Prepared in cooperation with East Tennessee Natural Gas and the
U.S. Fish and Wildlife Service

Continuous Turbidity Monitoring in the Indian Creek Watershed, Tazewell County, Virginia, 2006–08

Scientific Investigations Report 2009–5085

U.S. Department of the Interior
U.S. Geological Survey

Cover photograph. The water-quality monitoring station located on Indian Creek above Route 631 near Cedar Bluff, Virginia; view looking upstream.

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KEN SALAZAR, Secretary

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Conversion Factors and Vertical Datum

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
ounce, fluid (fl. oz)	0.02957	liter (L)
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Specific conductance is reported in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Water year is the 12-month period that extends from October 1 through September 30. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the year ending September 30, 2008, is called the 2008 water year.

Continuous Turbidity Monitoring in the Indian Creek Watershed, Tazewell County, Virginia, 2006–08

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Abstract

Thousands of miles of natural gas pipelines are installed annually in the United States. These pipelines commonly cross streams, rivers, and other water bodies during pipeline construction. A major concern associated with pipelines crossing water bodies is increased sediment loading and the subsequent impact to the ecology of the aquatic system. Several studies have investigated the techniques used to install pipelines across surface-water bodies and their effect on downstream suspended-sediment concentrations. These studies frequently employ the evaluation of suspended-sediment or turbidity data that were collected using discrete sample-collection methods. No studies, however, have evaluated the utility of continuous turbidity monitoring for identifying real-time sediment input and providing a robust dataset for the evaluation of long-term changes in suspended-sediment concentration as it relates to a pipeline crossing.

In 2006, the U.S. Geological Survey, in cooperation with East Tennessee Natural Gas and the U.S. Fish and Wildlife Service, began a study to monitor the effects of construction of the Jewell Ridge Lateral natural gas pipeline on turbidity conditions below pipeline crossings of Indian Creek and an unnamed tributary to Indian Creek, in Tazewell County, Virginia. The potential for increased sediment loading to Indian Creek is of major concern for watershed managers because Indian Creek is listed as one of Virginia's Threatened and Endangered Species Waters and contains critical habitat for two freshwater mussel species, purple bean (*Villosa perpurpurea*) and rough rabbitsfoot (*Quadrula cylindrical strigillata*). Additionally, Indian Creek contains the last known reproducing population of the tan riffleshell (*Epioblasma florentina walkeri*). Therefore, the objectives of the U.S. Geological Survey monitoring effort were to (1) develop a continuous turbidity monitoring network that attempted to measure real-time changes in suspended sediment (using turbidity as a surrogate) downstream from the pipeline crossings, and (2) provide continuous turbidity data that enable the development of a real-time turbidity-input warning system and assessment of long-term changes in turbidity conditions.

Water-quality conditions were assessed using continuous water-quality monitors deployed upstream and downstream from the pipeline crossings in Indian Creek and the unnamed tributary. These paired upstream and downstream monitors were outfitted with turbidity, pH (for Indian Creek only), specific-conductance, and water-temperature sensors. Water-quality data were collected continuously (every 15 minutes) during three phases of the pipeline construction: pre-construction, during construction, and post-construction. Continuous turbidity data were evaluated at various time steps to determine whether the construction of the pipeline crossings had an effect on downstream suspended-sediment conditions in Indian Creek and the unnamed tributary. These continuous turbidity data were analyzed in real time with the aid of a turbidity-input warning system. A warning occurred when turbidity values downstream from the pipeline were 6 Formazin Nephelometric Units or 15 percent (depending on the observed range) greater than turbidity upstream from the pipeline crossing. Statistical analyses also were performed on monthly and phase-of-construction turbidity data to determine if the pipeline crossing served as a long-term source of sediment.

