit, vegetable, and flower crops on approximately 28,500 irrigated acres. Average water usage in the valley is 55,000 acre-feet/year (AFY), with groundwater providing over 95% of the supply. Decades of groundwater overdraft have induced seawater intrusion, which was first documented in 1953. The Pajaro Valley Water Management Agency (Agency) was formed by an act of the state legislature in 1984 to “efficiently and economically manage existing and supplemental water supplies in order to prevent further increase in, and to accomplish continuing reduction of, long-term overdraft.” The Agency developed its first Basin Management Plan (BMP) in 1993 and has updated twice since that time to reflect changing conditions. The BMP guides PVWMA’s efforts to reduce groundwater production and develop supplemental water supplies in an effort to balance the basin and halt seawater intrusion. Implementation of BMP projects occurs in phases as funding allows. Between 2000 and 2009, the Agency constructed a managed aquifer recharge and recovery facility, water recycling facility, and over 20 miles of distribution pipeline. While these projects reduced the magnitude of groundwater overdraft and seawater intrusion affecting the basin, they were not able to solve these problems entirely. In 2010 the Agency set out to identify the next phase of projects and programs needed to solve the water resource issues affecting the basin. The Agency’s extensive monitoring program, which includes among other things the metering of production wells and collection of groundwater levels, provided valuable data for the development of a regional scale hydrologic model that was used to estimate the basin’s water budget. The Pajaro Valley Hydrologic Model (PVHM), is an integrated hydrologic flow model that uses MODFLOW-OWHM, a code which fully couples the simulation of the use and movement of water throughout the hydrologic system, was created to help inform water resource management decisions. Stakeholder driven committees were formed to guide development of a suite of projects and programs to address a shortfall in the simulated water budget of ~12,000 AFY. The PVHM was later used to evaluate the effectiveness of proposed solutions toward attaining the co-equal goals of balancing the groundwater basin and stopping seawater intrusion. Following nearly two years of meetings, the planning committee decided on a suite of seven projects and programs that include conservation (5,000 AFY), optimizing the use of existing supplies (3,000 AFY), and developing new supplies (4,100 AFY). Projects are being implemented in phases. If basin monitoring shows continued overdraft and/or seawater intrusion following the completion of each phase, additional projects identified in the BMP Update will be considered for implementation.

## **RZWQM Simulations of Nitrate Loss to Subsurface Drains from a Midwest Bioenergy Production System**

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Goals have been established to replace 30% of U.S. transportation fuels that are currently derived from petroleum with biofuels by 2030. The allowable quantity of first-generation, corn (*Zea mays* L.) grain-based biofuel (i.e., ethanol) has been capped at 15 billion gallons, thus requiring 16 billion gallons of second generation, biofuels to be derived from various cellulosic feedstock sources. Due to global demand for corn grain, not only for biofuel but also as an animal feed, food, and export commodity, the crop has been planted in the U.S. on an average of 88.9 million acres each year between 2005 and 2015. From a sustainability perspective, increased corn production has had positive economic benefits, but environmentally, corn production is a “leaky” process that has resulted in substantial loss of nitrate to surface and groundwater resources and thus created tensions between rural and urban sectors of our society. Incorporating a cover crop such as cereal rye (*Triticale cereale* L.) into current cropping systems, water quality concerns can be mitigated and demands for corn grain, stover, and other cellulosic feedstock can be met. The Root Zone Water Quality Model (RZWQM) was used to estimate the effects of corn production with and without a winter rye cover crop on shallow groundwater quality. We used a calibrated and tested version of RZWQM to estimate N loss in subsurface drainage (1.2 m) assuming a sustainable amount of corn stover (~1.7 tons/acre or 50% of the residue from a 175 bu/acre crop) is harvested and a winter cover crop is grown. Simulated nitrate-N dynamics with or without harvesting the cover crop will help determine if both economic and environmental sustainability goals can be met.

## **Inter-Comparison of C2VSim and CVHM Groundwater Budgets for DWR Sub-Regions in the Central Valley**

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Accurate estimation of groundwater (GW) budgets and effective management of agricultural GW pumping remains a challenge in much of California's Central Valley (CV) due to a lack of irrigation well metering. CVHM and C2VSim are two regional-scale integrated hydrologic models that provide estimates of historical and current CV distributed pumping rates and changes in GW storage. However, both models estimate these components of the GW budget using conceptually different agricultural water models with uncertainties that have not been adequately investigated. Here, we evaluate differences in distributed agricultural GW pumping and change in storage estimates for both models at the regional and sub-regional scale. Results show wide-ranging, but mostly poor agreement for model estimates of distributed agricultural GW pumping and changes in GW storage. Discrepancies were generally greater at the sub-regional scale than at the regional scale. These findings suggest that estimates of these important water budget components are sensitive to conceptual differences between models, which ultimately can impact conjunctive-use water management decisions in the CV.

## Exploring the Origin and Migration of Antibiotics in Aquifers to Evaluate their Impact on Groundwater Resources Quality

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Emergent organic contaminants (EOCs), especially veterinary antibiotics related to farming activities, are of great concern on groundwater quality. Their presence affect microbial communities inhabiting aquifers, shaping their composition and stimulating the spread of antibiotic resistance among community members. This study focuses on the behavior of antibiotics in groundwater in an agricultural area. Nevertheless, aquifer interaction with stream recharge, fertilization and infiltration of treated wastewater creates a mixture of both domestic and veterinary antibiotics. As reactive compounds, their migration is controlled by soil processes, mainly adsorption. Their origin and fate in the subsurface are key factors for designing mitigation and prevention strategies; not only in terms of water quality, but also in relation to the spread of antibiotic resistance in groundwater microbiota. A field study is being conducted in a fluvio-deltaic aquifer (Fluvià River, NE Catalonia). Samples collected during spring 2015 consist of 47 groundwater, 7 surface water, and 2 wastewater treatment plant effluents. We measured their hydrochemistry, including isotopic data for water and nitrate molecules. Antibiotics were pre-concentrated by solid phase extraction and quantified using an optimized protocol based on liquid chromatography tandem mass spectrometry (UHPLC–QqLIT). The phylogenetic composition of groundwater bacterial communities was analyzed by high throughput sequencing. Concentrations of antibiotic resistance genes (ARGs) were determined using qPCR and specific primers for target genes (*qnrS*, *ermB*, *tetW*, *sul-I* and *blaTEM*). Also, copy numbers of the Class I integron integrase gene (*intI1*) was analyzed as a proxy for anthropogenic pollution. Copy numbers of bacterial 16S rRNA gene were also determined to estimate bacterial abundance and to normalize ARG data. Seasonal campaigns are being conducted in 8 representative wells. Average nitrate concentration in groundwater and surface water was 42.4 mg/L and 7.3 mg/L. Up to 21% of the groundwater samples had nitrate concentrations above 50 mg/L. Antibiotics found in groundwater were fluoroquinolones (Ciprofloxacin, Danofloxacin, Enrofloxacin, Norfloxacin, Ofloxacin, and Orbifloxacin), macrolides (Azithromycin), quinolones (Flumequine, Oxolinic Acid, and Pipemidic Acid) and sulfonamides (Sulfamethoxazole). Sulfamethoxazole was detected in 80% of the samples with a mean concentration of 6.1 ng/L with a highest concentration of 28.6 ng/L. Ciprofloxacin was measured in 45% of the samples, with mean concentration of 77.2 ng/L and highest concentration of 298.3 ng/L. In turn, only fluoroquinolones (Ciprofloxacin, Enrofloxacin, Norfloxacin and Orbifloxacin) and sulfonamides (Sulfamethoxazole) were detected in surface water samples. Most detected antibiotics were Sulfamethoxazole and Ciprofloxacin (mean concentrations of 8.5 and 211.8 ng/L; highest concentrations of 211.8 and 287.7 ng/L, respectively), similarly to the results obtained for groundwater. Enrofloxacin was also quantified in 2 samples with relatively high concentration (290 ng/L). Results showed presence of all analyzed ARGs, and allowed to distinguish the origin of the antibiotics, whether veterinary or



clinical. In particular, sul-I and intI1 were the most abundant ARGs in all samples (averages of  $1.10 \times 10^5$  and  $1.63 \times 10^4$ , respectively). In summary, despite the widespread occurrence of veterinary antibiotics detected in the Baix Fluvià aquifer, the stream influence may also contribute to the groundwater antibiotic load with antibiotics used in human health. Despite the diffuse origin of most veterinary, no continuous spatial concentration trend has been observed in the aquifer. This suggests that soil adsorption and dilution may locally alter the antibiotic composition of groundwater. Some wells showed a high relative abundance of several ARGs highlighting that antibiotic pollution maintain a reservoir of resistance in groundwater that may eventually pose a risk for human health. This field study points out the multifaceted aspects of antibiotic pollution that finally control the impact on groundwater quality and its management. Acknowledgements: This study is part of the PERSIST project funded by the EU Water JPI (JPIW2013-118).

## Characterization of Agricultural Nitrate Pollution in a Mediterranean Region: What Should be the Next Step to Deal with this Environmental Problem?

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During the last fifteen years, our research groups have characterized several aquifers in Catalonia (NE Spain) looking for the extent of nitrate pollution and the occurrence of denitrification processes from hydrogeological and hydro-geochemical perspectives. Moreover, some statistical methods have been applied to discern the main factors that control aquifer vulnerability to nitrate pollution. Five out of ten of the aquifers declared as vulnerable to nitrate pollution in Catalonia, as a result of EU directives have been investigated and the results published in distinct scientific journals and PhD dissertations (Vitòria, 2006; Otero et al., 2009; Menció et al., 2011, 2016; Folch et al., 2011; Puig et al., 2013; Boy et al., 2013). In this contribution, we analyze the hydrogeological characteristics of the affected aquifers, the extent of the pollution and denitrification processes, the rate of groundwater exploitation and its final use as well as the occurrence of alternative water resources for human uses, and lastly the pressures upon groundwater quality (fertilization, waste water infiltration, ...). This analysis provides a qualitative evaluation for the future availability of suitable groundwater resources in these aquifers. Such evaluation is further on conducted on the light of the expected water scarcity related to global change, as defined by the climatic scenarios for the western Mediterranean area and land-use changes. Such a regional analysis, which includes present circumstances and future situations, ranks all the aquifers according to the extent of their overall impact and prioritizes potential actions to overcome nitrate pollution as one of the potential limiting factor for groundwater uses in the next decades. Acknowledgements: This study is part of the REMEDIATION project (Spanish National Program on Water Resources; CGL2014-57215-C4-2-R).References: Boy, M., B.T. Nolan, A. Menció, J. Mas-Pla (2013). Journal of Hydrology, 505: 150-162. Folch, A., A. Menció, R. Puig, A. Soler, J. Mas-Pla (2011). Journal of Hydrology, 403: 83-102. Menció, A., J. Mas-Pla, N. Otero, A. Soler (2011). Hydrological Sciences Journal, 56(1): 108-122. Menció, A., J. Mas-Pla, A. Soler, N. Otero, O. Regàs, M. Boy-Roura, R. Puig, J. Bach, C. Domènech, A. Folch, M. Zamorano, D. Brusi (2016). Science of the Total Environment, 539C: 241-251. Otero, N., C. Torrentó, A. Soler, A. Menció, J. Mas-Pla (2009). Agriculture, Ecosystems and Environment, 133: 103-113. Puig, R., A. Folch, A. Menció, A. Soler, J. Mas-Pla (2013). Applied Geochemistry, 32: 129-141. Vitòria, L. (2006). PhD Dissert. University of Barcelona.

## Spatial and Temporal Variability of Nitrate in Wisconsin's Groundwater

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Nitrate is a widespread groundwater contaminant found in agricultural regions throughout the world. Wisconsin, USA is located in a humid-continental climate. Nearly one-quarter of its land base is classified as farmland; primary cropping systems include corn (32% of farmland), hay and forage (27%), and soybean (13%). Wisconsin is fortunate that groundwater is generally abundant freshwater with low salinity and easily accessible. Major aquifers include materials from the Quaternary (sand/gravel), Ordovician (dolomite/sandstone), and Cambrian (sandstone) periods. With over 850,000 domestic wells and 97% of communities relying on public water supply wells, groundwater is the primary water supply for nearly 70% of the state's 5.8 million residents and many of its industries. Due to the heavy reliance on groundwater wells – both domestic and public – Wisconsin has amassed an extensive set of well water data. The extensive spatial distribution of data has helped create a detailed picture of groundwater quality across the state. The information is useful for helping communities to understand the relationship between land-use in groundwater. Here we investigate what is known about the extent of nitrate pollution in Wisconsin's groundwater as well as trends in nitrate concentrations over time. Post well construction, private wells are not required to test or report results; however some of that data has been captured by UW-Extension, state agencies and county health departments. Data from these sources has been aggregated into the Wisconsin Well Water Quality Viewer. It contains information on nitrate for 133,882 water samples spanning 1985 to present. Statewide 10% of well samples exceed the 10 milligrams per liter nitrate-nitrogen drinking water standard; while 42% contain concentrations above 2 milligrams per liter providing evidence that land-use is impacting well water quality. Wells located in agricultural regions and installed into sand/gravel aquifers or shallow carbonate rock aquifers are particularly impacted with nitrate. Due to most private wells aren't sampled regularly the data isn't particularly useful at a local scale for understanding how water quality has changed over time. As a way to investigate temporal variability, we turned to data from transient non-community water systems (bars, restaurants, churches, etc.), which are required to regularly test water for nitrate and report results. This dataset provided a unique opportunity to evaluate temporal changes in shallow groundwater nitrate concentrations using linear regression. While the temporal analysis indicates nitrate statewide has increased in more areas than decreased, the shallow groundwater accessed by 7,447 (87%) of TNC wells did not indicate a significant trend either way. Of the 13% wells with a trend, 726 increased (8%) while 421 decreased (5%). This information will help Wisconsin prioritize outreach strategies to private well users and assist communities in those areas most affected by elevated and potentially increasing nitrate concentrations in groundwater. It may also help other regions with less detailed nitrate data communicate the role of land-use, soils and geology on groundwater quality.

## **Sustainable Groundwater Management: What We Can Learn from California's Central Valley Streams**

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Groundwater is intimately connected to surface water, which has profound implications for sustainable water resource management. California has historically overlooked this important interaction and as a consequence, decisions about groundwater extractions have generally failed to address the resulting impacts to surface flows and aquatic ecosystems such as rivers, wetlands and springs. This has contributed to a loss of approximately 95 percent of the historical wetlands and river habitat in California's Central Valley. With the passage of the Sustainable Groundwater Management Act (SGMA), groundwater sustainability agencies across the state will soon be required to manage groundwater resources to avoid causing undesirable results to groundwater levels and interconnected groundwater and surface water. These groundwater levels and areas of interconnection support groundwater-dependent ecosystems (GDEs). Therefore, an important first step in sustainable groundwater management is to understand how groundwater pumping impacts surface water, including streams, and GDEs. To build the case for ecosystem protections now found in SGMA, The Nature Conservancy completed a study to illustrate how groundwater pumping is affecting streams and rivers in California's Central Valley. The report uses an integrated hydrologic model to reconstruct the historical impacts of groundwater use on groundwater levels and stream flow conditions. Our study focused on the state's Central Valley because of its importance in California's overall water supply. We used a model developed by the Department of Water Resources (DWR) to simulate the Central Valley's hydrologic conditions during the years from 1922 to 2009, a period during which groundwater production grew threefold. The results reveal profound impacts to the stream flow conditions due to increased groundwater pumping. Across the Tulare Basin, San Joaquin Basin and Sacramento Valley these changes have differed in magnitude, but share a similar trend. In areas with hydraulic connection between groundwater and surface water, increases in groundwater extraction continue to cause declines in groundwater levels that reduce stream flow. In many of these historically interconnected areas, declines in groundwater levels have caused segments of streams to change from gaining to losing reaches. In other words, portions of streams that once gained surface flows from groundwater were converted to losing reaches, where surface flows are being lost to groundwater. This reversal from gaining streams to losing streams has been most dramatic in the Tulare Basin, which converted largely by the 1920's, with the San Joaquin Basin largely converting in the 1960's. Our results indicate that the Sacramento Valley may be at a tipping point in this transformation, with some areas likely beginning to lose stream flows to groundwater. The results of our study pre-date the extended drought that began in 2011 and it is likely that the drought has exacerbated stream depletions. In addition, our study illustrates that the effects of groundwater pumping can take years – even decades– to recover. This means that the full extent of the impacts of groundwater pumping during the drought will continue to plague California for many years.

## **Cr(VI) and Nitrate in Groundwater and Sediments of the Southwestern Sacramento Valley, California, USA**

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Naturally occurring hexavalent chromium (Cr(VI)), derived from leaching of Cr-rich ultramafic sediments in the unsaturated zone, is found at levels above California's drinking water limit (10 µg/L) in groundwater of the southwestern Sacramento Valley. Increasing evidence suggests agricultural irrigation may be enhancing natural Cr(VI) release from the unsaturated zone, as evidenced by the correlation between Cr and nitrate in shallow groundwater. The unsaturated zone has been identified as a key location where Cr(VI) is generated. Nevertheless, the processes governing this depth distribution and the corresponding Cr(VI) loading to groundwater under different irrigation and groundwater pumping scenarios have not been quantified. We conducted a nested study investigating regional groundwater quality down to the micrometer-scale chemical concentration and speciation of solids and fluids from 25 m sediment cores that extend through the unsaturated zone, variably saturated zone, and into the shallow groundwater aquifer. Regionally, we found Cr levels to be highest in shallow groundwater, decreasing with depth and increasing over time; all of these patterns mirror nitrate. Chromium(VI) depth profiles in sediment cores suggest a geogenic source and appear to be governed by changes in lithology (e.g. ultramafic content, sand, clay) and redox reactions associated with changing water content. Chromium(VI) concentrations from sediment extractions are elevated relative to the drinking water limit (up to 75 µg/L), reaching a maximum from 2-6 m depth coinciding with an enrichment in magnetic susceptibility and elevated Cr(s) concentrations. Chromium-rich minerals were found to be co-located with Mn(III/IV)-oxides (based on in situ chemical mapping and speciation). To our knowledge this study reveals the first micron-scale evidence for geogenic Cr(VI) generated by oxidation on Mn(IV)-oxides in California sediments. In variably saturated sediments, from 5-25 m depth (where the water table fluctuates seasonally), Cr(VI) concentrations are lower (10 to 40 µg/L) than in overlying unsaturated sediments. In this depth interval, the presence of dissolved Mn and Fe and extensive mottling and gleying in sediments suggest reduction attenuates Cr(VI) levels. Based on calculations for native and agricultural land and water use scenarios, increased infiltration through Cr-Mn bearing sediments and water level fluctuations within the variably saturated zone have likely led to heterogeneous regional Cr(VI) levels in shallow groundwater that are above California's drinking water limit (> 10 µg/L) and parallel patterns of nitrate contamination.

## **Does Variable Rate Irrigation Decrease the Loss of Water Quality Contaminants from Grazed Dairy Farming?**

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The irrigation of grazed dairy farms in New Zealand has been cited as a cause of the contamination of shallow groundwater with nutrients (nitrogen (N) and phosphorus (P)) and the fecal indicator bacteria – E. coli. Drainage from uniform spray irrigation (URI) systems can be decreased if irrigation is matched to variations in soil type. Decreasing drainage with variable rate irrigation (VRI) may also decrease contaminant losses. However, no direct measurements or comparison of contaminant losses to shallow groundwater from VRI compared to URI systems exist under grazed dairying. Over a five year period, fortnightly base flow and periodic storm flow samples were taken from artificial drainage channels that crossed a 150-ha dairy farm, but entered and exited the farm at single points upslope and downslope of the irrigated area. These channels sat just above the water table (on average 1.1-m below the soil surface, and therefore served as good proxies for contaminant concentration in shallow groundwater. Irrigation was delivered via a center pivot irrigator at a uniform rate (18-mm per week) from October to May for three years. Irrigation then changed to rates that varied from 3-20 mm per week according to the mean daily soil moisture deficit in the top 20-cm (detected at three locations over the farm.) Under URI, median concentrations of dissolved reactive P, total P, ammoniacal-N, E. coli were not significantly different upslope and downslope of the irrigated area, whereas both nitrate-N and total N showed increases downslope (53% and 28%, respectively). Following the installation of VRI, median concentrations of all analytes except E. coli at the downslope site decreased by at least 50%. Approximately, 40% less water was used under VRI than under URI, while median flow rates at the downslope site decreased by 27%. Since the application rates of N and P did not change during the trial, the greater decrease in nutrient losses compared to drainage suggests that nutrient use efficiency had also improved. Pasture production and milk solids per hectare did not decrease following the installation of VRI, providing surplus water to expand production if desired. The data suggest VRI decreases the loss of contaminants to shallow groundwater under grazed dairy farming compared to those using URI.