Results of this intensive water-quality monitoring effort indicate that values of turbidity in Indian Creek increased significantly between the upstream and downstream water-quality monitors during the construction of the Jewell Ridge pipeline. The magnitude of the significant turbidity increase, however, was small (less than 2 Formazin Nephelometric Units). Patterns in the continuous turbidity data indicate that the actual pipeline crossing of Indian Creek had little influence of downstream water quality; conversely, these data indicate upland runoff from the construction right-of-way was the primary source of turbidity detected in Indian Creek. Results from the analysis of continuous turbidity data collected during the three construction phases from the unnamed tributary indicate that the pipeline crossing did not adversely alter long-term water-quality conditions. Turbidity data collected during the active construction of the pipeline crossing through the unnamed tributary indicate that short-term turbidity increases did occur downstream; however, these increases were shown to be minimal compared to the turbidity values measured during natural runoff events.

Introduction

Elevated suspended-sediment concentrations are of major concern for water-resource managers because of the potential adverse impact on living resources and streams, rivers, and estuaries (Lloyd and others, 1987; Ryan, 1991; Waters, 1995; Wood and Armitage, 1997). Suspended sediments are derived from natural processes of upland erosion, lateral movement of channels into streambanks, and downcutting of streambeds (Waters, 1995). Human activities such as agriculture, logging, mining, and urbanization, however, increase the rate of sediment loading to these aquatic systems through accelerated soil and stream-channel erosion (Ryan, 1991; Waters, 1995). Anthropogenically derived sediment often overwhelms the natural assimilative capacity and alters the structure and function of the aquatic ecosystem (Cairns, 1977). Elevated suspended-sediment concentrations may impair the growth of aquatic vegetation by reducing light levels, burying filter-feeding organisms, reducing habitat available for macroinvertebrates, and contributing to decreased fish populations (Lenat and others, 1981; Dennison and others, 1993; Box and Mossa, 1999; Madsen and others, 2001). An ancillary and often overlooked impact of these elevated sediment concentrations is the transport of particle-associated contaminants, such as bacteria, nutrients, and metals (Griscom and others, 2000; Christensen, 2001).

Thousands of miles of natural gas pipelines are installed annually in the United States (True, 1998; Tobin, 2003). Streams, rivers, and other water bodies are routinely crossed during pipeline construction. Pipeline construction can lead to increased sediment loading to aquatic systems through trench excavation and backfilling, erosion and runoff from adjacent upland worksites, and discharge of water from hydrostatic pipe testing or trench dewatering (Reid and others, 2004).

Three possible pipeline-crossing techniques are typically used when installing pipeline beneath streams, rivers, or other water bodies: open-cut wet crossing, open-cut dry crossing, and horizontal-directional drilling (HDD) (Zwirn, 2002). The open-cut wet crossing approach involves trenching, pipe installation, and backfilling in the open stream channel while streamflow continues; sediment and pollutant runoff can be severe (Zwirn, 2002). The open-cut dry crossing approach involves trenching, pipe installation, and backfilling in the open stream channel while streamflow is diverted using a pump or flume; sediment and pollutant runoff is considerably reduced because of the lack of streamflow to transport sediment (Zwirn, 2002). HDD involves drilling a small-diameter tunnel at least 5 feet beneath the stream channel and subsequently pulling the preassembled pipeline through the tunnel. The HDD method is the least disruptive to the ecological integrity of the associated aquatic ecosystem (Zwirn, 2002).

Several studies have evaluated the impact on the aquatic ecosystem associated with various pipeline-crossing techniques. Many of these studies found that the open-cut wet crossing method had the greatest impact to the aquatic ecosystem through increased sediment loading downstream from the pipeline crossing (Phillip and others, 1981; Young and Mackie, 1991; Reid and others, 2004). Reid and others (2002) found that the open-cut dry crossing method, using either dam and pump or flume crossing, had considerably less downstream transport of sediment compared to the wet-crossing method; the greatest impact was observed when the dam/flume was removed and stored sediment was mobilized. The HDD-crossing method has become the preferred method when crossing ecologically sensitive streams and rivers because of the lack of sediment mobilization; however, this crossing method is time-consuming and expensive (Reid and others, 2002; Lévesque and Dubé, 2007).