## **Economics of Long Term Groundwater: A Case Study for the Tulare Lake Basin, California**

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Groundwater serves as a buffer for droughts especially in areas with low precipitation and high reliance on imports. However, a steadily increasing proportion of permanent crops and persistent groundwater overdraft tend to jeopardize long-term sustainability of agriculture in some areas. Increased groundwater pumping especially during drought has the potential of increasing pumping costs due to lower water tables and loss of shallow wells in some areas. This study explores an area over the Tulare Lake Basin using hydro-economic model for agricultural production, information on well depth distribution and remote sensing data for land and water use. Results highlight economic net benefits of reducing irrigated areas, managing groundwater reserves sustainably and intensification in the crop mix. Challenges ahead in achieving sustainability in agriculture and groundwater are discussed.



## **Framing the Issues Associated with Groundwater Governance and Agriculture in the United States**

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Groundwater use in the United States is governed by a mosaic of state approaches, which may differ by water use sector and regions within a state. The presentation will first consider the question: What is sustainable groundwater in agriculture? It will then address key issues associated with groundwater governance, drawing upon analysis and initial national survey work on the variation in approaches for address groundwater quantity and quality across the United States. Using Arizona as a location within the Colorado River Basin, the presentation will address opportunities and obstacles to developing pathways to sustainable water use, communities, and agriculture. In the context of groundwater regulations and/or lack thereof, the presentation will examine key factors determining groundwater availability and use. These factors include drought, differential priorities to surface water supplies, aquifer recharge and water banking programs, use of reclaimed water by agriculture, and municipal and industrial development (including solar fields). State and regional governance and policies related to agricultural water demand and conservation will be discussed. In the context of Arizona's groundwater regulations and Colorado River water supply conditions, programs of the Central Arizona Project provide interesting examples of the complex interrelationships of surface water supplies and groundwater use by the agricultural and municipal sectors. Though the policy elements to addressing projected gaps in water supply and demand are similar regionally, nationally, and even internationally, actual solution pathways will depend on local and regional governance frameworks and other circumstances. The presentation will conclude by highlighting the importance of robust stakeholder engagement and input in developing these pathways.

## **Can California Groundwater be Sustainably Managed with Agricultural Water Transfers? Effects on Aquifer Declines, Energy, and Food Production**

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California recently passed the Sustainable Groundwater Management Act, which requires that groundwater users develop sustainable groundwater management plans. However, California imports more water than any other place on Earth and is the largest producer of food in the USA. This creates competition between the “sustainable” uses of groundwater. Furthermore, recent droughts place even more pressure on water supplies (2013 was identified as the driest calendar year in California’s records). The ability to transfer water places pressure on northern California farmers to sell/lease their water, and decrease production and/or increase groundwater pumping to offset these transfers; however, the impacts of these transfers on regional economies and aquifer levels are often poorly understood. This work examines the effects of water transfers from northern California by using the United States Geological Survey’s Central Valley Hydrologic Model (CVHM) to simulate groundwater-pumping scenarios corresponding to water transfers. The CVHM allows analysis of the spatial and temporal effects of pumping on the groundwater levels which are used to estimate: (1) the impact of additional groundwater pumping on aquifer levels, (2) the energy costs associated with additional lift due to aquifer declines throughout the region, and (3) the impacts associated with land fallowing for surface water transfers.

## **FREEWAT, a HORIZON 2020 Project to Build Open Source Tools for Water Management: a European Perspective**

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FREEWAT is a HORIZON 2020 EU project. FREEWAT's main result will be an open source and public domain GIS integrated modelling environment for the simulation of water quantity and quality in surface water and groundwater with an integrated water management and planning module. FREEWAT aims at promoting water resource management by simplifying the application of the Water Framework Directive and related Directives. Specific objectives of the project are: to coordinate previous EU and national funded research to integrate existing software modules for water management in a single environment into the GIS based FREEWAT and to support the FREEWAT application in an innovative participatory approach gathering technical staff and relevant stakeholders (policy and decision makers) in designing scenarios for application of water policies. The open source characteristic of the platform creates an initiative ad includendum, as further institutions or developers may contribute to the development. The main expected impacts of FREEWAT are to help produce scientifically and technically sound decisions and policy making based on innovative data analysis tools and to support a participatory approach through all phases of a project, from scenario generation to the final stage of discussion. Core of the platform is the SID&GRID framework (GIS integrated physically-based distributed numerical hydrological model based on a modified version of MODFLOW 2005; Rossetto et al. 2013) ported to QGIS desktop. Current development includes: 1) module for water management and planning; 2) module for calibration, uncertainty and sensitivity analysis; 3) module for solute transport in unsaturated zone; 4) module for crop growth and water requirements in agriculture; 4) tools for investigating groundwater quality issues; 5) tools for the analysis, interpretation, and visualization of time series and hydrogeological data. Activities are carried out on two lines: (i) integration of modules to fulfill the end-users requirements, including tools for producing feasibility and management plans; (ii) a set of activities to fix bugs and to provide a well-integrated interface for the different tools implemented. Through creating a common environment among water research/professionals, policy makers, and implementers, FREEWAT's main impact will be on enhancing a science- and participatory approach and evidence-based decision making in water resource management, hence producing relevant and appropriate outcomes for policy implementation which is critical for sustainable management of water resources.

## Operational Mapping of Evapotranspiration over Agricultural Land in the California Central Valley

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A key challenge in groundwater modeling in California is the limited historic data on groundwater withdrawals for irrigation. Satellite mapping of evapotranspiration (ET) is an efficient way to quantify consumptive water use and can play an important role in filling this data gap. Recent advances in satellite mapping of ET have made it possible to largely automate the process of mapping ET over large areas at the field-scale. This development allows for the creation of multi-decade time series that can be used to constrain groundwater models and improve estimates of groundwater withdrawals in agricultural regions. We present an approach for operational mapping of ET in California that leverages two automated ET mapping capabilities to estimate ET at the field scale over agricultural areas in the California Central Valley. We utilized the NASA Earth Exchange and applied a python-based implementation of the METRIC surface energy balance model and the Satellite Irrigation Management Support (SIMS) system, which uses a surface reflectance-based approach, to map ET over agricultural areas in the Central Valley. Though theoretically and computationally quite different from each other, the combined approach increases data continuity and reduces reliance on a single satellite or sensor. We present a comparison of results from both models, and discuss the strengths of limitations of the combined approach. We also discuss comparisons against ET measurements collected on commercial farms in the Central Valley and discuss implications for accuracy of the two different approaches. The objective of this analysis is to provide data that can support planning for the development of sustainable groundwater management plans, and assist water managers and growers in evaluating irrigation demand during drought events.

## **Understanding the Timing and Duration of Implementation Processes of Groundwater Management Plans (GMPs) Under AB3030 in California**

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The Sustainable Groundwater Management Act (SGMA) of 2014 endows all groundwater sustainability agencies (GSAs) with regulatory and financial powers to develop and implement groundwater sustainability plans (GSPs). Prior to its passage, however, there were a number of existing governance structures for groundwater management. Assembly Bill 3030 (AB3030) authorized local agencies to voluntarily prepare and implement groundwater management plans (GMPs) across the State. Given the passage of AB3030 in 1992, how long did local institutional processes take until the adoption of voluntary GMPs? We intend to apply an event history model where the outcome variable of interest is the number of months required for each groundwater basin to implement GMPs under AB3030. We will estimate the model using a variety of independent variables such as heterogeneity in socioeconomic status and race, physical variables such as groundwater basin size, level of overdraft and groundwater dependency for water supply, and a capacity variable such as the size of the water district. Understanding the timing of institutional change provides a deeper understanding of the political and economic dynamics involved with the development of local groundwater institutions. Some of the same variables that influenced the implementation of AB3030 will also influence the implementation of SGMA, which builds on previous efforts.

## The Future Of Agriculture In A Changing World With Less Water And More Regulations

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With drought or water supply shortages occurring around the globe, the State of California has taken unprecedented steps to overcome historic shortages and drought conditions, yielding lessons for other jurisdictions - regionally, nationally and internationally. Challenges arising from drought in California include adjustments to the proverbial regulatory line in the sand for groundwater, impacting agricultural and other water users. While water supply and transfer agreements illustrate that stakeholders can navigate toward calmer waters with proper strategies and the right dynamics in place, disputes are certain to erupt in some instances, with the unanswered question being where those disputes will inevitably arise. Agriculture is specifically placed by media outlets and other stakeholders (public or private) in the middle of debates about solutions for solving water supply shortages, often cast as criticisms of water usage by farmers. Irrespective of one's personal views toward agricultural use and methods utilized for irrigation, agricultural operations, while necessary for producing food, will be impacted by the historic and relatively new regulatory requirements in California. These requirements bear value for other regions and jurisdictions to decide how to regulate groundwater, particularly with population growth, changing land use patterns (such as agriculture to land development), and climate change. As of last year, California's statewide regulatory framework for groundwater took effect with what is known as the Sustainable Groundwater Management Act ("SGMA," pronounced "sigma" and codified as Water Code § 10720 et seq.). SGMA is designed to establish sustainable groundwater management, with local agencies to manage groundwater by forming a Groundwater Sustainability Agency ("GSA") by June 30, 2017. A GSA would then need to form a Groundwater Sustainability Plan ("GSP") by January 31, 2020 for basins in "critical overdraft," and by January 31, 2022 for "medium- and high-priority" basins not deemed by the state to be in critical overdraft. Ultimately, SGMA's goal is to achieve "long-term sustainability." Part of achieving long-term sustainability requires recognition of specific challenges of today and tomorrow that arise from California's legal and regulatory challenges, such as a hybrid water rights regime of riparian and appropriative rights; the state regulating surface/subterranean stream water for the past 100 years while now implementing a statewide regulatory program for groundwater; use limitations arising from water quality, time of year, and place of use; and compliance with "reasonable and beneficial use" requirements under the California Constitution. Other challenges include "technical" conditions involving geological characteristics for determining and maintaining a groundwater basin's sustainable yield, as well as most of the state's surface water supply being in northern California with approximately two-thirds of the state's population located hundreds of miles away in southern California. Today's collaborative dialogue often seeks the elusive balance between environmental interests and human consumptive needs, making long-term sustainability all the more necessary to avoid the alternative too often seen with litigation, where a zero-sum game mentality exists. In turn, proactive and cooperative efforts for solutions provide a prudent approach, particularly for creating sustainability of water supplies and agricultural operations.

## **N-E-W Tech™: Advancing the Agricultural Circular Economy at the Nutrient-Energy-Water Nexus with Technology Innovation**

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Water sustainability is the most critical challenge to the future of agriculture. Concomitant with the challenges of a changing climate, new ground and surface water quality directives, and increasing water competition and food demand from a growing population, agriculture will certainly need to adapt to change in the waterscape of the future. N-E-W Tech™ is an innovative water treatment process at the nutrient, energy, and water nexus. N-E-W Tech™ integrates reactive filtration with iron-functionalized biochar and ozone for catalytic oxidation water treatment, sterilizing reclaimed water, and producing a value-added nutrient up cycled, Enhanced Efficiency Fertilizer (EEF) product that addresses the need for carbon sequestration, rhizosphere nutrient and moisture stability and soil tilth. Our membrane-free approach addresses the negative aspects of several current alternative technologies to water reuse and recycling including their high-energy inputs, removal but not destruction of contaminants and pathogens, high capital-maintenance-operations costs, and their poorer sustainability footprint. In this work we report on the design-build, water treatment performance, energy efficiency and general operations of this technology built as a 15-gpm pilot process on a mobile trailer. Recognized as one of twenty-five innovations that changed the world, reactive filtration is our commercialized, high efficiency nutrient removal process installed at 10+ MGD at water treatment plants; it uses an iron oxyhydroxide adsorptive process in a moving sand bed filter. In N-E-W Tech™ we demonstrate the addition and recovery of 1 to 10 grams of micronized iron-functionalized biochar per gallon, using this substrate as a sorbent and as a sacrificial catalyst with ozone to form hydroxyl radicals. Oxidizing potentials ranging from 1100 to 1300+ mV are maintained in the reactor during the 10-15 minute process time. Nutrients selectively adsorb to the recovered functionalized biochar demonstrating fertilizer potential in this carbon sequestering substrate. Initial N-E-W Tech™ effluent results from municipal secondary water demonstrate turbidity <0.5 NTU, 3+log removal of microbial pathogens, total P <10 ppb and other promising results that indicate a positive future for the use of degraded water resources for the agricultural circular economy.



## **On-Farm Recharge: Acceptance and Use by Farmers and Water Managers in the San Joaquin Valley, California**

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Decades of groundwater depletion in California are recognized as a threat to the reliability and quality of water available to farms, communities and the environment. The new California Sustainable Groundwater Management Act (SGMA) requires local Groundwater Sustainability Agencies (GSAs) to develop plans to manage groundwater supplies to ensure long-term sustainable yields. Replenishing depleted groundwater supplies will be essential to achieving this balance. The current default for groundwater recharge – dedicated recharge basins – is costly, and requires the purchase and retirement of many acres of productive land in order to capture the infrequent but large flood flows needed to achieve balance. On-farm recharge is an innovative solution to get water into the ground without taking agricultural land out of production. It can be implemented quickly using existing irrigation surface canals during heavy floodwater conditions without investing in costly new infrastructure. Accelerating the replenishment of groundwater supplies through on-farm recharge can also reduce the extent to which GSAs may need to restrict groundwater pumping. The success of this new practice will depend on acceptance of the strategy by individual farmers and GSA managers. This presentation will present the findings of interviews and surveys with farmers who have experimented with applying floodwater on working cropland in excess of their crop's water demand. In response to four years of drought and concerns about declining groundwater, farmers on over 100 fields with highly permeable soils volunteered to accept flood flows during the 2015-2016-flood season to accelerate groundwater recharge. In the absence of rigorous scientific data about the tolerance of crops on sandy soils to periodic over application of water, farmers growing 10 different crops as well as fallow ground were asked about the management decisions they make regarding acceptable timing and duration of water for recharge. The acceptable quantity of water applied in excess of crop demand also provides a starting point for determining the potential of this practice to address basin wide groundwater depletion under different cropping systems. The acceptance of this strategy also depends on acceptance by GSAs who must weigh the financial and social costs and benefits of alternative groundwater management methods. The presentation will compare the costs of on-farm recharge with dedicated recharge basins in terms of construction and operation expenses as well as potential incentives that may be needed to achieve widespread use. Unlike traditional recharge basins, on-farm recharge places individual farmers at greater risk of crop damage while their voluntary actions benefit all groundwater users in the basin. Information and decision support tools about the feasibility of on farm recharge will enable GSAs to consider on-farm recharge as a cost-effective and immediate option to include as part of their Groundwater Sustainability Plans. This presentation addresses the social and economic dimensions of on-farm recharge and complements presentations by other collaborators that address hydrologic infiltration potential, the effect on nitrate management and groundwater quality, and crop health. All these issues must be more fully understood before this strategy is promoted at scale to achieve groundwater sustainability goals.

## Soil Water Repellency - A Concern for Groundwater Recharge and Quality?

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Water repellency has been shown to occur in many soil orders under different types of vegetation and climate. It is now understood that the transient development of water repellent soil conditions is the rule rather than the exception. While it is easy to measure how repellency impedes the infiltration of single water droplets into soil, the effect of repellency on water dynamics at larger scales and over longer time periods has hardly been quantified. When water infiltrates into repellent topsoils, preferential flow can develop and bypass large parts of the soil matrix. Repellency could thus also accelerate contaminant transport to aquifers and could negatively affect groundwater recharge rates. Lack of mechanistic process understanding limits prediction of how soil water repellency affects infiltration, runoff generation, contaminant transport and groundwater recharge at larger spatial scales in different seasons. Our research aims to isolate the effects of repellency on soil water dynamics by directly quantifying how repellent soil conditions affect water sorptivity, infiltration and runoff at the mesoscale. We developed a fully automated tension disc infiltrometer and a runoff measurement apparatus. Using these in laboratory infiltration and runoff experiments with intact soil cores and slabs we studied water fluxes in a water repellent pastoral soil from New Zealand. In all our experiments, we compared the behavior of water to that of an aqueous ethanol solution to directly quantify the effects of repellency. New insight into the transitory character of water repellency was inferred from early- and late- time infiltration and runoff patterns as well as analyzing the behavior of soil collected at different times of the year. In addition, in the infiltration experiments we compared flux dynamics at different effective tensions. Results highlighted the fractional wettability of soil. We showed that pore size classes differ in wettability. We also measured the soil's repellency dynamics over a range of volumetric water contents using the sessile drop method. Our novel measurement technologies were combined with models based on the resulting soil water repellency characteristic curve. Our research highlights the opportunity to develop new approaches for gaining insight into these complex transitory processes, particularly over time scales of infiltration and groundwater recharge. Our preliminary results emphasize that soil water repellency should be included in hydrological and solute transport modeling. It also highlights that research is required to assess the effects of repellency at field and catchment scales.

## **Drawing the Line: Borders and Boundaries Governing Conjunctive Use**

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Nature creates intricate boundaries that interconnect natural ecosystems - land to water, forests to rangelands, and groundwater to soil. When it comes to the management, allocation and regulation of these resources the lines become significantly blurred. In exploring the interface between natural boundaries and administrative borders to the case of groundwater law in California, this presentation aims to distil lessons that can be applied to the Nile Basin. Focusing on the conjunctive use of surface and groundwater my analysis is based on the overlap of administrative borders and with selected river basins under the Department of Water Resources (DWR) Bulletin 118. In particular, I highlight the administrative complexities that accompany the local primacy provisions of the 2014 Sustainable Groundwater Management Act and the election of Groundwater Sustainability Agencies under section § 10723(a) of the Act. My aim in this presentation is to answer two questions: a) How are GSAs designated for an overlapping area where two or more local agencies (overlying the same groundwater basin) elect to become GSAs? b) Given that the determination of water rights is outside the remit of GSA authority, and prior to reverting to state intervention (§ 10735.2(e), what management options does SGMA present for mitigating undesirable results from depletion of interconnected surface waters induced by pumping? The answers to these questions will form the basis for indicative measures that Nile Basin states may adopt in managing shared surface and groundwater under the Nile Basin Cooperative Framework Agreement 2010.

## Recharging Depleted Groundwater Basins in California: Operational Issues for Recovery

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This presentation will address operational constraints and policy issues related to withdrawal of previously stored water in regional groundwater aquifers, in the context of both groundwater banking and the anticipated greater level of effort in the state of California to replenish depleted groundwater basins. California is one of the most productive agricultural regions in the world, contributing significantly to the economy of the state and the United States. In 2014, the output from California's 76,000 farms and ranches was about US\$54 billion that included foreign exports amounting to about \$24 billion. A substantial portion of this agricultural production is supported by use of groundwater, particularly when surface water availability is constrained due to drought and regulatory requirements. In addition, long-term use of groundwater in California exceeds long-term aquifer replenishment, resulting in statewide overdraft of 1 to 2 million acre-feet per year for at least the past 30 years. California's groundwater overdraft has had two important consequences: (1) the vacated aquifer storage provides the opportunity to develop groundwater banking programs, and (2) the need for sustainable groundwater supplies is pushing for greater replenishment of aquifers, which is necessary to sustain agricultural production in the very long term. This second consequence is driven by the California's 2014 Sustainable Groundwater Management Act, which requires that all groundwater basins achieve sustainable conditions by the next 25 years. This presentation will address both groundwater banking and groundwater replenishment in the context of the fate of additional water added to aquifers. We will address both in the context of impacts to basin groundwater users and implications to policy issues, based on current California legal and regulatory requirements. In general no groundwater users in a region will object to putting more water into storage. The difficulty comes with extracting previously-stored water, and the extent to which this may impact water levels and well production for groundwater users who are not direct recipients of the benefits of the extraction. Water that is banked by specific parties for later extraction for their own purposes could pose a problem to the extent that water is extracted several years after it is recharged. This is due in large part to migration of recharged water to areas remote from where the water was recharged or to areas outside of control of the water bank authority. Impacts associated with a general recharge of a groundwater basin may be of far less concern, to the extent that the water to be recharged is for the benefit of all water users in the basin and will not be extracted as a "banked supply". In such case it is anticipated that all impacts to groundwater users would be positive as compared to conditions without the additional recharge. A key will be how the groundwater replenishment strategy is set up, including designation of beneficiaries and how recharge activities will be funded.

## A Statistical Learning Framework for Groundwater Nitrate Models of the Central Valley, California

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Nitrate is one of the most common anthropogenic contaminants in domestic well water and exceeds the maximum contaminant level of 10 mg/L as N in many wells of the Central Valley, California. Empirical models commonly are used to estimate nitrate potential in groundwater, and can benefit resource managers by identifying the most vulnerable areas. Linear regression and classification methods have been popular choices for estimating nitrate impacts on groundwater. However, such methods can be hampered by hypothesis testing assumptions such as linear and monotonic responses and normally distributed data. Machine learning methods are promising alternatives that dispense with traditional hypothesis testing. For example, tree-based methods do not require data transformation; can fit nonlinear and non-monotonic relations, and automatically incorporate interactions among predictor variables. However, such methods are prone to over fit, which causes the models to not predict well to new data (i.e., samples not used in model training). We used a statistical learning framework to optimize the predictive performance of three machine-learning methods for Central Valley groundwater nitrate data: boosted regression trees (BRT), artificial neural networks (ANN), and Bayesian networks (BN). The statistical learning framework uses cross validation (CV) training and testing data to tune the complexity of the models, and a separate hold-out data set for evaluation of final models. With these data the order of prediction performance based on both CV testing and hold-out R<sup>2</sup> values was BRT>BN>ANN. For each method we identified two models based on CV testing results: one with maximum testing R<sup>2</sup> and a simpler version with R<sup>2</sup> within one standard error of the maximum (the 1SE model). The former yielded training R<sup>2</sup> values of 0.94 - 1.0 and the 1SE versions had R<sup>2</sup> values of 0.90 - 0.91. Cross-validation testing R<sup>2</sup> values indicate predictive performance, and these were 0.22 - 0.39 for the maximum R<sup>2</sup> models and 0.19 - 0.36 for the 1SE models. Evaluation with hold-out data suggested that the 1SE BRT and ANN models predicted better to new data (R<sup>2</sup> = 0.12 - 0.26) compared with the maximum CV-testing R<sup>2</sup> versions. In contrast, a multiple linear regression model explained less than half the variation in the training data and had a hold-out R<sup>2</sup> of 0.07. Scatterplots of predicted vs. observed hold-out data obtained for final models helped identify prediction bias, which was greater for ANN and BN than BRT. Spatial patterns of predictions by the final, 1SE BRT model agreed reasonably well with previously observed patterns of nitrate in domestic wells of the Central Valley. According to a map of model predictions, groundwater at domestic well depth in the San Joaquin Valley (south part of the Central Valley) generally is more vulnerable to nitrate than that of the Sacramento Valley to the north, particularly in the eastern and western alluvial fans. Sediments generally are more fine-grained in the Sacramento Valley and have higher Fe and Mn concentrations, conditions that are less conducive to nitrate occurrence in groundwater.

## **Mexico's Emerging Illegal Groundwater Market: The Product of Corruption and Neoliberal Regulations**

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Mexico has limited freshwater resources, heavily relying on an extensive network of groundwater aquifers. In fact, groundwater resources have been the state's buffer in the face of increasing urbanization and explosion of the agricultural sector. Over the course of forty years, Mexico has instituted increasingly neoliberal water policies, resulting in over-drafted groundwater reserves and social differentiation. Dr. Nadine Reis has conducted extensive research in the arid Valley of Toluca, concluding that there is a complex hydrological nexus of government actors, private developers and the agricultural sector. This nexus revolves around the regulation limiting public access to groundwater, which in turn has led to the illegal transfers of water rights from small farmers to private developers with minimal legal consequences. In light of Dr. Reis' case study, this paper proposes that Mexico's regulations and lack of enforcement will create a statewide market of illegal transfers of groundwater rights. Without complete water management reform, Mexico will institutionalize groundwater exploitation, and in turn, encapsulate the unsustainable neoliberal approach to groundwater management by generating a statewide water crisis.

## Groundwater Management in Mexico – Embarking on New Horizons?

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The main law governing water resources management in Mexico is the National Water Law of 1992, which lays out the top-down key legal functions and responsibilities of the National Water Commission (CONAGUA). CONAGUA's mission is to "manage and preserve national water resources, working with society, to achieve water sustainability." CONAGUA administers major federal programs to support investments in water supply, sanitation, irrigation, and manages key hydraulic facilities that meet most of the water demand in Mexico City. CONAGUA also owns and operates most dams in Mexico and the country's water monitoring network. The state Water Commissions are autonomous entities that generally fall under the authority of the State Ministry of Public Works. Their responsibilities and authorities vary between states and include water resources management, irrigation, water supply and sanitation services. Besides CONAGUA and the state Water Commissions, other entities including the Ministry of Finance, the Federal Congress, State Governments and State Congresses, Ministry of Environment and Natural Resources are important policy-makers in the sector. CONAGUA is responsible for issuing water use permits and levying groundwater extraction charges to help manage the demand versus supply. However, the total volume of water for which permits have been granted exceeds the total supply in some regions. Water resource pricing through extraction charges is carried out on the basis of the Federal Rights Law, which classifies the country in nine water scarcity zones. However, the major water user, agricultural, is exempt and charges are paid only by industry and municipal users, which considerably limits the effectiveness of the charge as a tool for water demand management. Through amendments of the National Water Law in 2004, two new entities were created intended to provide more local bottom up responsibilities and involvement: Basin Councils and Basin Agencies. The 26 basin councils created are advisory bodies that include representatives of the federal government, state and municipal governments, with at least half the council representing water users and Non-governmental organizations. The basin agencies are local decision-making bodies and regional administrative branches of CONAGUA. Despite progress and many achievements, Mexico still faces significant water resources challenges not uncommon to much of the modern world, including:

- 1) Increasing water scarcity
- 2) Over-exploitation of freshwater resources, especially groundwater
- 3) Increasing water quality degradation
- 4) Sustainable water industry funding and finance
- 5) Modernization of facilities and services
- 6) Improving agricultural irrigation efficiency
- 7) Strengthening of local water institutions
- 8) Climate change adaptation to periodic droughts and floods

Recognizing the need for further progress and to improve groundwater management, CONAGUA made the decision to begin work on groundwater management policy principles to use as a framework to amend the water resources law in the near future. The dialogue on developing groundwater management policy principles began in late 2015 and was continued through two working sessions at the Ninth International Symposium on Managed Aquifer Recharge (ISMAR9) in Mexico City in June 2016. This presentation will provide outcomes of the groundwater management discussions of ISMAR9, including the draft policy principles for groundwater management in Mexico.



## **Fate of Nitrogen on California Dairies as Measured by Regulatory Reporting**

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California is the largest dairy producer in the United States, generating over 20% of U.S. milk and cheese. Much of the California dairy herd lives in concentrated animal feeding operations (dairy CAFOs) in the Central Valley. Dairies also manage a significant amount of forage land, typically surrounding the CAFO, where animal waste is recycled. Through expansion and better production, the milk and manure output of Central Valley dairies increased nearly exponentially for five decades, until animal numbers leveled off in the 2000s. Since 2007, the dairy industry has been subject to new nonpoint source groundwater emission regulation in California. In the Central Valley, the dairy industry poses significant concerns for groundwater nitrate levels but also for groundwater salinization. We have digitized and are analyzing annual dairy reports submitted by individual operators to the regulatory agency (Regional Water Board) to assess the fate of nutrients on dairies in the Central Valley. In addition, we are able to assess data completeness and consistency, annual trends over the first eight years of the program, and evaluate the reporting program. Our analysis can be used to determine potential groundwater nitrate impacts based on field nitrogen mass balances.

## Options for Viable Small-Scale Groundwater Irrigation Systems in the Least-Developed, Water-Rich Case of Lao PDR

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In a poorly developed, water-rich country such as Lao PDR, most attention has historically been given to surface water development issues with limited consideration to groundwater. However, even with such relative abundance, spatial or temporal shortfalls and occasional droughts are faced, and groundwater is being increasingly relied upon to achieve broader socioeconomic development goals. Whilst groundwater development for domestic supplies has progressed ‘below the radar’ with mixed success under rudimentary governance arrangements, the consequence has been little knowledge and capacity to manage the groundwater resources and virtually no groundwater use for irrigation. All this is gradually changing with groundwater beginning to be included in water policies and development plans. A research project which began in 2012 (<http://gw-laos.iwmi.org/>) seeks to explore the role of expanding groundwater use for agriculture to address food security issues and enable diversification of cropping beyond paddy. Considering this challenge from an integrated, multidisciplinary perspective, the project is working towards creating: • improved understanding of the hydrogeological systems and water balance across regions and scales; • clarity on the way groundwater is perceived and used under different contexts; • clearer definition of the socio-economic costs and benefits of groundwater irrigation through establishment of pilot trials; • tools that assess how to achieve sustainable groundwater development and avoid negative environmental impacts; and • strengthened technical and institutional capacity within government, universities and other important stakeholders. This paper will focus on presenting the key findings from a techno-economic and institutional evaluation of irrigation pilot trials that have been setup on the Vientiane Plains; one of the major ‘food bowls’ of the country. Dry season small-scale groundwater irrigation of cash crops using shallow wells that are managed by individual farmers as well as deep tube wells that are managed by user groups are being evaluated and compared. These performance evaluations consider the profitability of various crop types, source of energy, irrigation methods and water use efficiency, labor availability, land tenure and other factors. On the whole, they reveal that there are viable alternatives to the current portfolio of publically supported, medium or large scale surface water irrigation schemes which provides viable livelihood options for smallholders residing beyond the command areas. This completely neglected area of government policy would include greater emphasis to decentralized systems of irrigation based on the use of tube wells, dug wells (or even small on-farm ponds), managed by individual farmers or small collectives who have greater control over water delivery.

## **Community Owned Village Ponds to Mitigate Floods and Meet Local Irrigation Demands: A Novel Conjunctive Water use Management Approach**

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Managing the frequent floods occurring in a region during monsoons and utilizing it for the unmet irrigation demands during the dry season in the same river basin is a novel conjunctive water management method termed as ‘Underground Taming of Floods for Irrigation’ or UTFI (pronounced ‘utify’). This strategy was first piloted in the Indian part of the Ganges river basin. This study aimed to monitor the UTFI piloting operations and to address the operation and maintenance related issues such as clogging and geochemical/ microbial effects of the recharged water and groundwater, which is recovered. This study also serves as an experiment to upscale the technique at the watershed/ river basin scale. Site selection was based on a detailed remote sensing based analysis, which was also built upon field visits and support from local institutions. A village pond in Ramganga sub-basin located in Uttar Pradesh state in India was chosen for the piloting. Seasonal flooding from a nearby river affects the livelihood of the villagers. There also exists unmet irrigation demand during the summer months due to unavailability of surface water and groundwater depletion. A village pond was modified and retrofitted with ten recharge wells to serve as a scientific trial and as a practical demonstration. Three piezometers were also installed within the village at different distances from the pond to monitor the effect of recharge on water levels and water quality. The trial and the monitoring that started in September 2015 indicate that the groundwater level has improved at the three monitoring piezometers due to additional recharge from the pond. This will provide more water for irrigational activities in the dry season. Also the salinity has decreased in the groundwater due to dilution. This pilot operation carried out to demonstrate the UTFI concept would be handed over to the community to be driven and maintained by them. As a part of this exercise training will be provided to the villagers and local institutional arrangements will be finalized. These preliminary results of the piloting that have been designed to test the operational performance of the UTFI structures are encouraging and this site will be monitored continuously.

## **Anthropogenic Depletion of Water Resources in the TG Halli Catchment Near Bangalore, India**

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The TG Halli watershed outside of Bangalore, India, faces a multitude of challenges due to urbanization and intensification of agriculture. Groundwater irrigation became popular in the 1970s, followed by shifts from traditional crops to eucalyptus plantations and in-stream check dams for aquifer recharge. The river, which supplied Bangalore with all of its water through the early 1970s, now yields only a small fraction of historical flows. Bangalore and its rapidly growing population have increasingly relied on imported water. We seek to understand the links between reductions in stream flow and local anthropogenic activities (e.g., groundwater pumping, land-use change, and watershed management practices such as managed aquifer recharge). Using a series of Landsat images from the 1970s to present, we classified over 500 surface water bodies in the catchment in each image and found that stream flow depletion is present throughout the catchment, except in the vicinity and downstream of urban areas. We conducted a suite of field research analyses, which demonstrate that most present-day stream flow is generated as infiltration excess runoff. Observed land-use changes within the catchment are unlikely to cause a reduction in infiltration excess runoff. We conclude that reductions in stream flow are caused by the loss of the shallow groundwater table due to groundwater pumping, and in-stream check dams, which impound stream flow for groundwater, recharge. While local water managers are aware of the changes within the catchment, the details of the local water balance are not well understood. Sustainable solutions are often overlooked as the incentives favor addressing short-term water needs, both for farmers and urban water managers. Farmers continue pumping as much as possible to sustain irrigated agriculture and the city continues to look further away for its water supply, with major projects for inter-basin transfers underway. Our work is a step towards understanding the local water balance and sustainable use of water resources in the Bangalore area.

## California's Sustainable Groundwater Management Act: A Perspective Looking Across the Southwestern US

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As the 2015 New Year dawned on one of the worst droughts in the history of California, the state's Sustainable Groundwater Management Act (SGMA) came into effect. The legislation is not only momentous in California's legal history, but also it is significant in the context of western United States (US) groundwater legislation. This work analyzes the SGMA from the comparative perspective of groundwater legislation across the southwestern US. We focus on the regulation of groundwater extraction in pursuit of sustainable use of the resource. We focus on five key elements in extraction permit (or, in the terminology of the SGMA, "allocation") regimes: first, criteria for issuing groundwater permits; second, requirements to meter and report withdrawals; third, exemptions from permit requirements; and fourth, penalties for violating permit terms. Fifth, we explore how the overarching balance between state and local powers supports these elements. We compare the powers granted to local agencies in California with those available under permit regimes that apply broadly throughout the states of the south-west, as well as in "special groundwater management areas", which typically impose more stringent requirements on groundwater permitting relative to "default" state groundwater laws. We developed a template and an associated codebook to record, in a standardized way, how each jurisdiction reflects these elements. Data were collected using a range of standard legal research techniques (e.g., legal text searches and analysis, reviewing secondary literature, interviews with state agency staff). These data enable us to demonstrate how these southwestern permit regimes vary along several dimensions in relation to each of the permit regime elements. Relative to southwest states, we find that local agencies in California have the powers to establish relatively rigorous permit and allocation regimes, with comprehensive well registration, metering, and reporting of extraction, and relatively limited exemptions from these requirements. Nevertheless, California local agencies will not have the benefit of the stronger enforcement provisions available elsewhere in the southwest. Consistent with California's local-centric model of groundwater governance, local agencies retain significant discretion in these matters, especially in relation to criteria for issuing permits. Southwestern permit regimes may provide useful models of regulatory options for California local agencies contemplating establishing a groundwater extraction permit or allocation regime. Under the SGMA, and for the first time, California local agencies will have a clear, broad-scale permit power with relatively few legal constraints, as well as accompanying powers related to metering, reporting, exemptions, and enforcement, which are vital to the effectiveness of a permit regime. But having these powers will not be sufficient to meet sustainability goals. History suggests that local agencies will need to overcome substantial practical and political obstacles to using these powers in order to ensure they contribute meaningfully to the pursuit of groundwater sustainability. Pointing to the precedents set by regimes in the southwest may also help to overcome these obstacles.

## Groundwater Protection and Raising of Farmers Awareness

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Changes local Farmers behavior on groundwater's protection and quality sanitation are most important areas of our NGO Activities. We are facing global and regional changes including environmental factors, climate change and human-induced changes. The pesticide residues content of agricultural soil and groundwater was investigated by monitoring five sampling sites located in different regions of Georgia and GC analyses of soil samples allowed the description of vertical distribution of pesticide residues in the soil profile and groundwater as pesticides can contaminate surface of water, soil and groundwater. Pesticides typically enter surface water during rainfall or irrigation exceeds the infiltration capacity of soil and resulting runoff then transports pesticides to streams, rivers, and other surface-water bodies and by soils erosion. As we investigate the contamination of groundwater may result directly from spills near poorly sealed wellheads and from pesticide applications through improperly designed or malfunctioning irrigation systems that also are used to apply pesticides. Groundwater contamination also may come indirectly by the percolation of agricultural and urban irrigation water through soil layers and into groundwater and from pesticide residue in surface water, such as drainage ditches, streams, and municipal wastewater. Our NGO concept relays on a key focus area of the protection of groundwater's and rivers, as sea coastal zones in West part of Georgia. It proposes to re-orient the search for sustainable solutions on the interface between sectors and disciplines. Work Closely with Rural Communities for upstream on policy-relevant water and energy initiatives to maintain the dynamics and competitiveness of drinkable waters and sanitation of sea coastal zones.

## **Ecosystem-based Groundwater Recharge to Help Farmers and Fish: Why California Needs 10,000 More Dams**

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In stream structures such as wood jams, living vegetation, beaver dams, certain geomorphic features and other obstacles that slow the downstream movement of surface water and sediment are essential to the restoration of streams and the recharge of alluvial aquifers. In particular, such ecologically functional dams help restore complex fluvial ecosystems with high groundwater recharge potential and multiple and synergistic ecosystem goods and services. We provide an overview of how ecologically functional dams can be used to increase groundwater recharge of alluvial aquifers and provide examples from pilot studies in California and Oregon where such ecologically functional dams have been used to increase groundwater levels in agricultural landscapes, providing water that benefits both farmers and the taxa that utilize fluvial ecosystems. Despite the promise of such ecosystem-based groundwater recharge efforts, numerous regulatory and policy obstacles cast doubt as to whether such an approach can be used on a widespread basis, despite the fact that many of the technological challenges have been addressed. Many of the regulatory and policy obstacles derive from the fact that surface water management has historically been focusing on mitigating flood damage rather than sustaining natural groundwater recharge rates. Thus streams and rivers have been viewed as drainage networks rather than groundwater recharge networks, and managed accordingly, such that much of the surface water that historically would have contributed to recharging alluvial aquifers has instead been managed for rapid transport out to sea. We conclude that new approaches to stream restoration and surface water management are needed that take into account society's economic and ecological imperatives to create resilient, structurally complex and dynamic fluvial systems that can substantially increase groundwater recharge rates in agricultural landscapes.

## CA Central Valley Irrigated Lands Regulatory Program: The Sacramento Valley Rice Growers Approach to Groundwater Quality Management

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The California Rice Commission (CRC) is a statutory organization representing approximately 2,500 rice farmers who farm approximately 550,000 acres of Sacramento Valley rice fields. The CRC is an approved Coalition Group under the Central Valley Regional Water Quality Control Board's (RWQCB) Irrigated Lands Regulatory Program. This program aims at reducing impacts to surface water and groundwater from agricultural non-point source discharges, by requiring various planning and implementation actions by the Coalition Groups. Under this program, a rice-specific Waste Discharge Requirements Order (Order) was adopted in March 2014. The CRC has led pro-active measures to comply with this requirement, even before the final Order was approved. As such, a detailed rice-specific Groundwater Assessment Report (GAR) was developed ahead of the Order that describes the shallow groundwater quality conditions underlying rice fields and provided an analysis of potential impacts of rice agriculture to groundwater resources. The GAR was approved in July 2013 and included in the Order. Following this foundational assessment, several additional actions were taken to comply with the Order's Monitoring and Reporting Program: development and implementation of a web-based farm evaluation template to facilitate Growers' farm practices input and reporting, establishment of a Groundwater Quality Trend Monitoring Work plan, and development of a Nitrogen Management Planning tool, also web-based. This pro-active approach taken by the CRC has allowed for a streamlined rice-specific implementation of the ILRP requirements through negotiations with the RWQCB, and helped educate rice growers on upcoming regulatory requirements. Initial program investments and innovative approaches for compliance were developed that have both the grower in mind, and establish reporting and monitoring procedures in a simplified and collaborative fashion for the future. The purpose of this presentation is to provide a summary of the activities undertaken by the CRC over the last decade to help manage surface water and groundwater quality and reduce potential impacts from rice agriculture.



## Estimating Applied Water in Alfalfa using the IWFDM Demand Calculator Model

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Irrigation is vital to produce acceptable quality and yield of crops on arid climate croplands. Irrigation and crop evapotranspiration are also key drivers of hydrologic fluxes in semi-arid agricultural basins. In California, alfalfa (*Medicago sativa*) was the single largest user of water in 2010, with an estimated 5.2 million acre-feet of applied water. Irrigating alfalfa is different from most common commodities such as corn or soybeans: alfalfa is a perennial crop with a deep rooting system that can access water from deep within the soil profile. For hydrologic assessments, accurate estimation of applied water, root zone storage, crop water uptake, and groundwater recharge are critical outcomes. Agricultural crop water requirement is a function of climate, soil and land surface physical properties as well as land use management practices which are spatially distributed and evolve in time. These variables can be modelled using either integrated hydrologic models and/or irrigation scheduling models. The California Department of Water Resources (CADWR) has integrated the benefits from these two approaches and has developed a new model that estimates the irrigation water requirements and routes soil moisture through root zone in the context of an integrated hydrologic modelling tool, Integrated Water Flow Model (IWFDM) - Demand Calculator (IDC). This root-zone simulation engine is a stand-alone program that simulates land surface and root zone flow processes as well as agricultural and urban water demands under user specified land-use, soil, climate and farm management conditions. In this study, we compare applied water estimates for alfalfa crops at eight alfalfa sites in semi-arid Scott Valley of California with measured water application, soil moisture data, and evapotranspiration.