In 2005, East Tennessee Natural Gas filed an application with the Federal Energy Regulatory Commission (FERC) to install the Jewell Ridge Lateral natural gas pipeline in Smyth and Tazewell Counties in southwest Virginia. This 32-mile, 20-inch-diameter pipeline would connect the East Tennessee Natural Gas mainline to CNX Gas Company LLC’s existing Cardinal States Gathering System (fig. 1). As part of the FERC permitting process, a Biological Opinion was prepared by the U.S. Fish and Wildlife Service (USFWS) to determine the effects of the Jewell Ridge pipeline on federally listed species and federally designated critical habitat (U.S. Fish and Wildlife Service, 2006). The USFWS determined that 45 water bodies would be crossed by the Jewell Ridge pipeline. Of these 45 water bodies, 4 are listed as State-designated Threatened and Endangered Species Waters because of documented occurrences of federally and State-listed endangered freshwater mussel species and (or) federally designated critical habitat for freshwater mussels. Although the Jewell Ridge pipeline will cross three other Threatened and Endangered Species Waters, Indian Creek was selected by the USFWS for intensive monitoring as a tool to help protect the critically endangered mussels or their required habitat. The USFWS requested that intensive turbidity and macroinvertebrate monitoring be performed prior to, during, and after pipeline crossing.

The USFWS was concerned about the Jewell Ridge pipeline construction because Indian Creek is listed as one of the Virginia Department of Game and Inland Fisheries’ designated Threatened and Endangered Species Waters and contains federally designated critical habitat for two endangered freshwater mussel species, purple bean (*Villosa perpurpurea*) and rough rabbitsfoot (*Quadrula cylindrical strigillata*), and the last known reproducing population of the tan riffleshell (*Epioblasma florentina walkeri*). The purple bean, rough rabbitsfoot, and tan riffleshell are filter-feeding mussels that feed on algae and other microorganisms suspended in the water column. These mussels require relatively silt-free substrate for survival. The USFWS in accordance with Section 7 of the Endangered Species Act (ESA) of 1973 (87 Stat. 884, as amended; 16 U.S.C. 1531 et seq.) requested “sound and reasonable monitoring” to document potential water-quality impacts. The primary impact of concern is that instream suspended-sediment concentrations, due to pipeline-related construction activities, could be detrimental to the quality of the habitat required by these threatened and endangered species.