## **Reducing Environmental N Losses and Increasing N Uptake on Grazed Dairy Farms with Simple, Low Cost Detection and Treatment of Fresh Cow Urine Patches**

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Consumers who are seeking more natural food increasingly prefer dairy products produced from cows gaining most of their food intake grazing pastures. A significant environmental concern under grazing, especially under intensive farming under higher rainfall or irrigation is the significant nitrogen (N) losses to the environment from cow urine patches, as nitrate leaching and/or as emissions of nitrous oxide greenhouse gas. These losses come about essentially as a result of the very high concentrations of N applied to the urine 'patch' or deposition area, mainly as urea. Within any one patch, the N application rate typically ranges from 500-1200 kgN/ha, far greater than the amount that can be recovered by the pasture before significant losses to the environment occur. This presentation describes the development of new technology which, towed behind a 4-wheel motorbike or other vehicle, enables the farmer to detect fresh cow urine patches and simultaneously treat them with various products such as N inhibitors and growth promotants, greatly increasing the recovery of urine-N by the pasture and reducing losses of N to the environment. The equipment developed, known as 'Spikey', uses a row of light, spiked metal wheels spaced 10 cm apart to measure the electrical conductivity of the top few mm of the soil, as well as the soil surface resistance, to locate fresh (1-3 days old) urine patches with a very high degree of certainty and accuracy. The ionic content of urine is very much higher than that of the soil solution; each urination is typically applying a 10mm 'irrigation' with urine, which saturates the topsoil, and causing easily detectable 'spikes' in soil conductivity for typically 3 days. Treatment of individual fresh urine patches in this way has been found to increase pasture N recovery by up to 70%, and as a consequence significantly reduce N losses to the environment. The Spikey equipment can be scaled up to whatever is the most appropriate for the farmer to do on a given farm. For New Zealand, this is like to be a width of 8m initially. Many farmers follow the cows' paddock rotation or electric fence-controlled strip grazing with applications of fertilizer N to whatever area has been grazed in the last 1-3 days. For these farmers, the fertilizer hopper and spreader can easily be mounted on the Spikey equipment. For these farmers, the additional time requirement to detect and treat urine patches is minimal. For those that do not, the time requirement is typically 20-30 minutes per day. Treatment of the urine-affected area only, which is typically only 2-5% of the area grazed on any one occasion or area, means that the use of chemicals such as urease and/or nitrification inhibitors and growth promotants is greatly reduced compared to technologies that involve treating the entire area grazed. The period of the year for which Spikey is used will be a function of local climate and soil conditions, farm management practices such as irrigation, and the sensitivity of local receiving waters to nitrate enrichment. The Spikey technology, when combined with fertilizer N application, will allow prevention of fertilizer N to urine patches, with consequent calculated savings in N requirements of 5-15%.

## Experiences of Participatory Irrigation Management in the APWELL Project

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The Andhra Pradesh Ground Water Bore well Irrigation Schemes (APWELL) project was initiated in the mid 90's in the erstwhile state of Andhra Pradesh in India with financial assistance from the Netherlands Government. Andhra Pradesh State Irrigation Development Corporation (APSIDC) of the Ministry of Irrigation executed the project with technical assistance from by a consortium led by ARCADIS-Euroconsult (Netherlands). The project with the construction and operation of sustainable small scale bore wells was implemented in 7 drought prone districts of the state and a total of 4476 wells have been drilled, of which 3460 successful wells with more than 1500 GPH were commissioned. The project covered around 14,000 ha of irrigated agriculture in 370 villages, involving 14,500 small and marginal farmers organized into Water User Groups (WUGs) and Borewell User Associations (BUAs). All the activities were implemented through APSIDC, in partnership with non-governmental organizations (NGOs) and various line departments at district level. Although the primary objectives of APWELL were promoting rural groundwater development, a project assessment showed that due to the introduction of micro-irrigation practices:

- Groundwater use had become more efficient
- Crops had diversified towards less water-consuming types, with crop yields and agricultural incomes increasing
- Felling of trees and deforestation had decreased
- Employment for landless had increased, with poverty being reduced
- Migration from the land had stopped even reversed
- Land values had tripled and the social status of farmers increased.

The key innovation was of the concept and practice of Participatory Hydrological Monitoring (PHM) – with the training of some 3,450 Water User Groups, 600 Female Self-Help Groups and 250 Groundwater (Bore well) Users Associations. The impacts of project in strengthening the village institutions, improving the extension network and enhancing the skills of water, gender balance, increased agricultural productivity, adoption of proper water management practices, hydrological monitoring, improved cropping patterns, and environmentally sound interventions in resource conservation will be presented. The participatory irrigation management process in the APWELL project has demonstrated that farmer participation in-group irrigation management is viable and relevant with empowerment of women in participating irrigated agriculture. Recent significant observations in the field will be presented.

## **Bayesian Nitrate Source Apportionment to Individual Groundwater Wells in the Central Valley by Use of Elemental and Isotopic Tracers**

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Groundwater quality is a concern in alluvial aquifers that underlie agricultural areas, such as in the San Joaquin Valley of California. Nitrate from fertilizers and animal waste can leach to groundwater and contaminate drinking water resources. Dairy manure and synthetic fertilizers are prevailing sources of nitrate in groundwater for the San Joaquin Valley with septic waste contributing as a major source in some areas. The rural population in the San Joaquin Valley relies almost exclusively on shallow domestic wells (less than 150 m deep), of which many have been affected by nitrate. Knowledge of the proportion of each of the three main nitrate sources (manure, synthetic fertilizer, and septic waste) contributing to individual well nitrate can aid future regulatory decisions. Mixing models quantify the proportional contributions of sources to a mixture by using the concentration of conservative tracers within each source as a source signature. Deterministic mixing models are common, but do not allow for variability in the tracer source concentration or overlap of tracer concentrations between sources. In contrast, Bayesian mixing models treat source contributions probabilistically, building statistical variation into the inferences for each well. The authors developed a Bayesian mixing model on a pilot network of 56 private domestic wells in the San Joaquin Valley for which nitrogen, oxygen, and boron isotopes as well as nitrate and iodine were measured. Nitrogen, oxygen, and boron isotopes as well as iodine can be used as tracers to differentiate between manure, fertilizers, septic waste, and natural sources of nitrate (which can contribute nitrate in concentrations up to 4 mg/L). In this work, the isotopic and elemental tracers were used to estimate the proportional contribution of manure, fertilizers, septic waste, and natural sources to overall groundwater nitrate concentration in individual wells. Prior distributions for the four tracers for each of the four sources were estimated based on end member measurements, literature, or as a part of our previous work. The Bayesian method produces estimates of the fractional source contributions to each well, which can be compared to surrounding land use types. Estimated source contributions were broadly consistent with nearby land use types in this sample.

## Groundwater Pathways for Nutrient Transport from Agricultural Land to the Great Barrier Reef

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The World Heritage listed Great Barrier Reef (GBR) off the northeast coast of Australia is the largest reef in the world. Unfortunately, agricultural production in GBR catchments over the past 150 years has contributed to a decline in water quality entering the GBR lagoon. Riverine discharge has been identified as the single largest source of nutrients to inshore areas of the GBR lagoon. However, the contribution of groundwater discharge to nutrient concentrations in rivers and streams in GBR catchments is currently uncertain. One of the GBR catchments of particular interest is the Lower Burdekin catchment. In this catchment, the predominant crop grown is sugarcane and there are ongoing concerns related to soil and water management. A significant body of research has been undertaken in this catchment, focusing mostly on paddock scale monitoring and modeling. In addition to this, a regional scale modeling toolkit has been developed which aims to support decision making for water management by addressing local groundwater management issues including: declining groundwater quality, rising water tables and increased discharge of poor quality groundwater to the environment. In recent years, there has been a significant increase in the monitoring of groundwater nutrient concentrations underlying agricultural land in the Lower Burdekin, including a program of voluntary monitoring by cane-growers where 962 samples were taken over a 12-month period. Around 40% of the groundwater samples from this voluntary monitoring program contained nitrate at concentrations > 5mg nitrate-N/L, the fate of this nitrogen remains unclear. Some preliminary research has been conducted in the Lower Burdekin into nitrogen transport both from aquifers directly to the marine environment and from aquifers to surface water. This research has identified the need to better define; **i)** groundwater flow paths to the marine environment and the possible role of preferential flow paths **ii)** spatial and temporal variations in redox conditions in these environments and the processes that underlie them. Further research, incorporating isotopic analyses and geochemical modeling, is required to better understand the processes occurring and to improve estimates of nutrient fluxes to the GBR via groundwater.

## To Maximize Net Benefits, Abolish or Limit Water Data Confidentiality to 1-5 Years

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With water supplies constrained by prolonged drought and future climate change and water demands rising with population growth, California faces a future of increasing water scarcity and attendant impacts on water quality. Improvements in resource management will require greater integration of surface and groundwater supply quantity and quality, more extensive and accurate measurement of relevant water parameters, and storage of this critical information in comprehensive databases available to government planners, affiliated and independent researchers, and the public. However, in a recent assessment by state-funded groundwater quality researchers: Inconsistency and inaccessibility of data from multiple sources prevent effective and continuous assessment... [W]e often faced insurmountable difficulties in gaining access to data already collected on groundwater and groundwater contamination... A statewide effort is needed to integrate diverse water-related data collection activities... Comprehensive integration, facilitation of data entry, and creation of clear protocols for providing confidentiality as needed are key characteristics of such an integrated database structure.<sup>1</sup>The benefits to society from detailed, publicly accessible data has routinely been dismissed or ignored at the local resource agency level. Increasing scarcity demands that the unexamined consequences of “confidentiality as needed”, often leading to the continued acceptance of indefinite water data confidentiality, be thoroughly analyzed in light of the pressure on current water institutions and how they are likely to evolve. This paper frames the analysis of societal tradeoffs in a farming context with respect to the literatures on patents, proprietary information, emissions reporting law, and peer effects. We first analyze the physical properties of water (and contaminant) flows and the legal conventions governing its use. Both the physical and legal dimensions only exist in relationship between any extractive user and other extractive users, which constitute the public at large, as well as in relationship to societal benefits from non-extractive uses and the public trust.<sup>2</sup>We then discuss the potential public and private benefits and losses of limiting or abolishing water data confidentiality. We conclude that permanent confidentiality is not in the public interest. Disclosure of water data can produce societal gains through better public water resource modeling, better monitoring and transparency of local water institutions charged with managing extractive and non-extractive uses leading to better performance, accountability, credibility and confidence in the integrity of laws governing water use, by reducing delays caused by those who use water data confidentiality as a barrier to the development and implementation of socially beneficial water quantity or quality regulations, and by encouraging more efficient private use of water. From the analysis, we identify two potential subsets of individual farming unit data for disclosure, either contemporaneously or after a fixed time delay. Recommended water data disclosure is limited to that which is necessary for the public purpose and structured to mitigate potential profit losses from disclosure of proprietary information. Finally, in light of water system security concerns, we discuss potential adjustments to the spatial resolution of readily accessible data or to methods for gaining accessibility to more precise locational data.<sup>1</sup>Harter, Thomas and Jay R. Lund et al. of Center for Watershed Sciences, “Addressing Nitrate in California’s Drinking Water, With a Focus on Tulare Lake Basin and Salinas Valley Groundwater: Report for the State Water Resources Control Board Report to the Legislature, California Nitrate Project, Implementation of Senate Bill X2 1”, p. 74, January 2012.<sup>2</sup> Qureshi, M., Andrew Reeson, Peter Reinelt, Nicholas Brosovic, Stuart Whitten, “Factors determining the economic value of groundwater”, Economics of Groundwater Management special issue, Eds. Reinelt, Brosovic, Qureshi, Hellegers, Hydrogeology Journal, International Association of Hydrogeologists, 2012.

## **The Importance of Rural, Farm working Communities in Advancing Policy Solutions that Address Agricultural Pollution of Groundwater**

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Access to safe drinking water is a guaranteed right under California law (AB 685) that many Californians are still waiting to access, in part due to inadequate regulatory programs protecting groundwater from nonpoint source contamination. Unsafe drinking water impacts over one million Californians annually, and over 10,000 Californians have recently experienced complete household water loss as wells dried up in the drought. The communities forced to deal with unreliable, unaffordable, and unsafe water are disproportionately Latino and disproportionately low-income. They are concentrated geographically in the state's agricultural regions, where nitrates, pesticides, and other nonpoint source contaminants enter groundwater due to current farming practices. The poorest rural, agricultural communities are not only most impacted by unsafe water; they are also driving solutions to the drinking water crisis facing California by advancing unprecedented campaigns for groundwater protection. Ninety percent of communities in the agriculturally rich San Joaquin Valley rely on groundwater for their drinking water sources. In 2014, the San Joaquin Valley was home to 432 community water systems with maximum contaminant level violations. Thus, 30 percent of the community water systems statewide that were out of compliance with drinking water standards were located in this agricultural region that is heavily reliant on groundwater for its drinking water supplies. Not all drinking water violations are due to agriculture, but many of these community water systems have had to close wells, drill new wells, or install treatment facilities to address nitrate and pesticide pollution from agriculture. Nitrate contamination alone is costing families, local governments and the state tens of millions of dollars a year. These drinking water problems will only get worse unless regulatory programs secure significant changes in current agricultural practices. In fact, if nothing is done to prevent it, by 2050, nearly 80 percent of the residents in the Tulare Lake Basin and Salinas Valley will be impacted. The AGUA Coalition was formed as a regional, grassroots coalition of impacted community residents and allied nonprofit organizations dedicated to securing safe, clean, and affordable drinking water for the San Joaquin Valley. Through community organizing and policy advocacy, the AGUA Coalition and its partners have advanced critical policies to promote drinking water solutions and address regulatory gaps that have left groundwater in the region unprotected from nonpoint source pollution. Due to the AGUA Coalition's advocacy and stakeholder engagement, the Central Valley Regional Water Quality Control Board has begun to implement the Irrigated Lands Regulatory Program and the Dairies Program to protect groundwater sources from agricultural nonpoint source pollution. These innovative regulatory programs will not remain successful without continued outreach to and engagement with the agricultural communities impacted by unsafe water. We share lessons learned from working with the AGUA Coalition for over a decade toward the goal of protecting groundwater from nonpoint source pollution.



## Quantifying the Role of Agricultural Groundwater Use for Drought Mitigation

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Quantifying the role of agricultural groundwater use for drought mitigation. The 2015 drought in Washington State had a severe impact on the more than 300 crops grown in the state, including an initial estimated loss of \$86.52 million on the iconic Washington apple industry alone [Washington State Department of Agriculture, Interim Report: 2015 Drought and Agriculture, 2015]. The full agricultural impact of the Washington drought has yet to be assessed. Groundwater plays an important role in drought mitigation in Washington's agricultural industry, just as it does in California's Central Valley. However, a key difference is Washington's requirement for permit applications to use emergency drought wells, only after the governor makes an official drought declaration. This contrasts with an overall historical lack of regulatory structure for groundwater use in California, though this will change with the 2014 Sustainable Groundwater Management Act. In either location, the decision to use supplemental groundwater is rooted in a farmer's cost-benefit analysis that may be a function of crop types, seniority of water rights holdings, and capital cost to access groundwater. The cost-benefit analysis is dynamic in time and space and will likely change as a function of groundwater availability. Climate change is predicted to decrease the availability and accessibility of surface water supplies into the future, leading to greater dependence on groundwater. As a result, an improved understanding of how today's groundwater mitigation for drought impacts groundwater availability into the future is necessary for sustainable groundwater planning. The goal of this study is to create a baseline to quantify the value of groundwater for drought mitigation in agricultural regions, with a comparison of Washington and California's recent droughts. An analysis is conducted to estimate the total amount of groundwater use in the Columbia River Basin in Washington based on a combination of drought well permits provided by the Washington State Department of Ecology for 2001, 2005, and 2015, and additional observation wells. In addition, we assess the potential for value-added information on groundwater use with NASA's Gravity Recovery and Climate Experiment (GRACE) satellite mission to understand regional scale impacts. By comparing the increased reliance on groundwater during drought in the Central Valley and Columbia River Basin, we can better understand how groundwater dependence changes as a function of drought severity, drought length, and crop distribution. Ultimately, this work lays the foundation to assess the economic value of groundwater to mitigate crop losses in agricultural regions, especially into the future with changing regulatory structures and climate change.



## **The Netherlands Water Nexus Research Program: Brackish water as a resource for solving Agricultural and Industrial fresh water needs**

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Water Nexus is developing integral solutions for problems with water scarcity in delta areas worldwide. A paradigm shift is introduced, namely to consider salt impacted water as a resource, and not as a threat: saline water where possible, freshwater where essential. The economy of deltas becomes increasingly impacted by freshwater scarcity as a result of reduced river discharges, sea level rise and salt-water intrusion. This is combined with growing fresh water demands, to a large extent originating from the agro and industrial sectors. WATER NEXUS started in October 2015 as a Dutch research program with a duration of five years and with a team of 17 PhD and post doc researchers to develop a coherent set of management and treatment approaches that support large volume water supply systems as needed for agriculture and industry. The approach is based on complete reuse and recirculation of used water, mild desalination and compound specific treatment of natural and used salty water streams, storage and treatment of water in green infrastructure, and fresh water recharge in shallow (under agricultural land), and deeper (in aquifers) subsurface systems. The program develops approaches for: i) Water distribution & control: control models are developed to create an optimal spatial distribution of saline and freshwater (in support of saline water where possible, freshwater where essential). ii) Use of alternative sources: treatment technologies are developed to make saline water suitable for large, specific applications (such as industrial cooling and agro and horticulture usages). Minimization of energy, costs, i.e. by removing those substances that hinder use (e.g. monovalent salts, organic chemicals), and maintaining substances beneficial to use (e.g. nutrients for agriculture). Key to WATER NEXUS is that program partners cover the entire innovation chain: i.e. partners are from universities (7), institutes for applied research (4), technology providers & consultants (11), water managers (5) and large agro and industrial end users (4). WATER NEXUS combines excellence in fundamental and applied sciences with application knowledge from private companies. The end users have defined various cases for the salinity and chemical specs of the water resources to be considered for reuse in recycling, and this is the base for the research that has now been initiated. The first results of that research will be presented during the conference also to discuss international collaboration.

## Will Our Traditions for Groundwater Sampling in Agricultural Settings Survive the 21<sup>st</sup> Century?

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For the evaluation of policy action programs to improve groundwater quality in agricultural catchments, research institutes and governments intensively monitor concentrations of agrochemicals in shallow or near surface groundwater. Conventionally, groundwater is sampled from irrigation or drinking water wells, specially designed groundwater sampling wells or temporary open boreholes. The samples are transported to laboratories and analyzed. These conventional procedures are time consuming, expensive, and sometimes unsuitable for the assessment of groundwater quality status and trends. The spatial extent of point sampling from vertical wells and boreholes usually does not align with the scale of our research questions. In addition, the common yearly sampling intervals for upper groundwater do not capture short-term weather induced variations in concentrations (Rozemeijer et al, 2009). This causes uncertainty in the groundwater quality status assessment and hampers the detection of trends. Innovative monitoring technologies, like chemical sensors and passive samplers may enhance groundwater quality research. High frequency groundwater quality monitoring using sensors reveals the temporal variability in upper groundwater quality. This reveals the groundwater response to groundwater recharge events as well as diurnal and seasonal cycles. Passive samplers produce time-integrated concentration values at low levels of detection. As long as a detailed assessment of field scale spatial heterogeneity of concentrations in upper groundwater is not the monitoring purpose, a conventional vertical groundwater well may not be to best option. Sampling from a horizontal well, or from a subsurface tile drain that taps the upper groundwater, has proven to yield a spatially field-scale integrated sample of upper groundwater (Rozemeijer et al., 2010). Modern horizontal drilling technology enables the installation of horizontal drains or groundwater monitoring wells at any depth or in any spatial configuration without disturbing the soil structure. Sensors, auto samplers, and passive samplers can be installed at the drain outlet for continuous monitoring and time or flow averaged concentration measurements. Distributed fiber optic sensing has been applied for temperature monitoring at high temporal and spatial resolutions. Current developments in chemical sensing using fiber optic technology may yield detailed distributed groundwater quality data. Innovations in groundwater quality monitoring are retarded due to costs, standardization, and the fear of artificial discontinuities in time series. Groundwater monitoring experimental ‘playgrounds’ and demonstration sites may accelerate the introduction of new technology. After field trials and comparison to conventional monitoring techniques, the application of appropriate innovations can be scaled up. Rozemeijer, J.C., Broers, H.P., Van Geer, F.C. & Bierkens, M.F.P., 2009: Weather-induced temporal variations in nitrate concentrations in shallow groundwater. – J. Hydrol. 378: 119–127. Rozemeijer J.C., Van der Velde, Y., Van Geer, F.C., Bierkens, M.F.P. & Broers H.P., 2010: Direct measurements of the tile drain and groundwater flow route contributions to surface water contamination: From field-scale concentration patterns in groundwater to catchment-scale surface water quality. – Environ. Pollut. 158: 3571–3579.

## **Groundwater Remediation for Nitrate Contamination in Public Supply Wells: Challenge of the Non-Point Source**

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Elevated nitrate concentrations in public supply wells are being reported on an increasing frequency globally. Long term agricultural nutrient management practices are often identified as a principal cause. Best management practices (BMPs) designed to limit the regional loss of nutrients on agricultural land in the vicinity of the supply wells are frequently implemented to reduce the groundwater nitrate concentrations. Due to the intrinsically slow movement of groundwater both through the saturated and unsaturated zones, the influence of the BMP activity is often slow to arrive at the wellheads and during this time the concentration of nitrate in the drinking water supply remains high. As an approach to temporarily reduce the nitrate concentrations in the wells prior to the point when the BMPs become fully effective, enhancing the natural process of denitrification in situ offers promise. In this study, denitrification is stimulated through the injection of a carbon amendment (acetate) the production aquifer of a well field in southern Ontario where nitrate concentrations exceed the drinking water limit. The acetate is introduced to the subsurface through an injection-extraction well doublet within a zone of high nitrate mass flux where the groundwater flow field converges near the wellheads. The acetate amendment is pulsed on a regular basis over a period of 60 days and the groundwater geochemistry down gradient of the injection site is monitored in detail to track the fate of nitrate and by-products of the denitrification reaction. The data indicate that the upstream nitrate concentrations averaging 13 mg/l are reduced to below 2 mg/l as a result of the enhanced in situ denitrification. Concentrations of nitrite and other redox products remain very low. The extended field trial illustrates the potential value of enhanced denitrification as a temporary remedial option until the permanent influence of the regional BMPs become fully effective.

## **Economic Analysis of Groundwater Banking on Agricultural Lands in California**

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Since 1865 California has practiced underground water storage through artificial recharge; however, in many parts of the state, these efforts have been insufficient to meet growing water demands, particularly for irrigated agriculture. During dry periods, vast agricultural areas depend upon groundwater for irrigation. In these areas, groundwater banking (GB) can be an essential strategy for water management operations. GB is the practice of diverting surface water to percolation or injection sites for aquifer storage and later recovery. One variation of GB is agricultural GB -- the use of agricultural lands for GB (Ag-GB). The economic implications of Ag-GB are an unknown component of GB necessary to inform water agencies and farmers interested in implementing the practice. Therefore, this study proposes a conceptual model for determining the economic feasibility of Ag-GB at the irrigation district level. The Orland-Artois Water District (OAWD) in Glenn County is considered as the case study, and alfalfa as the test crop due to its tolerance to flooding and low use of pesticides and fertilizers (potential sources of aquifer contamination). The proposed model consists of four components: (1) an agricultural water demand calculator, which calculates agricultural water demands based on historic land use, monthly precipitation, and crop coefficient values, (2) a one-bucket aquifer mass balance model that quantifies inflows and outflows to the simplified aquifer, (3) an agronomic model, which estimates costs and benefits of Ag-GB in terms of energy savings from pumping and crop production, and (4) an economic feasibility output, in which costs and benefits are evaluated to determine economic feasibility.

## **Improvement of Phytoremediation by Using Chelating Agents**

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The purpose of the study is to investigate the remediation ratios of Pb by phytoremediation using the chelating agents on different Pb phases in order to improve the rehabilitation manner. The results indicate that water use only as irrigation solution has low remediation ratios. In simulated soils using EDTA, more than 90% of Pb has been removed except Fe-Pb soil. And most of the Pb removed from simulated soil passed through the adsorption layer and caused the increasing of Pb concentration in plants and cultivation soil.

## Numerical Evaluation of Managed Aquifer Recharge as a Conjunctive Water Resource Management Tool in the Walla Walla Basin

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The Walla Walla Basin, located in Eastern Oregon and Eastern Washington, USA, faces challenges in sustaining an agricultural water supply while maintaining sufficient flow in the Walla Walla River (WWR) to sustain endangered fisheries. Managed Aquifer Recharge (MAR) is currently used in the basin to supplement groundwater used for summer irrigation to allow greater in stream flow during dry summer months. The numerical groundwater-surface water model, Integrated Water Flow Model (IWFM), was calibrated to hydrological conditions in the Walla Walla Basin and applied to predict future hydrological conditions under current management practices (baseline model) and for three alternative water management scenarios. Alternative management scenarios assumed unlined canals were converted into pipelines to improve the efficiency of irrigation water deliveries and a concurrent reduction of diversions from the WWR during summer months. MAR is incrementally increased among the three management scenarios, with “Current MAR” using the current annual MAR input of 11.1 million cubic meters per year (Mm<sup>3</sup>/Y) at the seven currently active MAR sites, “Increased MAR” using 17.7 Mm<sup>3</sup>/Y among 22 MAR sites, and “Maximum MAR” using 29.3 Mm<sup>3</sup>/Y among 60 MAR sites. Model results indicate that canal piping without increased MAR will increase in stream flow in the lower portions of the WWR by up to 0.20 m<sup>3</sup>/s relative to baseline conditions. The predicted impact of MAR on in stream flow is minimal in the upper portion of the WWR. Under the “Increased MAR” and “Maximum MAR” scenarios summer flows in the lower portions of the WWR are predicted to increase by up to 0.45 m<sup>3</sup>/s and 0.51 m<sup>3</sup>/s, respectively, relative to baseline conditions due to an increase in groundwater return flows in the WWR and tributaries. Conversion of canals into pipelines is predicted to decrease seepage from canals as a source of groundwater recharge, resulting in decreased groundwater storage in the “Current MAR” scenario relative to the baseline model. Under “Increased MAR” and “Maximum MAR” scenarios groundwater storage was predicted to be greater than baseline conditions. Model results indicate that canal piping in combination with increased MAR provides benefits for riparian and in stream habitat by allowing for significantly increased summer flows in the WWR and inflowing tributaries, while stabilizing groundwater storage levels. This supports that MAR is a tool that can be used to apply conjunctive water management effectively in the Walla Walla Basin.

## California Groundwater Management – the 21st Century Gordian Knot

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Short deadlines and historic local conflicts make formation of a Groundwater Management Agency (GMA) and adoption of a Groundwater Management Plan a mirage for many under California's new Sustainable Groundwater Management Act (SGMA). Success is determined by a 2020 plan submittal mandate, one that may only be possible with cooperative and compatible local agencies and objectives. Why? The Pajaro Valley Water Management Agency, one of 15 state special districts that were already tasked with managing critically over-drafted basins in California prior to the new SGMA legislation, has accomplished this daunting task. Their experience demonstrates that it takes two years and \$500,000, plus existing staff time, to "revise" an existing plan and 18 months and \$500,000 to devise and adopt a financing scheme, required environmental studies, and hold a rate-setting election. PVWMA's prior experience, including a number of precedence-setting legal challenges, shows all of these steps need both be focused on a realistic basin plan and equally on the rate-setting benefits analysis. Local conflicts in San Luis Obispo, San Joaquin County and the Salinas Valley may cause both the formation and plan deadlines to be missed. There are three parts to this problem: 1) part of the problem is inherent in the state's definition of a high priority basin; 2) non-compatible local objectives whether urban versus agriculture, or county versus irrigation district versus cities. Furthermore, the SGMA specifically claims not to alter existing property rights and the alternative of adjudication mean that some participants may exercise greater sway in formation and planning; and, 3) no funding - you need a GMA to write a plan, which will require money, you need money to first evaluate and then run a GMA. How do you structure a "benefits analysis" for a mere agency without an idea of the plan? Again, money is needed to implement the plan. Three times to the well may be two too many for some taxpayers. After all what is the downside to not completing the plan? The county or state takes over the basin, and they also have no taxing authority so, from the perspective of some taxpayers there is no downside to failure. Placing meters on wells is an apostate to many farmers. Very few agricultural wells in California are metered. PVWMA metered all large groundwater wells (pumping more than 10 acre feet per year) in 1994 and began charging a fee to pumpers to fund the cost of managing the basin. This will be an affront to some farmers – a notoriously self-reliant independent group. The Gordian Knot was a tightly wound ball of rope with no beginning or end visible to the observer. No one was able to untie it, so failed the test. Alexander the Great was confronted by the unsolvable riddle, analyzed it for a moment, then drew his sword and cut the knot in half. Problem solved. It is not certain if California can devise such a clean solution to the dilemma created by the SGMA.



## **Nitrate in Groundwater – Implementing Groundwater Monitoring Requirements for Irrigated Agriculture and Ensuring Safe Drinking Water in the Central Coast Region of California**

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Protecting groundwater that serves as a drinking water source is among the highest priorities for the Central Coast Regional Water Quality Control Board (Central Coast Water Board). In March 2012, the Central Coast Water Board adopted an updated Conditional Waiver of Waste Discharge Requirements for Dischargers from Irrigated Lands (Agricultural Order No. R3-2012-0011), including the requirement for growers to conduct groundwater monitoring and report data electronically to the Central Coast Water Board. The objectives of these initial groundwater monitoring requirements are to evaluate groundwater conditions in agricultural areas, identify areas at greatest risk for excessive nitrate discharge and loading and exceedance of drinking water standards, and identify priority areas for nutrient management. Growers enrolled in the Central Coast Water Board's Irrigated Lands Regulatory Program (ILRP) must sample all domestic drinking water wells and also the primary irrigation well, or participate in an approved cooperative groundwater monitoring program. As of January 2016, the Central Coast Water Board received groundwater monitoring data for approximately 4000 groundwater wells in agricultural areas. Consistent with existing reports, the data confirms wide-spread nitrate impacts to groundwater in the Central Coast Region. In general, nitrate concentrations ranged from less than the detection limit to 870 mg/L Nitrate (as N) – a maximum that is 87 times the drinking water standard for nitrate (10 mg/L Nitrate as N). Overall, approximately 26% of the groundwater wells sampled region wide exceeded the nitrate drinking water standard, including both domestic drinking water wells and irrigation wells. In Monterey County, approximately 38% of the groundwater wells sampled exceeded the nitrate drinking water standard. Well construction information is limited; however the distribution of nitrate concentrations with depth demonstrates that, in general, nitrate concentrations decrease with depth. In response to these data, the Central Coast Water Board is implementing the Agricultural Order to control excessive nitrate loading from agricultural operations. In addition, the Central Coast Water Board and the State Water Resources Control Board - Division of Drinking Water (DDW) are coordinating together with county health departments to ensure safe drinking water by notifying domestic well owners and providing technical and financial assistance to small community water systems to implement innovative nitrate treatment solutions. Consistent with California's Human Right to Water Law, Central Coast Water Board staff is also coordinating with environmental justice organizations to support disadvantaged communities affected by nitrate contamination to help ensure they have safe, clean, affordable, and accessible water adequate for human consumption, cooking, and sanitary purposes. The Central Coast Water Board is responsible for protecting and restoring water quality in the approximately 300 mile long coastal region from southern San Mateo and

Santa Clara counties to the northern part of Ventura County. DDW is a statewide agency that regulates public water systems; oversees water recycling projects; permits water treatment devices; and supports and promotes water system security. Groundwater data submitted to the Central Coast Water Board is available to the public on the Water Board's GeoTracker data management system (<https://geotracker.waterboards.ca.gov/gama/>).

**Central Coast Regional Water Quality Control Board  
Irrigated Lands Regulatory Program  
Groundwater Monitoring Data (Nitrate as N, 2008 – 2016)**

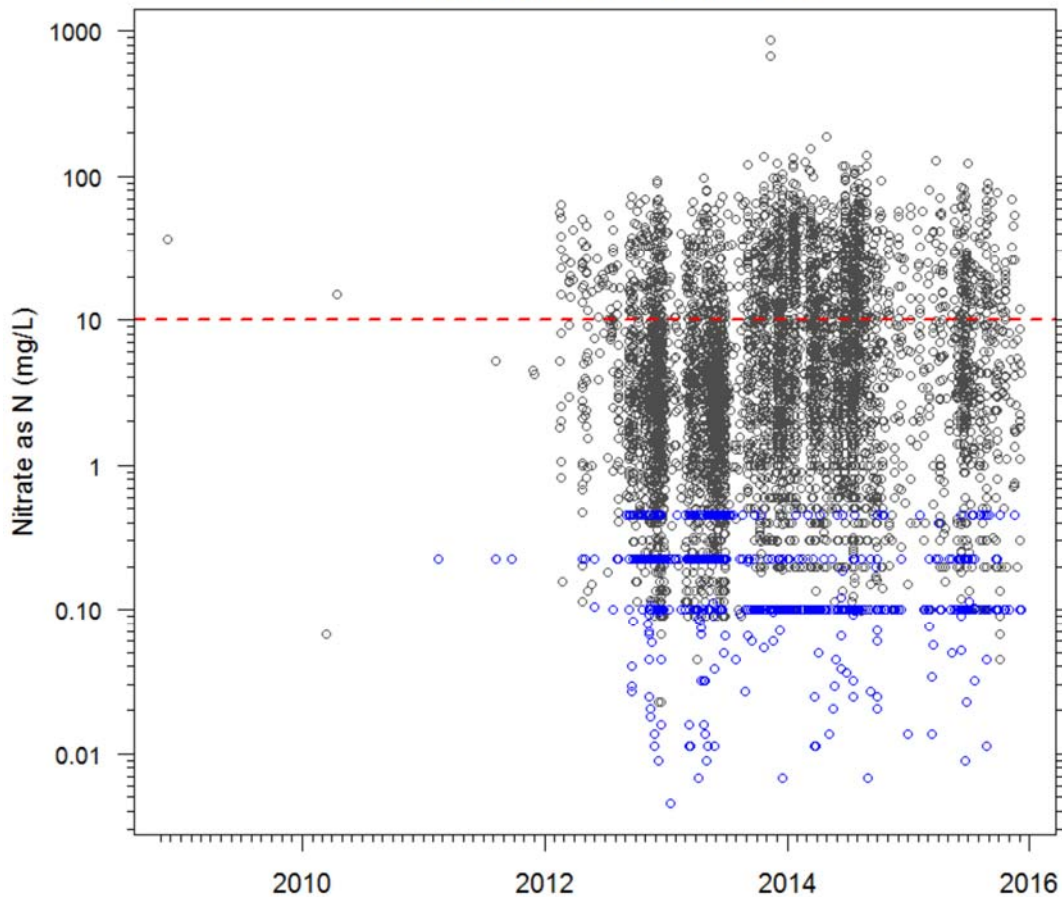


Figure 1. Groundwater data collected by the Central Coast Regional Water Quality Control Board, Irrigated Lands Regulatory Program (ILRP) from Nov. 2008 to Dec. 2015. Number of groundwater wells = 4000; Number of samples = 6782. Logarithmic scale. Dashed line is the California maximum contaminant level (MCL) for Nitrate (10 mg/L Nitrate as Nitrogen). Points in blue represent samples that are at or below the method detection limit. Groundwater wells include both domestic drinking water wells and irrigation wells located on parcels regulated by the ILRP.

## California Almond Water Footprint

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The domestic and international media have recently focused on the water footprint of California almonds and have related the water footprint to water use and the drought. The water footprint is an index of the complete use of and impacts to water systems. It is the sum of water impacts from production of a good or service used by people. It is typically expressed per unit production, per region, or per capita. It goes beyond consideration of water use (e.g., from irrigation) and according to the International Standards Organization is similar to the life cycle analysis approach. Besides the problem of perception that California almonds have a large water footprint, there is the additional problem that the water footprint estimate quoted in the media is not accurate and has gradually improved over time. Finally, the many nutritional and economic benefits that almond production and almonds provide are lost in a water footprint calculation that reports volume of water per unit weight of almonds. Almond production provides a large economic and employment benefit to California. Almonds are also high in food value, especially relative to other high water footprint foods, such as beef. We are calculating the water footprint in terms of economic benefit, protein (g), or total food benefit in order to provide a better representation of the benefits of almonds relative to the water footprint. Almond water footprints show a great deal of variability around the state based on yield, evapotranspiration (ET) rates, and recently updated crop coefficients (Kc). The lowest almond water footprints are in the southern San Joaquin Valley and the highest are in the northern Sacramento Valley. This is due primarily to differences in yields between north (low) and south (high). However, the agricultural water sources and water quality concerns that are present in the north vs. the south are also quite different. While current estimates of an average almond water footprint may be only slightly (+20%) revised by this research, we find almonds to have economic and health productivity advantages over other crops commonly grown in the region. Further, we see potential for management actions that reduce water footprints synergistically with greenhouse gas and other ecological footprint indicators.

## **Groundwater for More Resilient Agriculture in the Lower Mekong: Governance Challenges and Lessons at the Local Level**

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Agricultural groundwater use in the Lower Mekong is gradually gaining attention due to increasing uncertainty over water availability. Although this region is blessed with abundant rainfall and a network of rivers, climate change, commercial agriculture, and competition for hydropower, ecosystem and urbanization are shifting demand-supply pattern and affecting water available for irrigation. Groundwater is increasingly seen as a viable alternative to tackle growing uncertainty over water security, either as a supplement or as a main source of irrigation. Before the expansion of agricultural groundwater could become a norm, countries in the Lower Mekong should have appropriate governance mechanisms in place so that “tragedy of groundwater commons” due to unplanned and uncontrolled resource exploitation, as observed in other Asian countries, such as China and Indo-Gangetic plains was not repeated in the first place. This study examines the challenges of establishing vibrant institutional mechanisms at different levels for promoting sustainable groundwater use. Lessons were drawn from existing mechanisms of groundwater governance in Asia and their potential implication on promoting groundwater management, in the Lower Mekong is discussed. Review of groundwater governance cases across Asia reveals that challenges are often encountered in situations where there is inadequate decision support information to address multifaceted management complexity such as lack of knowledge on resource system, uncontrolled abstraction, high cost of energy and low profit margin. On the other hand incentives and access to information are the binding factor for groundwater management decisions, which often lead to a group formation and subsequent institutional development. Secured access to groundwater abstraction facilities and affordable cost sharing mechanisms are basic incentives for a viable group formation either at community level or among a group of farmers. Information about groundwater resources, agronomic and water management technologies, and markets are vital for productivity enhancement and higher returns. Making groundwater irrigation viable and climate resilient agriculture in the Lower Mekong is therefore about equipping farmers with information and securing year round access to groundwater in sufficient quantity and quality. At the local level a strong linkage with local bodies (such as village leaders, agriculture traders, agriculture extension staffs, etc.) and their effective coordination can lead to a productive groundwater use. More difficult is to establish a vertical linkage with line agencies such as electricity, land use, agricultural development, water resources which have an important role in providing support, clearing regulatory hurdles, and mainstreaming sustainable groundwater management in the national policies. It is now timely that governments in the Lower Mekong make best use of successful and unsuccessful lessons from other regions to manage groundwater in a sustainable manner and to make irrigated farming climate resilient.

## **Assessing the Impact of Existing and Future Water Demand on Economic and Environmental Aspects (Case Study from Rift Valley Lake Basin, Ethiopia)**

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In the development of water resource projects there is an increase and extensive use of water resources, which causes exploitation of the existing systems and ecosystem of the natural environment. The Water Evaluation and Planning (WEAP) model is used to assess water demand by considering the existing development situation and future water resources development with scenarios analysis in the study area (Ziway Meki Sub Basin, Ethiopia). Three different development scenarios were developed to simulate Water use at demand sites. In the simulations, the catchment was divided into 5 main sub-catchments where the supply and demand nodes were spatially located. The competing water sectors were irrigation development, domestic users, soda ash industry and environmental flow requirements. Hydro Meteorological data, net evaporation from Lake Reservoir, and monthly water demand from user sectors were the basic inputs to the model. The results of the reference scenario were validated using observed flows and the simulation result revealed that the total average annual inflow volume into the study area is decline significantly for reference scenarios and water availability is limited in the month of January (17Mm<sup>3</sup>) and December (171Mm<sup>3</sup>) while in the other months the availability is efficient and all users have 100% coverage; except langano irrigation site which have between 33.33% to 86.5% coverage in average during the month of Feb to May (2.57Mm<sup>3</sup>) and April in Bulbula 95.2% coverage. The minimum reliability observed mostly in the ongoing and likely future development scenarios at Bulbula irrigation demand sites which have 92.11% and 66.67% reliability in langano irrigation demand sites throughout over all development scenarios while in Sher Ethiopia expansion 51.75% reliability is observed in ongoing and likely future development scenarios and in demand site of Katar irrigation .diversion and Meki irrigation from dam 51.75% is observed in likely future development scenarios. The simulation result revealed that the total average annual inflow volume into Lake Ziway might decline significantly for Reference scenarios. This inflow volume reduction is likely to drop the lake level of Ziway. This combined with the unbalanced supply-demand equation in the watershed is expected to have significant impact on the lake water balance. Hence, in Lake Ziway, runoff is likely to decrease in the future and be insufficient to meet future demands for water of the ever-increasing population in the region. Key Words: Central Rift Valley, WEAP Model, Water Allocation, Demand Sites, demand coverage, reliability, Scenario Analysis.