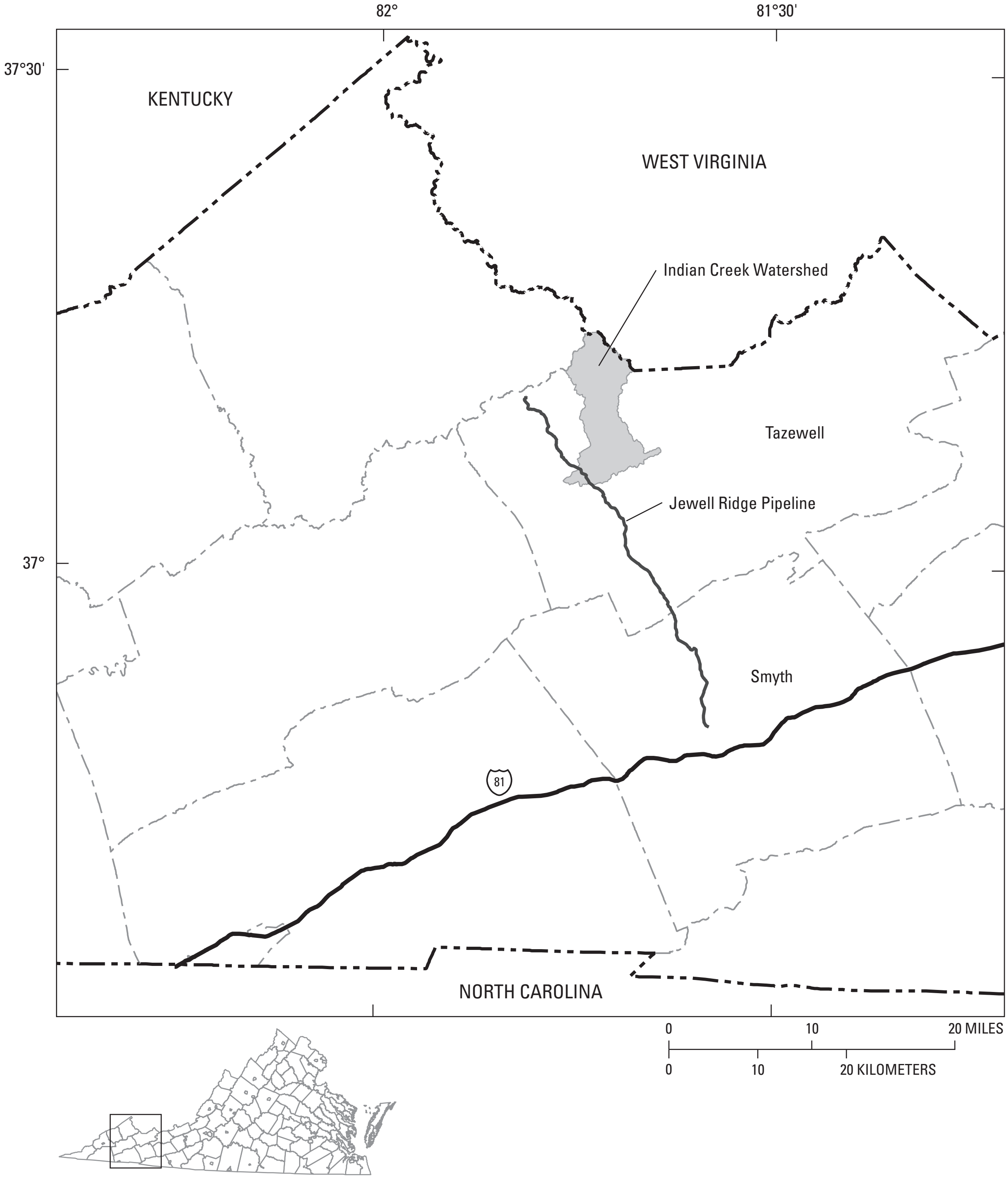

Figure 1. The Jewell Ridge Lateral natural gas pipeline, Virginia.

In 2006, the U.S. Geological Survey (USGS), in cooperation with East Tennessee Natural Gas and the U.S. Fish and Wildlife Service, began a study to monitor water-quality conditions in Indian Creek and an unnamed tributary to Indian Creek. Turbidity, a well-documented surrogate for fine suspended sediment (Christensen, 2001), was the primary water-quality property to be monitored prior to, during, and after construction of the pipeline crossing of Indian Creek and the unnamed tributary to Indian Creek. The primary objective of the USGS monitoring effort was to identify whether the construction of the Indian Creek pipeline crossing would adversely impact the suspended-sediment concentrations in Indian Creek. The specific study objectives were to (1) develop a continuous turbidity monitoring network that attempted to measure real-time changes in suspended-sediment conditions (using turbidity as a surrogate) downstream from the pipeline crossing in Indian Creek and the unnamed tributary to Indian Creek, and (2) provide continuous turbidity data that allow for the development of a turbidity-input warning system and assessment of long-term changes in turbidity conditions.

Purpose and Scope

This report describes monitored turbidity conditions in Indian Creek and an unnamed tributary to Indian Creek prior to, during, and after construction of the Jewell Ridge Lateral natural gas pipeline crossing. Turbidity values were collected every 15 minutes upstream and downstream from the pipeline crossing in Indian Creek and an unnamed tributary to Indian Creek from April 2006 to April 2008. This report also describes the methods of collection and the results of using these continuous turbidity data as a near real-time and long-term indicator of elevated suspended sediment downstream from the pipeline crossings. This information will provide East Tennessee Natural Gas and USFWS with information on the influence of the Jewell Ridge Lateral natural gas pipeline crossings on instream turbidity conditions.

Description of Study Area

The Indian Creek watershed is located in Tazewell County, in southwest Virginia (fig. 1). The headwaters of Indian Creek originate in the primarily forested northernmost part of Tazewell County. Indian Creek flows to the southwest, where it joins the Clinch River near Cedar Bluff, Virginia (fig. 2). The Clinch River, which is known for its biodiversity and large number of imperiled species, flows southwest where it joins the Tennessee River and ultimately, the Mississippi River. Indian Creek has a drainage area of 33.9 square miles and is composed of forest (78.5 percent), agricultural (13.9 percent), and residential (7.6 percent) land use.