## **Sensitive Catchments – Managing Nutrient Pathways and their Attenuation in NZ Agricultural Catchments**

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Productive farms and their associated processing industries make a significant contribution to New Zealand's economic and social welfare. However, grazed pastoral systems and other intensive land uses are inherently leaky with respect to nitrogen (N), the key nutrient implicated in the deterioration of surface and ground water quality in New Zealand's agricultural catchments. Current N management efforts in sensitive agricultural catchments are focused within the farm boundary and concentrate on identifying and reducing N loss from the root zone of farms. In many regions, the predicted farm root zone N loss must comply with a set limit or allocation. Farm N loss allowances, as specified in regional council rules, are generally derived using assumptions about the attenuation of nitrate-nitrogen (NO<sub>3</sub>-N) as it passes from the paddock root zone to rivers and lakes. This approach ignores the spatial and temporal dynamics of the transport and transformations of NO<sub>3</sub>-N along flow pathways from farms to rivers and lakes as relatively little is known about these processes in NZ agricultural catchments. This information is increasingly being sought to derive a robust understanding of the contribution farming systems make to water quality outcomes, as is required by New Zealand's National Policy Statement for Freshwater 2014. Our research in the Manawatu River catchment suggests that N loads measured in the river are significantly smaller than the estimates of N leached from the root zone. The on-going field observations, surveys and experiments indicate that denitrification is a key NO<sub>3</sub>-N attenuation process in the catchment. This N attenuation capacity appears to vary among the sub-catchments within the catchment. We, therefore, suggest that more cost-effective improvements in water quality can be achieved by selecting land use practices and mitigation options according to the N attenuation capacity in the subsurface environment (below the root zone) in sensitive agricultural catchments. Further research to understand and quantify this N attenuation capacity in NZ agricultural catchments is important for a number of reasons. Firstly, by taking a catchment perspective, we will be able to help redesign land use practices in a coordinated fashion by spatially aligning intensive land use practices with high N attenuation pathways, i.e. 'matching land use with land suitability', to increase agricultural production while reducing environmental impacts. Secondly, we will be able to align the spatial and temporal variation in N loss with built or enhanced attenuation to improve water quality outcomes.



## Field Kites: Evaluating Supplemental Irrigation with Climate Change

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Field kites are a novel tool to evaluate agricultural production under water compromised conditions by explicitly considering the farmers' capacity to manage their water resources. Supplemental and deficit irrigation are necessary initiatives to increase agricultural and water productivity, and to buffer the vulnerabilities of precipitation-fed agriculture. Under water limiting conditions, the crop-water production function quantitatively evaluates the relationship between seasonal water use and crop yield, and previous efforts have attempted to describe the crop-water production function as a function of seasonal water use. However, these representations do not account for the effects of temporal distribution and trivialize the associated variability in yields by assuming an optimized or arbitrary temporal distribution of water use. This over-simplification renders these functions inappropriate for recommendations related to water management and assessing the role of supplemental and deficit irrigation, in particular given projections of increasing climatic variability. We propose Field Kites, an interpretation of the crop-water production function that determines crop yield as a function of both seasonal water use and irrigation agency, defined as the ability of farmers to manage and determine both the quantity and temporal distribution of irrigation water. Assuming maximum irrigation agency may be inappropriate for farmers subject to pre-defined irrigation schedules and amounts, while it may be appropriate for farmers irrigating with groundwater with generally more facility to tailor both the timing and amount of water. However, the assumption of optimized water use distribution is particularly inappropriate for evaluating supplemental irrigation on mainly precipitation-fed agriculture where water use from precipitation is significant. Field kites are constructed using AquaCrop and previously validated cultivar-specific variables and the climate- and cultivar-specific field kite for spring wheat characteristic of western Canada is presented. The soil- and climate-specific field kites are then constructed for each cell over a grid at local-scale in the region of southern Alberta, Canada and evaluated under both the present and future period of 2041-2070 using different regional climate models. The simulations range in potential precipitation, temperature, and CO<sub>2</sub> changes and allow us to evaluate the potential for supplemental and deficit irrigation to increase or stabilize crop yields, prevent crop failure, or increase water productivity. Supplemental and deficit irrigation are appropriate initiatives for regions experiencing increased competition for water resources, rising costs associated with water withdrawal and irrigation application, compromised surface water and groundwater availability, and a declining health of associated ecosystems. It is essential to consider the effect of varying levels of irrigation agency on crop yields for water managers and policy makers to evaluate developing and supporting the necessary infrastructure for supplemental and deficit irrigation to both increase agricultural production and buffer the vulnerabilities of precipitation-fed agriculture.



## Evolution of Water Availability and Land Subsidence in California's San Joaquin Valley

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The San Joaquin Valley covers about 26,000 km<sup>2</sup> and is one of the most productive agricultural regions in California. Because the valley is semi-arid and the availability of surface water varies substantially from year to year and season to season, the agricultural industry developed a reliance on local groundwater for irrigation. Groundwater pumpage caused significant and extensive drawdowns, resulting in land subsidence at rates up to 0.3 meters per year. The completion of state and federal water distribution systems by the early 1970s eased the reliance on local groundwater as dependence shifted to diverted surface water. As a result, groundwater levels recovered and subsidence virtually ceased. In the last 20 years, however, land-use changes and an assortment of restrictions to surface-water availability—including droughts and environmental flows—have resulted in increased pumping and renewed land subsidence. The spatially variable subsidence has changed the land-surface slope in some places and caused operational, maintenance, and construction-design problems for water-delivery and flood-control canals as well as other infrastructure. The location, extent, and magnitude of land subsidence from the 1920s to 2015 were examined using Interferometric Synthetic Aperture Radar (InSAR), geodetic survey (spirit leveling and Global Positioning System surveys), extensometer, and continuous Global Positioning System (CGPS) data to estimate subsidence. Spatially and temporally dense data types are complementary and are needed to understand the mechanisms that underlie the spatial subsidence patterns and improve subsidence simulations. Since InSAR data became available in 1992, the comprehensive spatial coverage it provided has allowed the delineation of the spatial extent of subsidence: Geodetic survey, extensometer, and CGPS measurements show monthly, seasonal, and (or) inter-annual variations in subsidence rates at specific locations. Spirit-leveling surveys between the 1920s and 1970 indicated that more than half of the valley was affected by at least 0.3 m, and a local maximum exceeded 8 m of subsidence. Data from extensometers, combined with geodetic survey or CGPS data, indicated that compaction of sediments below the Corcoran Clay was the primary cause of subsidence. Data from extensometers, combined with other data sources, indicated that beginning around 1970, subsidence during the remainder of the 20th century occurred largely during drought periods. However, data from InSAR, geodetic surveys, extensometers, and CGPS during the 21st century showed subsidence patterns have changed, and in some circumstances, subsidence occurred irrespective of climatic conditions and was tied to land-use changes. Planning for the effects of subsidence in the San Joaquin Valley is important for water managers. As land use and surface-water availability continue to vary; long-term groundwater-level and subsidence monitoring, analysis, and modeling are critical to understanding the dynamics of historical and continued groundwater use resulting in water-level and groundwater-storage changes, and associated subsidence. Modeling tools, such as the USGS Central Valley Hydrologic Model, can be used in the evaluation of management strategies to mitigate adverse impacts due to subsidence while also optimizing water availability. This knowledge will be critical for successful implementation of recent legislation aimed toward sustainable groundwater use.

## **Global Scale Study for Determining Groundwater Contribution to Environmental Flows and Sustainable Groundwater Abstraction Limits for SDGs**

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Goal 6 of the Sustainable Development Goals (SDGs) has at least three targets that explicitly or implicitly cover issues of sustainability of water resources development and freshwater ecosystem maintenance. To incorporate sustainability, environmental flows (EFs) and sustainable groundwater abstraction have to be an integral part of the SDG discourse, but there is a lack of awareness and application of EFs at multiple levels. If countries are to accept and implement EFs over the next 15 years in the context of achieving the SDG targets, some initial EF information is in high demand. In this work, the first global EF assessment carried out by International Water Management Institute from 2004 is modified, specifically to provide initial EF information useful for the calculation of SDG target indicators. The spatial resolution of the analysis has been improved from 0.5 to 0.1 degrees and enables assessment at any larger aggregated scale. Importantly, the EFs are also split into the surface runoff contributed EFs and groundwater contributed EF. The groundwater-contributed EFs help in defining sustainable groundwater abstraction from renewable sources. The desired conditions of rivers are defined by four environmental flow management classes (EMCs). The EF (as percentage of flow required relative to the pristine conditions) and volume of groundwater abstractable without impacting the EFs are calculated for each EMC. The EFs are determined based on modifying synthetic pre-development natural flows (derived from the global hydrological model PCR-GLOBWB). In reality, the current flow and environmental condition of the rivers vary globally. A modified Index for Global Threat to River Biodiversity determined globally by other researchers was used to link the current condition of the rivers to the desired EMC. The results suggest that total accumulated global EFs vary from 80% to 42% of natural flows, from the highest to lowest EMC, and the groundwater contribution ranges from 77% to 39% of natural base flows. Globally, 149-to 376-km<sup>3</sup> yr<sup>-1</sup> of groundwater can be abstracted sustainably, depending upon the EMC. An online interactive tool was developed, where the user, based on selected area and EMC, can determine the acceptable EF requirements, base flow contribution and sustainable groundwater abstraction. This can then be compared either directly with the information on water withdrawals in the selected area or can be fed into the SDG target equations to determine the sustainability indicators.

## Vietnam to Produce more Coffee with Less Water-Hydrogeological Study of the Basaltic Plateau in Dak Lak province, Vietnam

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Vietnam is the second largest coffee producer in the world and leading Robusta coffee exporter. Water demand has increased considerably in the Central Highlands of Vietnam over the past decades due to the considerable increase in coffee production. Coffee production heavily relies on irrigation during the dry season, mainly from groundwater, leading to numerous shallow wells running dry, thus threatening the sustainability of the local groundwater resources and eventually the Vietnamese Robusta coffee production. A hydro-geological study was conducted in order to better understand the risks and opportunities related to the local groundwater resources and their use. The main objective of the study was to identify the spatio-temporal groundwater availability at two different scales (provincial and basaltic plateau scale) and in response to different irrigation practices. On the provincial scale, the geological domains were described in order to obtain the spatial distribution of aquifer types, revealing that the central basaltic plateau is the largest continuous aquifer system. Combining this analysis with land use mapping showed that 86% of the coffee production is located on the basaltic plateau, presenting favourable soil conditions. A provincial water balance was established, using rainfall, discharge and satellite-based evapotranspiration data. Spatial water availability maps were elaborated, using the spatial difference between the annual average rainfall and evapotranspiration distribution, calibrated with discharge measurements from two catchments, Krong Buk and Gian Son. Water-scarce hot-spot maps were obtained by deducting the dry-seasonal irrigation requirements from the water availability map. To identify the processes leading to the drying up of shallow wells on the basaltic plateau, a general hydrogeological description of the aquifer system was performed using detailed water level analysis from monitoring data. The basaltic plateau is a dual aquifer system, consisting of an upper shallow aquifer (weathered basalts) underlain by a variably thick fractured basaltic aquifer, with distinctly different hydraulic characteristics. The water level analysis revealed no long-term, large-scale declining water level trends. Groundwater recharge was found to take place between 60-100 days after the onset of the rainy season, compensating water extractions during the dry season. However, seasonal water level fluctuation amplitudes, responsible for the drying up of shallow wells, were found to correlate with the thickness of the unsaturated zone, the distance to the closest discharge area (spring, stream, lake, river) and the effect of irrigation-practices. Excess irrigation water is likely to be 'stuck' in the soil column during the dry season and during over-irrigation, thereby enhancing water level amplitudes and the falling dry of shallow wells. In order to identify areas prone to falling dry of shallow wells, a numerical model experiment was used to delimit the areas that are close to local highs and prone to drying up of shallow wells from a hydrodynamic perspective. The map of these areas at risk was then combined with water-deficit maps, reflecting the ratio between irrigation extractions and groundwater recharge, identifying micro-catchments, where both the water availability is critical and the groundwater dynamic setting is such that a change in irrigation practice would have the highest impact.

## **California's New Groundwater Management Laws, and Strategies to Avoid Adverse Impacts on Agriculture in Urbanizing Communities**

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On September 16, 2014, California enacted the first comprehensive program for managing and regulating groundwater extraction and use in its history (AB 1739 (Dickinson), SB 1168 (Pavley) and SB 1319 (Pavley)). The policies and regulations set in motion by the new laws will impact existing and future agricultural wells and land uses throughout the State. This presentation will educate attendees about California's new sustainable groundwater management policies, and provide practical strategies for agricultural businesses in urbanizing areas to join with their local water district, city and county to focus regulatory efforts on increasing the yield of local groundwater basins, and avoid unintended consequences that could reduce available water supplies and restrict existing and future agricultural production. The presentation will discuss key changes that the new laws set in motion, opportunities for agricultural groundwater users in urbanizing areas to have a voice in how the State and local agencies will implement them, and examples of emerging groundwater governance structures that urbanizing communities would be wise to follow or avoid. Groundwater accounts for about a third of all water used in California in an average year, and more than half in a drought year when surface water supplies are unavailable. Some communities are totally reliant on groundwater. Yet, efforts to allocate and manage groundwater in California have often been reactionary, initiated after groundwater use was already impaired by existing or imminent overdraft condition or groundwater quality degradation. The new laws establish a State policy requiring all groundwater resources to be managed "sustainably". They also establish a new Sustainable Groundwater Management Act. The Act gives groundwater sustainability agencies broad authority to regulate the extraction and use of groundwater supplies under their groundwater sustainability plans. Any local public agency having water supply, water management or land use responsibilities within a basin (such as public water suppliers, flood control districts, cities and counties) may elect to be the basin's groundwater sustainability agency. The Act also allows cities and counties to participate in a groundwater sustainability agency. Their participation could bring broader public perspectives to the planning process and help alleviate the concerns of agricultural landowners, who hold superior overlying water rights, potentially being subjected to the control of municipal water agencies in urbanizing areas that operate wells competing for the same limited groundwater supplies and are primarily concerned with their own customers' interests. The Act defines sustainable groundwater management to include the use of groundwater. By January 1, 2017, the California Department of Water Resources is to publish Best Management Practices to be included in groundwater sustainability plans. Groundwater sustainability plans are also to specify efficient water management practices. Once the BMPs and efficient water management practices are included in a local groundwater sustainability plan, they can be enforced against groundwater users. The presentation will discuss the importance of including agricultural groundwater users in the local groundwater management process in order to maintain production of food and fiber in urbanizing areas.

## Nitrates, Groundwater and Drinking Water – A Tale of Two Communities

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Washington has over 14,000 public water supplies and over 600,000 private wells. Most of the state's drinking water supplies are of high quality and are not polluted by anthropogenic contaminants, but universally this is not the case. The most common contaminant affecting groundwater and drinking water is nitrate. While most systems and most of the state's population use drinking water supplies with barely any detectable levels of nitrates. Almost 5% of the public supplies have sources with elevated nitrate. The impact on private supplies is not nearly as well documented, but in areas like the ones in this paper the impact on private well may be as high as 15%. This paper describes how two areas in Washington, served by major aquifer systems, are addressing the challenge of nitrate pollution. The areas are Abbotsford Sumas Aquifer located in northwestern Washington and the Lower Yakima River Basin in south central Washington. They are primarily agricultural communities, and the issue of nitrate in groundwater is not new. The contribution from legacy activities versus current agricultural practices is part of an ongoing debate in both communities. What isn't dateable – is the public health impacts when drinking water supplies are not safe. These are active and growing communities trying to assess, manage and mitigate the threat to their water supplies. This paper compares how two very different communities have faced the challenge at the local level and compares their approaches, struggles, and success. Some of the challenges they face include, aquifers that transect international boundaries, state and tribal boundaries and equally diverse jurisdictional perspectives and authorities. How these communities, their state, and provincial partners can provide insight to other communities and regulators looking for paths forward.

## Produced Water from Oil & Gas Fields as a Potential Source of Irrigation Water

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In many cases, more water than oil is extracted from hydrocarbon-bearing formations, especially from older hydrocarbon reservoirs that are no longer in primary production. Oil and gas (O&G) production occurs in close proximity to agricultural production in many arid regions and there is intense interest in using produced water (PW) for crop irrigation. Growers are looking for new sources of water in the face of extended droughts and O&G producers are interested in both alternatives to current water management practices and the potential to increase revenue. From a global perspective, there is interest in the potential energy savings from reclaiming water that has already been pumped to the surface and reducing the demand on shallow groundwater resources. The utility of PW for irrigation depends on the quality of the produced water and the technical and economic sustainability of applying treatment processes to meet water quality requirements for irrigation. PW has widely varying compositions and typically contain dissolved salts, hydrocarbons, metals, and other constituents undesirable in irrigation water. However, not all PW contain high salt concentrations and treatment processes are available to treat almost any potential contaminate. In this study, we use biogeochemical analysis to select and predict treatment processes performance and inform the development of treatment trains and the systems optimization efforts. PW are characterized by direct chemical analysis and supplemental information available from federal, state, and industry databases. Biogeochemical modeling and engineering analysis are used to predict the fate of individual constituents and constituent mixtures in individual modules of a matrix of possible treatment train combinations. We include an assessment of treatment trains needed to remove additives, including biocides, corrosion inhibitors, and surfactants, used during hydraulic fracturing and other O&G development activities. By integrating an understanding of geochemistry with the performance of different treatment processes, we intend to provide a decision support tool for design of treatment processes and anticipate the sustainability of treatment process performance and water reuse.

## **Agricultural Groundwater Use in the Vientiane Plains, Laos: Farmers' Perceptions of Opportunities and Constraints**

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Agricultural groundwater use has the potential to improve rural households' income and reduce poverty. We argue, however, that these linkages are not always straightforward. For example, whether or not farmers decide to use groundwater to support their farming activities is defined not only by their access to groundwater, but also by other factors such as access to land, markets, energy policy, and a range of institutional considerations that would affect the economic viability of groundwater use. Taking Laos as a case study, we attempt to further the discussion on the opportunities and constraints of agricultural groundwater use in poverty reduction through better understanding of how farmers perceive it in relation to their overall farming strategies. This article illustrates how access to water, land, and capital differentially shape farmers' livelihood strategies in two villages of the Vientiane Plains, Laos. It shows how farmers' perceptions of opportunities and constraints to agricultural groundwater use are shaped by their farming strategies. In particular, it highlights the importance of access to water, land, capital, as well as tenure security as key determining factors in the shaping of farming households' decision to place groundwater use as integral part of their farming strategies. From a policy perspective, it brings to light the need to better recognize how farmers view groundwater in relation to their overall farming strategies, if groundwater resources are to be successfully used as a means to reduce poverty and offer tangible support to the government's agricultural development strategies. Such an understanding of how farmers actually use groundwater as well as its potential role for supplementary and/or dry season irrigation is crucial for the Government of Laos' objective to promote agricultural intensification and crop diversification to ensure food security and reduce rural poverty.



## Linking Microbial Community Composition to in Situ Natural Attenuation of Emerging Contaminants

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The presence of low concentrations of hydrophilic, organic emerging contaminants pose a threat to the quality of groundwater resources utilized for drinking water purposes. While extensive monitoring of the chemical composition of groundwater has revealed the presence of a variety of organic contaminants, relatively little is known about the natural attenuation of these compounds in situ. Biodegradation has been shown to be an effective transformation processes for a wide variety of emerging contaminants. However, it remains difficult to translate these results to in situ degradation in (usually) oxygen-depleted, oligotrophic groundwater with heterogeneous distribution and low emerging contaminant concentrations. Research was performed to gain insight on biodegradation of emerging contaminants in groundwater by examining microbial community composition and geochemistry. Groundwater samples collected at discrete depths ranging from 12 to 55 m in two monitoring wells were chemically analyzed to determine groundwater chemistry and contaminant distribution. Additionally, samples were analyzed for microbial community composition by sequencing of a PCR-amplified fragment of the 16S rRNA gene. Results indicate a distinct difference in both groundwater composition and microbial community diversity between wells and in depth. The groundwater profiles demonstrate the heterogeneity of subsurface geochemistry, highlighting the fact that contaminated water travels through a variety of environments between its source and extraction for drinking water. Differences in the abundance of electron acceptors, concentration of nutrients, and presence of electron donors, such as DOC, in addition to emerging contaminants play an important role in microbial community composition and in situ biodegradation. Redundancy analysis of groundwater geochemical characteristics, emerging contaminant concentrations, and microbial community diversity indicates a negative correlation between the availability of electron acceptors (nitrate and sulfate) and the presence of contaminants. In contrast, dissolved organic carbon correlated with the presence of organic contaminants. Overall, the results presented here are a first step towards better understanding the geochemical and microbiological factors affecting in situ emerging contaminant biodegradation.