Indian Creek lies within the Appalachian Plateaus Physiographic Province, which is a narrow chain of westward-facing folded mountains that extend from southwestern Virginia to central New York (Fenneman, 1938). The Appalachian Plateaus consist of the Allegheny Plateau and the Cumberland Plateau. The Cumberland Plateau is the dominant physiographic feature in the Indian Creek watershed. The underlying geology in the Appalachian Plateaus is dominated by shale, sandstone, and coal (Fenneman, 1938). Extensive erosion has resulted in topography consisting of steep slopes and narrow ridges and valleys (Hayes, 1991; Woods and others, 1999).

Jewell Ridge Pipeline Construction

The Jewell Ridge pipeline was brought into the Indian Creek watershed by employing overland- and stream-channel crossing methods in accordance with Federal regulations and guidelines. The overland pipeline construction required the creation of a 100-foot-wide construction right-of-way (ROW). The ROW measured 65 feet on the working side and 35 feet on the spoil side. The overland-pipeline construction method involved installing the pipeline as a moving assembly line with activities that proceeded in the following sequence: surveying and flagging of the ROW, clearing and grading, trenching, stringing and bending, welding, lowering-in, backfilling, hydrostatic testing, cleanup and restoration, and post-construction monitoring. Erosion- and sediment-control measures were employed along the entire length of the ROW.

Two stream-channel crossing techniques were utilized in the Indian Creek watershed. Indian Creek was crossed using HDD. This method allows for the installation of pipelines beneath roadways, railroads, and streams to minimize the potential impact of elevated sediment loading to the threatened and endangered mussel species and their associated habitat. The HDD method allowed for the installation of the pipeline more than 5 feet below the channel bottom of Indian Creek. The Indian Creek pipeline crossing is approximately 1.6 miles east-northeast of Cedar Bluff, Virginia, and is approximately 1,100 feet upstream from Route 631 (fig. 2). The borehole under Indian Creek was continually dewatered during the boring process. The water and associated constituents were captured and stored in settling tanks on site. Once the particles settled from suspension, the captured water was returned to Indian Creek. Impacts to vegetative cover on both streambanks were minimized by leaving a 50-foot buffer on the south bank and a 35-foot buffer on the north bank of undisturbed vegetation.

The pipeline route also crossed an unnamed tributary (fig. 2), which flows into Indian Creek downstream from the Route 631 bridge, but still upstream from several of the critical mussel populations residing on the main stem of Indian Creek. The open-cut dam and flume dry-crossing method was used to install the pipeline across the unnamed tributary because no critical mussel habitat exists at or immediately downstream from the unnamed tributary crossing. This technique isolates flow from the construction area while the pipeline is installed in the dry channel. The dry channel is trenched so that the pipeline is installed at a minimum of 5 feet beneath the active channel.