## **Informing Restoration Practice through Estimation of Groundwater-Surface Water Time Lags with Windowed Cross-Correlation**

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California's floodplain ecosystems and their riparian wetlands provide habitat for wildlife and essential ecosystem services such as water quality regulation and flood protection, but have seen major declines due to land use changes and development of water management infrastructure. Resource managers are increasingly recognizing the benefit of restoring floodplains for the multiple benefits they provide. For example, floodplain restoration provides opportunities for aquifer recharge, a strategy that can boost flexibility in water management portfolios in terms of ameliorating water scarcity challenges due to drought, groundwater overdraft, and projected climate-driven precipitation shifts from snow to rain. Planning of multi-benefit floodplain restoration projects will need tools to support project siting and understanding of groundwater-surface water interactions while informing the regulation of stream flow regimes. Our research addresses this need through the application of standard time-series analysis of groundwater and surface water data in the lower San Joaquin River in the California Central Valley. Windowed-cross correlations were applied to times series data to estimate time lags between stage and groundwater levels, providing insight to the strength of these flow connections. This method allows for quick assessment of groundwater-surface water interactions that can be a preliminary step in developing monitoring action to help identify suitable floodplain restoration sites.

## Using a GIS to Develop Distributed Storm Water Collection Systems Linked to Managed Aquifer Recharge

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We are completing a regional geographic information system (GIS) analysis of Santa Cruz and northern Monterey Counties, CA to assess conditions amenable to distributed storm water collection linked to manage aquifer recharge (DSC-MAR). Many groundwater aquifers in this region are experiencing chronic overdraft and are at risk of contamination and seawater intrusion. In the face of ongoing drought, communities and water supply agencies across CA are struggling to develop secure and sustainable water supplies for long-term municipal, agricultural, environmental, and other needs. Enhanced groundwater storage is an important part of this effort in many basins and can be implemented with a variety of techniques such as infiltration basins, dry wells, or flooding of agricultural fields. Our project is especially timely because California's recently enacted Sustainable Groundwater Management Act requires the creation of groundwater sustainability agencies and the development and implementation of basin management plans. Our analyses focus specifically on the distributed collection of storm water runoff, a water source that has typically been treated as a nuisance or waste, from catchments having areas of 100 to 1000 acres. This part of our project is a GIS analysis-using surface and subsurface data. Developing complete and accurate data coverage for our study region requires considerable effort to locate, assemble, co-register, patch, and reconcile information from many sources, scales, and projections. We have complete spatial coverage for many kinds of surface data, including surface geology, soil infiltration capacity and slope, but subsurface data are limited in lateral extent. Sites that are most suitable for DSC-MAR have high soil infiltration capacity, are well connected to an underlying aquifer with good transmissive and storage properties, and have space to store additional water. Additional considerations include infiltration method, slope, and land use and access. Based on initial consideration of surface data, much of the study region appears to be suitable or highly suitable for MAR (in the top third of the rating system), including sites that are used for agricultural production, but there is considerable spatial heterogeneity based on the distribution of shallow soils and bedrock geology. Our GIS work is linked to regional runoff modeling to assess where there is a confluence of good conditions for MAR and likely supply of storm water runoff (please see related poster by Young et al.).

## Knowledge Based Protection of Groundwater Through Monitoring and Modeling of Nitrate in Groundwater in Rural Areas

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Cost efficient sustainable management of groundwater resources in rural areas calls for development of scientifically sound methods usable for mapping and monitoring as well as dissemination of results to planners and the rural communities. There is a growing awareness in the political and agricultural communities that cost efficient measures to reduce the environmental impact of nitrate and pesticides in the future should be site specific and not only based on overall national regulation. Scientific developments in mapping methods in regard to hydrogeology and geochemistry are a prerequisite before this goal can be realized. Especially a better site-specific knowledge of the nitrate reduction in the subsurface and aquifers is required in order to implement site-specific measures. The Danish case is a strong example of the potential of the science policy interface to develop better resource efficiency. In Denmark groundwater is synonym with drinking water. To preserve this highly valued resource a national strategy for sustainable abstraction and groundwater protection has developed over the last 50 years. The National Groundwater Mapping Program has detailed mapped the hydro-geo-chemical settings of about 40% of Denmark followed by delineation of nitrate vulnerable areas in drinking water abstraction areas. Strategic monitoring of the efficiency of implemented measures is part of the cost efficiency. Dating of groundwater has proved indispensable for interpretations. On a national scale regulations implemented by Danish farmers have succeeded in optimizing the nitrogen (N) management at farm level. Accordingly, since the 1980s the overall national upward trend of the nitrate concentrations in oxic groundwater has been reversed (Hansen et al., 2011). Locally, nitrate trend analyses in monitoring wells have shown a more varied pattern with both upward and downward nitrate trends underpinning the need for supplementary site-specific groundwater protection initiatives.

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## Indicators to Identify the Source of Pesticide Contamination to Groundwater

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In Denmark groundwater is synonym with drinking water. The mainstream Danish political approach favors prevention and action at source over advanced treatments of polluted groundwater. The main pollutants are nitrate and pesticides. Pesticides in groundwater can originate from either diffuse or point sources. Point sources are characterized by high pesticide concentrations leaching from small areas, while diffuse sources are characterized by low concentrations over large areas. Some source types can either be termed diffuse or point sources, e.g. line sources (uses at railways) or more intensive diffuse sources (clean keeping of farm yards). It is important to determine the source type in order to make proper management decisions. This project aimed to identify and develop a set of indicators that can be used to determine whether pesticides detected in a groundwater sample (e.g. in a monitoring or abstraction well) originate from a diffuse or a point source. Results historical data on pesticide sales in Denmark are a good indicator of the quantity and types pesticides that have been used over time. A statistical assessment showed that the distribution of sum concentrations and max concentrations clearly show that findings from point sources have higher concentrations than findings from diffuse sources. Here, “high” concentrations are considered to be  $> 1.0$  g/l, and “low” concentrations  $< 0.05$  g/l. The number of compounds detected in samples from point sources and diffuse sources also differ. Therefore, a useful indicator for point sources was defined: if a groundwater sample has findings of  $\geq 4$  compounds, and/or at  $\geq 2$  compounds above  $0.1$  g/l. Model results show that the breakthrough curves from point and diffuse sources differ, with diffuse sources resulting in flat breakthrough curves, while point sources results in steeper breakthrough curve. Model results also show that the spatial variability of pesticide concentration data is different for diffuse and point sources. Large variations of the same compound can indicate a point source. The outcome of the project is a set of indicators the origin of pesticides: from a diffuse source or a point source -and these are shown in the figure below. The indicators can only be used one-way; a “YES” implies the given result, but a “NO” answer does not imply any conclusion on the question posed. The indicators have been used in the municipality of Aarhus to identify whether pesticide findings originate from diffuse sources or point sources. This will have implications for future groundwater protection initiatives.

## **Predicted Impacts of Conjunctive Water Management on Late Summer Stream-flow in an Agricultural Groundwater Basin with Limited Storage, Scott Valley, CA**

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Late summer stream flow for the Scott River in northern California has decreased approximately 50% since the mid 1960's, resulting in increased water temperatures and disconnection of the stream. This negatively impacts aquatic habitat of fish species such as Coho and fall-run Chinook salmon. In collaboration with local stakeholders, the Scott Valley Integrated Hydrologic Model has been developed, which combines a water budget model and a groundwater-surface water model (MODFLOW) of the 200-km<sup>2</sup> basins. The goal of the integrated model is to better understand the hydrologic system of the valley and explore effects of different conjunctive management scenarios on stream flow during the critically dry months (Aug-Oct). The groundwater model has a 100 m lateral resolution with aggregated monthly stresses over a 21-year simulation period (1990-2011). The Scott River and tributaries are represented using the stream flow routing (SFR) package. Sensitivity analysis and calibration were performed using 812 head observations from 50 wells in the basin and average daily stream flow observations from a USGS stream gauge during the simulation period. The calibrated model was used to evaluate two different management scenarios: 1) in-lieu recharge where surface-water instead of groundwater is used to irrigate fields near the river while stream flow is sufficiently high, and 2) managed aquifer recharge during the winter months (Jan-Mar) on agricultural fields located in gulches on the eastern side of the valley using existing infrastructure. Preliminary results indicate that managed aquifer recharge may increase stream flow during the critically dry months at the basin outlet by 1-2 cubic feet per second (cfs), while in-lieu recharge may increase flows during the same period by 10-30 cfs. The greater increase in flow from the in-lieu recharge scenario is largely due to reductions of groundwater pumping by 10-25% from the base case scenario, with greater pumping reductions during wetter years. This increase in flow during the critically dry months decreases the length of dry reaches both spatially and temporally, allowing for earlier reconnection of the Scott River and decreased stress on fish.

## **Aquifer Studies and Recharge Assessment of the Northern California Lower Tuscan Aquifer System**

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The Sacramento Valley Groundwater Basin and the Redding Groundwater Basin represent the principal groundwater basins of the broader Sacramento River Hydrologic Region. The Sacramento Valley Groundwater Basin is bound by the Coast Ranges to the west, the Cascade Range to the northeast, and the Sierra Nevada to the east, extending from the City of Red Bluff in the north to the Delta in the south. As described by California Department of Water Resources (DWR), the Sacramento Valley groundwater basin underlies approximately 4,900 square miles of the Sacramento Valley. The Tuscan Aquifer system, a regional aquifer of the Sacramento Valley Groundwater Basin, is among the principal water bearing units in Butte County. The Lower Tuscan is a critical resource to the region. However, there is incomplete data pertaining to aquifer system functions in terms of source, recharge and recovery. Butte County was awarded grant funds from DWR through Proposition 50 (Water Security, Clean Drinking Water, Coastal and Beach Protection Act of 2002) for implementation of the proposed Lower Tuscan Aquifer (LTA) Project. The primary objective of the LTA project was to collect and analyze technical data through development of innovative analytical investigative tools to further the scientific understanding of the LTA system and assess potential recharge sources. Key components of the overall project included development of cost effective methods to conduct and analyze aquifer parameters during the agricultural pumping season using newly installed and existing groundwater monitoring systems; evaluation of LTA recharge from upper reaches of creeks and analysis of stable isotopes of hydrogen and oxygen from groundwater and surface water samples to assess the source of the recharge water. Aquifer tests were conducted during various agricultural pumping schemes including heavy continuous pumping used for flood irrigation and intermittent pumping used for drip and spray irrigation of orchards. Qualitative analysis of drawdown curves from aquifer tests provided significant insights into the interactions between stratigraphically adjacent aquifer systems as well as aquifer stresses to the LTA resulting from various agricultural pumping schemes. The results of this analysis indicated that the LTA is a complex interconnected aquifer system and that a major recharge source to the LTA is through the overlying aquitard and overlying aquifers. Over all, isotopic data for samples collected from groundwater wells throughout the area was indicative of precipitation from elevations that are not far above the valley floor. Moving out along the valley floor isotopic data suggested recharged water might be due to a mixture of lower-elevation precipitation along the basin perimeter and interaction with the Sacramento River and other local streams. The study also found that the upper reach of the creeks contributed little to LTA recharge. Results of water level studies compared to flows recorded from the Sacramento River also suggested a potential connection during high storm events.



## Improved Irrigation Scheduling Through Airborne Detection of Water Stress

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Innovations in remote sensing offer groundbreaking opportunities for large-scale reductions in agricultural water use, and hence also reductions in groundwater overdraft and application of saline irrigation. At Ceres Imaging, through a combination of high-resolution thermal imagery and physiological modeling, we produce a measure of stomatal conductance at the level of individual trees that maps extremely well to on-the-ground measures such as stem water potential (SWP). In highly saline conditions, however, SWP can underestimate actual water stress. We see evidence that our aerial imagery correctly detects trees showing obvious signs of water stress that would have been incorrectly deemed unstressed on the basis of their SWP values. Such technology offers the opportunity to more accurately identify those portions of fields experiencing high water stress, target them for proper irrigation levels, and reduce total water use by curbing irrigation of unstressed portions. This in turn reduces the need for groundwater pumping, and allows for a higher ratio of surface to groundwater use.

## Action Plans to Protect Groundwater from Pesticide Pollution in Aarhus, Denmark

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Analysis of some 20 years of monitoring data in the municipality of Aarhus, has shown pesticides in about every third well, with the drinking water threshold being exceeded in about one in every six wells. This article illustrates the efforts undertaken in Aarhus to map the vulnerability of groundwater to pollution and in finding solutions to deal with the pesticide pollution.

Groundwater in the Aarhus Municipality can only be protected against pesticide or nutrient contamination by a long-term, holistic effort involving water service providers, management agencies and stakeholders. This has necessitated development of: new geophysical methods to map clay thickness to assess the risk to aquifers from surface activities (both agricultural and urban); extensive monitoring of both groundwater level and quality; extensive stakeholder liaison and communication; and the development of multiple pieces of legislation including multiple amendments. This has taken decades at a considerable cost, but without this level of endeavor, optimal groundwater management would not be possible to protect Denmark and in particular, Aarhus's groundwater resources. During the course of the 1990s it was acknowledged that approximately one-third of the general abstraction wells in Aarhus Municipality were contaminated with pesticides. Aarhus University, Aarhus County, and Aarhus Water Inc. collaborated extensively in the period on technology development and mapping. In 1998 a new act was passed in Denmark on mapping of vulnerable areas, identification of groundwater protection zones and action plans for such zones. The experiences from the Aarhus area were employed in the preparation of the act. The methods to map groundwater vulnerability initially focused on nitrate, which was a known pollution issue as early as the 1980s both in Denmark and in the EU. Throughout the process there has been an understanding that pesticide vulnerability is a more complex issue than nitrate vulnerability. However, as they both commonly occur together, the presence of nitrate in groundwater may be a good indicator of pesticide risk. The mapping activities have shown that in the Aarhus area pesticide vulnerability and nitrate vulnerability coincide extensively. It was decided to designate the nitrate vulnerable areas as groundwater protection zones with respect to nitrate as well as pesticides. At the political level there is an ambition that all vulnerable areas should be protected by imposing a ban on the use of pesticides in these areas. Such a ban may be implemented under the provisions of the 1998 Act. Initially, the water works are to offer voluntary agreements, but if stakeholders fail to enter into a voluntary agreement, the municipality can issue a pesticide ban. Bans can be issued in well protection zones as well as groundwater protection zones. Since 1998 Aarhus Water Inc. as well as other water service providers have been offering voluntary agreements and providing advice on conversion into pesticide free farming. The efforts have been prolonged and persistent, and many agreements have been made. But nevertheless, the voluntary agreements only cover a fraction of the vulnerable areas. The local authorities have decided to exploit the facilities of the legal framework to introduce binding requirements on pesticide free production and in 2013 passed the first ever action plan, which makes use of injunctions. Based on the experience in Aarhus water quality protection through voluntary agreement is unlikely to succeed. A significant percentage of land holders in this jurisdiction only changed behavior as a result of enforced pesticide bans and injunctions. Costs for voluntary measures and injunctions will be equivalent to 0,07 Euro per m<sup>3</sup> abstracted water over the next 20 years. Additionally, all publicly owned areas are kept pesticide-free, and the authorities have initiated measures targeting historical point sources.

## Environmental Impact of Soil Moisture Monitoring Through Capacitance Probes Over Aquifer Contamination by Nitrates

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The pollution of aquifers by nitrates (NO<sub>3</sub>) is a major environmental problem. In Mexico there are few studies on NO<sub>3</sub> levels in drinking water and the source of this contamination. If the content of nitrates (N-NO<sub>3</sub>) of 10 mg L<sup>-1</sup> (NOM-127-SSA1-1994) is exceeded, it can be a health problem because nitrate intake can cause methemoglobinemia in infants and children, known as Baby Blue Syndrome (Comly, 1945; Magee and Barnes, 1956) syndrome and may be carcinogenic (Volkmer et al., 2005; Ward et al., 2005). Nitrate pollution of groundwater is related to the use of synthetic fertilizers or the existence of losses in septic systems. The objective was to evaluate the environmental impact exerted by the water management through micro sprinkler irrigation with optimized programming monitoring moisture capacitance probes FDR, compared with traditional management on pollution of aquifers by nitrates. This study was conducted during 2008 and 2009, in Cuauhtémoc, Chihuahua, in two apple (*Malus domestica* borkh) orchards: 1) Rosario orchard, with 570 hectares irrigated with 25 wells scheduled irrigation and FDR probes, 2) Macetas orchard (control), with 253 hectares irrigated with 13 traditional irrigation wells. In each orchard were installed 20 suction tubes with porous porcelain capsules to 150 cm deep. The leaching water was extracted at intervals equal to the moisture monitoring (weekly from March to September and monthly from October to February) analyzed the content of N-NO<sub>3</sub> by colorimetric. Monthly N-NO<sub>3</sub> content was analyzed in 38 wells. Water depths in 2008 was 948 mm in Rosario and 1720 mm in Macetas, and rainfall 212 mm; in 2009 water depths in Rosario was 564 mm, and 1570 mm in Macetas, and rainfall 592 mm. In both orchards two fertilizations were applied with equal doses per year, in spring and autumn. The results showed that where irrigation water is optimized with FDR probes no significant effect on water depths applied over NO<sub>3</sub> leaching. In orchard control there was a rise in the concentration of NO<sub>3</sub> after deep irrigation, showing a highly significant effect, which shows that if water depths exceed the water needs of the crop, NO<sub>3</sub> leached in depth washed away through the unsaturated zone soil (ZNS) contaminating aquifers.

## Harmonizing Agriculture and Vulnerable Drinking Water Abstractions in Overijssel, the Netherlands: A Collaborative Approach

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Since the seventies, in The Netherlands, the agricultural emissions of nutrients and chemicals used for crop protection to water systems have strongly increased. Since the early nineties, these emissions have been reduced by policy measures. In spite of these efforts, water abstraction sites in the sandy areas of the province of Overijssel, the Netherlands, are still experiencing an increasing impact of agricultural emissions on the quality of abstracted groundwater. To meet the requirements of *article 7.3* of the WFD, the province of Overijssel assessed the risks on water quality for drinking water abstraction sites in the province. Emissions from dairy farms were identified as significant sources for which measures were necessary in groundwater protection areas (GWPA). In 2011, a project was formulated based on voluntariness and mutual gains aiming at reducing nitrate leaching and N surpluses and increasing the financial benefits of the farmers at the same time. Farmers were invited to join the project and were supported by agricultural consultants. Measures were selected that would contribute to maintenance of the production intensity without violating values for nitrate leaching to groundwater. These values were transposed into operational boundary conditions, i.e. maximum acceptable N surplus (kg ha<sup>-1</sup>) on farm and on soil scale. The indicators of the agricultural management and the nitrate concentration of the shallow groundwater monitored the effect of the measures. The economic impact was established for each farmer based on the measures agreed upon and the characteristics of the farm. As result of this management, N surpluses of the soil balance decreased from 165 to 83 kg ha<sup>-1</sup>, in the period from 2012 to 2014. The nitrate concentration in the shallow groundwater fluctuated in 2011, 2012, and 2013 between 93 and 104, but tended to decline to 84 and 75 mg NO<sub>3</sub>-N in 2014 and 2015 respectively. The potential increase in financial benefits of measures implemented in 2015 ranges from € 80 – 135 /ha and € 3,200 - 6,850 /farm for soil measures only and up to € 290 /ha and € 14,500 /farm including all measures. These results were considered as a proof of concept for the approach. To meet the WFD objectives, it is required to extend this approach from farm level to a regional level, i.e. the entire GWPA. The initial group of farmers shared this dilemma, contributed to develop a strategy for extending the approach and participated in extension activities to commit and inform besides new farmers also contractors and consultants working with the farmers in the GWPA. Extending the proof of concept required a collaborative approach in which new ways of knowledge exchange were implemented.

## Contribution of Sustainable and Unsustainable Groundwater Use to Global Food Production

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Groundwater is crucial for global food security. At the same time, its contribution to global food production is largely unknown. Even more critical is the fact that groundwater depletion is occurring at an alarming and ever-increasing rate – mainly due to irrigated agriculture, progressively threatening global food security. Here we present for the first time estimates of the global food production derived from groundwater and in particular depleting groundwater. Based on an integrated GIS analysis combining global distributed datasets on groundwater depletion, irrigated areas, and food production for the year 2005, we show that 44% of global irrigated food production is derived from groundwater. Furthermore, depleting aquifers account for between 14 and 17 percent of global groundwater-irrigated food production, between 6.0 and 7.0 percent of global irrigated food production, and between 1.8 and 2.2 percent of total food production (including rain-fed). In total, between 124 and 150-mil tonnes per year are produced unsustainably. This production occurs primarily in arid and semi-arid areas with good sub-surface water storages, with the South Asia, East Asia, Near East/North Africa and OECD regions as dominating. Crop-wise, we found that while cereals and sugar crops exhaust most groundwater, crop groups like roots and tubers, non-food crops (mostly cotton), leguminous crops, and vegetables and fruits are disproportionally and preferentially grown by depleting groundwater due to their higher value linked to the reliable irrigation source provided by groundwater. The findings imply the critical importance of analyzing and developing congruent policies at multiple levels that account for the nexus between groundwater, groundwater depletion, and global food security.

## Hydro-Geochemical Characterization in Relation to Nitrate Concentrations in Central Valley (California, USA) Domestic Wells

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Agriculture and groundwater are both of vital socio-economic importance to the California Central Valley (USA). High nitrate concentrations from agricultural practices threaten the quality of domestic well drinking water. Hydro-geochemical characteristics of the aquifer can reduce or enhance the risk that nitrate or naturally occurring contaminants like arsenic or uranium exceed the Maximum Contaminant Level (MCL) at the domestic wells. We analyzed a data set of nitrate concentrations and isotopes,  $3\text{H}/3\text{He}$  groundwater ages, major ion chemistry (including arsenic and uranium) and hydrological setting, collected from 200 domestic wells in the San Joaquin Valley. Nitrate exceeds the MCL in 44% of the wells, uranium in 17% of the wells and arsenic in 11% of the wells. 13% of the wells produce pre-modern groundwater (recharged prior to 1950) with less than 1 pCi/L tritium and 6% of the wells produce anoxic water ( $\text{Fe} > 0.05 \text{ mg/L}$ ). Nitrate concentrations correlate strongest with area of manure lagoons ( $R=0.45$ ), corrals (0.41) or dairy manure application areas (0.26) within a 1.5 mile radius (Groundwater Nitrogen Loading Model input) but nitrate concentrations are difficult to predict reliably based on land use data alone. Nitrate negatively correlates with younger groundwater ages ( $R=-0.42$ ) and with water table depth ( $R=-0.31$ ). These findings are supported by k-means cluster analysis performed on nitrate, mean groundwater age, and average depth to groundwater near each well. Wells with the greatest mean age 52.3 years and relatively deep mean depth to groundwater (37.8 m) has the lowest mean nitrate concentrations (2.3 mg/L). Wells with relatively young mean age (9.6 years) and relatively shallow mean depth to groundwater (16.7 m) have the highest mean nitrate measurements (40.8 mg/L). K-means cluster analysis performed with groundwater age, nitrate, arsenic, and uranium reveals four groundwater contaminant groupings. One group represents groundwater with a mean age 51.1 years with low concentrations of all three contaminants. A second group represents old groundwater (mean age 46.6 years) with the lowest mean nitrate concentrations (1.65 mg/L) but with the greatest amount of arsenic (mean of 44.7  $\mu\text{g/L}$ ). Two groups contained mean nitrate concentrations above the MCL. The group with the greatest mean nitrate concentration (29.1 mg/L) also has the greatest mean uranium concentration (95.2  $\mu\text{g/L}$ ). In conclusion, predictions of nitrate, uranium and arsenic concentrations improve when hydro-geochemical parameters are included and are suited to predict the risk of wells to future contamination. The hydrogeochemical characterization also revealed risk factors for nitrate co-contaminants like uranium and natural contaminants like arsenic.

## **Factors Influencing the Adoption of Water Pollution Mitigation Measures by Farmers in England**

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A range of interventions is available to influence the uptake of farm practices, which mitigate groundwater pollution. Deciding which are the most appropriate for particular measures poses a challenge to policy makers. Whilst many measures remain voluntary, implementation will only be effective with the co-operation of stakeholders and evidence regarding the factors influencing measure uptake is crucial to aid policy design. Research conducted as part of the Demonstration Test Catchment (DTC) project explored the factors influencing farmer adoption of water pollution mitigation measures through three related surveys. Over two hundred farmers and farm advisors participated in interviews from three contrasting regions of England: the grassland dominated North West; the arable dominated East Anglia; and the mixed and dairy farming of the South West. Results from the two farmer surveys provided a baseline of current agricultural practices, insights regarding farmer attitudes to the adoption of other mitigation measures in the future and understanding of the motivations and barriers to the adoption of specific measures such as, cover crops, sub soiling and farm yard infrastructure. Results from the farm advisor interviews revealed the types of mitigation measures recommended by various advisors, which mechanisms (regulatory advice, financial incentives, signposting or voluntary approach) were being used to influence the uptake of measures, and whether differences occurred between sources of advice. The results illustrate the great diversity amongst the farming community, the range of factors influencing mitigation measure uptake and the differing complexities of farmers' decisions to change their behavior. Different combinations of interventions are required not only for each mitigation measure but also within the different regions surveyed. The importance of advice is illustrated but knowing which advisors are most suitable to deliver information and how is highlighted as being essential for policy design. Policy recommendations are provided as to what needs to change to influence adoption of specific mitigation measures to improve catchment management and advice provision.



## Addressing Model Uncertainty in Groundwater-Management Modeling: A Case Study from the Upper Klamath Basin, Oregon and California

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Resource-management agencies in the upper Klamath Basin (located in southern Oregon and northern California) require methods to determine groundwater-management strategies that augment surface-water irrigation supplies while simultaneously avoiding adverse effects of pumping on groundwater and surface-water resources. In an earlier study (Wagner and Gannett, 2014, U.S. Geological Survey Scientific Investigations Report 2014-5054, <http://dx.doi.org/10.3133/sir20145054>), we linked deterministic groundwater simulation with optimization to create a decision model that identifies practices that best meet the goals and constraints associated with groundwater development in the basin. The decision model was developed within the framework of the Klamath Basin Restoration Agreement (KBRA), which would establish a permanent limit on the amount of surface water that can be diverted for irrigation in the Bureau of Reclamation Klamath Project. The model evaluates groundwater-management alternatives to: (1) identify groundwater-pumping patterns that, to the extent possible, meet supplemental irrigation demand expected under the KBRA; (2) limit the effects of groundwater withdrawal on groundwater discharge to streams and springs that support aquatic habitat, as defined in the KBRA; (3) ensure that drawdown caused by managed pumping does not exceed limits allowed by water law; and (4) ensure that groundwater pumping does not adversely affect agricultural drain flows that supply downstream irrigators and wildlife refuges. The results indicate that groundwater pumping is limited primarily by drawdown restrictions defined by Oregon water law, and that the effects of managed pumping on streams and springs that support aquatic habitat are substantially less than limits defined in the KBRA. In this study, we extend the work of Wagner and Gannett (2014) to evaluate the effect of model uncertainty on groundwater-development planning in the upper Klamath Basin. We developed a stochastic management model that combines optimization with calibration-constrained uncertainty analysis to identify risk-averse groundwater-management plans. The calibration-constrained uncertainty analysis first generates a suite of 1000 parameter realizations, with each realization reproducing the groundwater-model calibration data within a specified tolerance. This set of parameter realizations forms the basis of model-prediction uncertainties obtained using Monte Carlo methods. The model-prediction uncertainties are then included in the optimization model using the chance-constrained method that defines the probability that the groundwater-management constraints will be satisfied. The resulting optimization model allows us to identify robust groundwater-management strategies that account for uncertainties associated with simulated drawdown and groundwater discharge, and to evaluate the trade-offs between pumpage and system reliability (as specified in the chance-constrained model). Preliminary results indicate that a robust groundwater-management strategy would reduce and redistribute managed pumping when compared to the deterministic results, and that the changes in pumpage result primarily from uncertainties associated with the calibrated values of hydraulic conductivity and specific storage for the model zones where managed wells are located. The results also indicate that, as with the original management-modeling effort, the pumpage associated with robust groundwater management is limited by drawdown restrictions and impacts to agricultural drain flows; the uncertainty-based constraints that limit the impact of pumping on groundwater discharge to aquatic habitat do not approach the limits defined in the KBRA.

## **USDA Conservation Programs and Groundwater – Advances in Data and Modeling**

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USDA's Economic Research Service is engaged in collaboration with researchers at USGS and at the University of Nebraska-Lincoln to link hydrologic and economic models for the High Plains Aquifer System. This talk describes the foundations of that research effort. The focus of this research is on the interactions between USDA conservation programs and groundwater characteristics. Both working lands and land conservation programs are critical to USDA's role in encouraging sustainable groundwater use. On the land conservation side, more than 8 million acres of lands over the High Plains Aquifer are currently enrolled in the Conservation Reserve Program (CRP), but that number is down by more than 2 million acres since 2008. On the working lands side, from 2008 to 2013, the Environmental Quality Incentives Program (EQIP) has provided financial assistance to support more than 5,000 improved irrigation systems (sprinklers and micro-irrigation) on more than 700,000 acres. Understanding how these programs have impacted the aquifer requires spatially explicit information on aquifer characteristics, which can be derived from new models developed by the USGS for their groundwater availability studies. Aquifer characteristics, in turn, play a crucial role in determining which farmers participate in these conservation programs or, in the case of CRP, decide to leave these programs. The farmers' participation decisions then interact with the aquifer characteristics and local water management institutions to influence the ultimate levels of water extraction and recharge rates. A better understanding of the interactions between aquifer characteristics, producer enrollment decisions, and resulting effects on groundwater systems ultimately provides an improved foundation for USDA's conservation programs.

## **Agricultural Emission Reduction Policy and its Effect on Groundwater Quality in Nature Areas in The Netherlands Over the Past 25 Years**

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The Netherlands Air pollution is a trans-boundary phenomenon. In the Convention on Long-Range Transboundary Air Pollution (CLRTAP) as well as in the European Union's Directive on National Emission Ceilings (NEC), international agreements have been reached on the reduction of emissions. Excessive deposition of nitrogen and sulfur induces acidification and eutrophication of the soil and its groundwater. To reduce air pollution and its negative effect on ecosystems, several policy measures were taken in The Netherlands, such as the obligation to reduce N emissions when spreading manure and the installation of air scrubbers on animal houses. The Dutch National Acidification Trend Monitoring Network (TMV) was established in 1989. The purpose of the network is to study the impacts of national emission reduction policies on the quality of groundwater in the Netherlands. It specifically monitors the quality of the upper meter of the groundwater under nature areas (forest and heath) with sandy soils. Any notable pollutants other than atmospheric deposition do not affect the groundwater under these areas. In addition, sandy soils have a limited capacity to neutralize the impacts of acidification. For these reasons, the impacts of atmospheric deposition on groundwater quality are most clearly detected under nature areas with sandy soils. In other monitoring networks, the effects of atmospheric deposition are difficult or impossible to discern from other sources of pollution. In agricultural areas, for example, the impacts of fertilizer application on groundwater quality obscure those of other sources of pollution. In addition to TMV, we used data on rainwater quality from the Dutch national monitoring network on Air Quality (LML), to quantify the amount of wet deposition. We also used the National Groundwater Quality Monitoring Program for data on the quality of groundwater at 10 m depth (LMG). Our analysis of the measurements shows that rainwater quality and groundwater quality in nature areas have improved significantly over the past 25 years. The impacts of decreased emission of nitrogen are found in rainwater, shallow groundwater and groundwater at 10 m below the surface. In 2014, the median N concentration in rainwater had decreased by 44% compared to 1988. The median concentration of N in the upper groundwater decreased by 61% between 1988 and 2014. A location-wise comparison of the observation data of TMV from 2014 and 1989, using a paired samples t-test, revealed that the pH was significantly higher in 2014 than in 1989, while the nitrate, sulfate and aluminum concentrations were significantly lower ( $\alpha < 0.05$ ). The analysis of the combined observations shows that the international measures taken to reduce emissions have resulted in less acidification and eutrophication in nature areas with sandy soil.

## Characterizing the Deep Groundwater System of Mount Shasta

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When determining a water budget for a region, it is necessary to understand the extent of the entire system. In volcanic systems high degrees of connectivity can lead to extensive aquifers with an unconstrained deep component. Mount Shasta of the California cascade volcanoes is one potential case of a deep groundwater system. The aim of this study is to develop a 3D model of the entire Shasta aquifer and use a combination of modeling and geochemical and geophysical surveys to determine the depth to its bottom. 1D modeling indicates that it could be reaching kilometer scale depths. Maximum estimates of hydraulic conductivity suggest that the three main hydrogeologic units in the area can support flow down to 3.2, 2.5, and 1.2 km, but fractures could increase this depth. In order to more thoroughly estimate the size of the aquifer, a combination of computational and field methods will be employed. 3D visualization using the UC Davis KeckCAVES will coordinate known models of the area's geology. MODFLOW, a hydrologic model developed by the USGS, will be utilized to input hydraulic conductivities of each rock unit within the Shasta system and an expected bottom depth of the aquifer. The output spring and creek discharges and flow paths will be compared to observations at Shasta, and the model will be adjusted accordingly. Certain observed trends in the Shasta springs will be replicated using the flow model. (1) The spring waters are oldest in the western springs, youngest in the southern springs, and of intermediate age in the Shasta Valley (2) The spring flow paths are generally longer on the western side, and possibly deeper. (3) The Shasta Valley Springs have the greatest temperature increase, and temperature decreases to the south, possibly due to deep flow paths or mixing with deeper waters to the north and west. (4) Low elevation springs tend to have high recharge elevations, and middle elevation springs have more local recharge. Later, magnetotelluric and geochemical surveys will provide depth and age data to calibrate the models. Shasta Valley is currently being pumped in numerous places for agricultural use. It is also home to threatened fish species, such as the Chinook salmon. Policies regarding water use in the region need to take both human use and wildlife protection into account. In order to understand the long term effects of pumping on the region, we need to know how the system as a whole is connected.

## Stable Isotopes as Indicators of Sources and Processes Influencing Nitrate Distributions in Groundwater Beneath Dairy Farms in California

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Dairies represent the majority of animal feeding operations in California, and have been shown to be potential sources of nitrate and salinity, dissolved organic carbon, and pathogens to groundwater. In California's Central Valley, nitrate contamination of drinking water wells is a significant concern, and there are multiple sources of nitrate including septic discharge, synthetic and manure fertilizers, and concentrated animal feeding operations. In order to better understand the potential contributions of dairy manure derived nitrate to both shallow and deep groundwater, we used a combined geochemical and stable isotope approach for water samples collected from a network of shallow groundwater monitoring wells on several California dairies located in two distinct geographic regions. In the northern region, the lower San Joaquin Valley, the water table is shallow (2- 5 m below surface) and therefore considered highly vulnerable to contamination, while in the southern region, the Tulare Lake Basin, the water table is much deeper (20 - 30 m). In each dairy, nitrate isotopes, water isotopes, nutrient concentrations, and other chemical and physical parameters were measured in monitoring wells located within different land use areas of the dairies. Monitoring wells were classified by the dairy-related land uses of corrals, fields receiving manure, waste lagoons, and mixed land use (undetermined). Across all sampled dairy-monitoring wells,  $\delta^{15}\text{N-NO}_3$  ranged from +2.9 to +49.4‰, and  $\delta^{18}\text{O-NO}_3$  ranged from -3.3 to +19.2‰. Mean nitrate concentrations, nitrogen isotopic composition, and oxygen isotopic composition were significantly higher in the northern (Stanislaus County) dairy wells in comparison to the southern (Kings and Tulare Counties) dairy wells. Nitrate isotope measurements indicated that many of the northern monitoring wells had consistently high contributions of manure-derived nitrate to the shallow groundwater during the 16-month study. Monitoring wells located in relatively new dairies in the south region showed little evidence of manure-derived nitrate, while those located in much older dairies in the south region showed a very wide range of nitrate isotope values, indicating significant nitrate contributions from multiple sources including manure and industrial fertilizer and biological processing effects. Combined nitrate concentration and isotopic data from all the monitoring wells showed very little evidence of significant saturated-zone denitrification. Monitoring well networks within individual dairies showed wide ranges of nitrate concentrations, nitrate isotopic compositions, and geochemical compositions, confirming the heterogeneity of the nitrate loading across dairy facilities and indicating that measurements from any single monitoring well may not be representative of general groundwater quality down gradient of an individual dairy.

## **Implementing California's Sustainable Groundwater Management Act: Farmer Perceptions and the Balance of Groundwater and Economic Sustainability**

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Implementation of the California Sustainable Groundwater Management Act (SGMA) will require policy creation at the level of individual groundwater basins. This will require cooperative efforts between counties, municipalities, irrigation districts and others to fully represent the array of stakeholders reliant on groundwater resources. The goal of the work described in this presentation is to develop and apply a decision making framework that can be widely used to address the planning challenges local agencies will encounter during the implementation of the SGMA. With funding from the USDA National Institute of Food and Agriculture and a focus on a high priority groundwater basin in Yolo County, the objectives are (i) to understand farmer behavior in light of the SGMA, (ii) develop a shared mental model for the study area amongst stakeholders using quantitative models embedded within formal participatory processes, and (iii) to develop a program of outreach and communication to increase the impact and scalability of both process and outputs. The overall approach utilizes the principles of Robust Decision Making (RDM). Specific tools used in implementing RDM include integrated water resources and economic models that are developed and driven by a stakeholder process involving farmer surveys, focus groups and a stakeholder advisory committee. In this talk we will present an integrated water resources model that was built to respond to the participatory decision making process, an assessment of risk perception to new policy among farmers in Yolo County, and how this participatory decision making framework that utilizes innovative visualization of results can inform and influence the risk perception of farmers and water managers in the context of SGMA, by co-developing a shared mental model amongst diverse stakeholders.

## Freshwater Storage in Brackish-Saline Aquifers for Irrigation Water Supply: A Bottomless Pit or a Fountain of Gold?

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Aquifer storage and recovery (ASR) can be successful in storing and recovering freshwater via wells for irrigation water supply. It is attractive thanks to the limited space requirements above ground and the generally successful conservation during storage. However, the ASR recovery efficiency ('RE', the fraction of the injected water that can be recovered with a satisfying quality) can be limited in brackish-saline aquifers. This is due to the lower density of the injected fresh water with respect to the ambient brackish or saline groundwater, which causes early contamination with ambient groundwater at lower parts of the ASR well. Successful recovery remains unattainable and temporal freshwater surpluses are then injected in a 'bottomless pit'. However, recent advances in hydrological engineering allow mitigation of buoyancy effects and an increase of RE. In this way, ASR can offer a fountain of gold in water-stressed coastal areas, which typically have shallow brackish-saline groundwater and therefore a lack of suitable ASR target aquifers. To test the ability of the hydrological engineering solutions to improve RE, two dedicated ASR set-ups were recently implemented in coastal areas of The Netherlands. The first used low-cost, independently operated multiple partially penetrating wells (MPPW) in a single borehole. An extra 20-40% of the injected water could be recovered at MPPW-ASR systems storing greenhouse roof water in confined, brackish aquifers, thanks to preferential deep injection in the target aquifer and recovery at the aquifer's top. Interception of brackish water via the deepest well screen further increased the RE (10-20%). Detailed hydrochemical monitoring also highlighted relevant water quality changes occurring during MPPW-ASR, mainly a Na-enrichment due to cation exchange. Also, the deeper aquifer had a dominant impact on the final water quality due to the preferential deep injection and the geochemical composition of this interval. In the second set-up, horizontal directional-drilled wells (HDDWs) were implemented in an ASR-system for the first time. Two 70m long, superimposed, low-cost HDDWs were assembled in a 'Freshmaker' system to enlarge a shallow freshwater lens by simultaneous infiltration (shallow HDDW) in the lens, and deep abstraction of underlying saltwater (deep HDDW). In dry periods, the shallow HDDW was used for abstraction of freshwater from the lens, while the deep HDDW prevented upcoming of deep saltwater by continuation of the abstraction. A maximum yearly volume of around 6,000 m<sup>3</sup> of surface water could be successfully injected, followed by successful abstraction of an equal freshwater volume for irrigation at a fruit orchard. The presented innovative ASR set-ups were successfully tested in the horticultural sector to provide irrigation water. The estimated costs per m<sup>3</sup> are 0.3 to 1.5 US \$/m<sup>3</sup>, and can compete with the local (yet less sustainable) alternatives (piped water, brackish water desalination). In the freshwater management strategy of the National Delta-program, the innovative ASR solutions were therefore embraced to attain local 'self-reliance'.