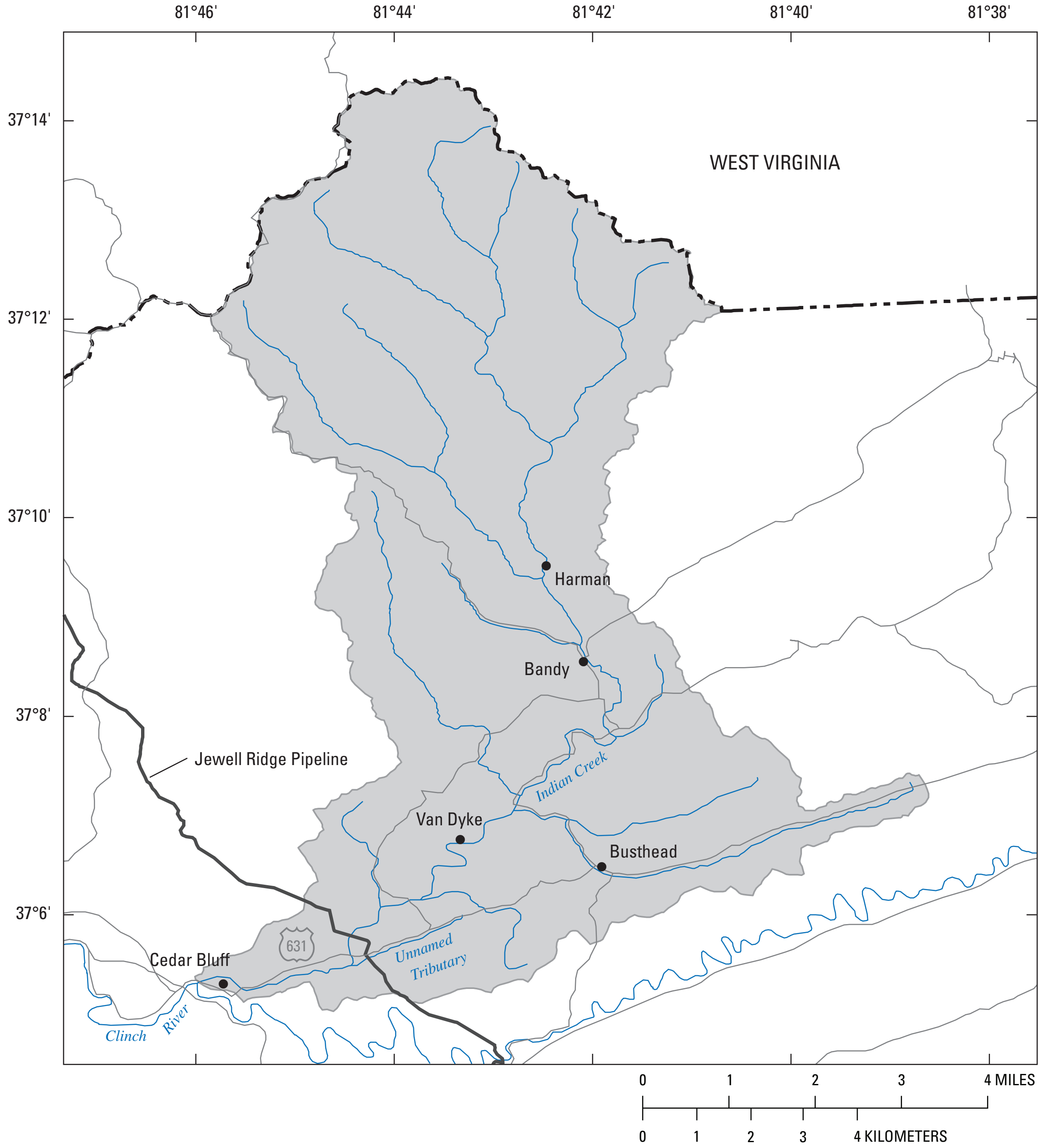

Figure 2. The Indian Creek watershed, Tazewell County, Virginia.

Methods of Investigation

In most streams, suspended sediments are generally transported during stormflow periods (Wolman and Miller, 1960), while rainfall-induced surface-runoff processes are active; however, during these runoff periods, the fewest suspended-sediment data are generally collected. One promising new technology for improved suspended-sediment determination involves the continuous monitoring of turbidity, using an in-situ sensor, as a surrogate for suspended-sediment concentrations. Turbidity measurements are usually well correlated to suspended-sediment concentrations; because turbidity represents an optical measure of water clarity, the presence of suspended sediment directly influences this measurement of clarity. Using turbidity values as a surrogate for suspended-sediment concentration is not new, but until recently, technological limitations have made this approach largely unusable. Walling (1977) described this surrogate approach using turbidity. The development of continuous turbidity records has gradually become more feasible because of technical improvements to in-situ water-quality sensors and improved telecommunications equipment. Continuous turbidity measurement has now become a more common field approach because it provides substantially more detailed and more accurate information on suspended-sediment concentrations than previously possible.

Continuous Water-Quality Monitor Installation

The continuous water-quality monitoring network was designed to detect sediment inputs, as indicated by turbidity, directly associated with the construction and pipeline crossing activities on Indian Creek and the unnamed tributary while also minimizing the chance of detecting sediment inputs unrelated to the pipeline construction. Therefore, a paired upstream-downstream design was implemented around the Indian Creek and unnamed tributary pipeline crossings (fig. 3).

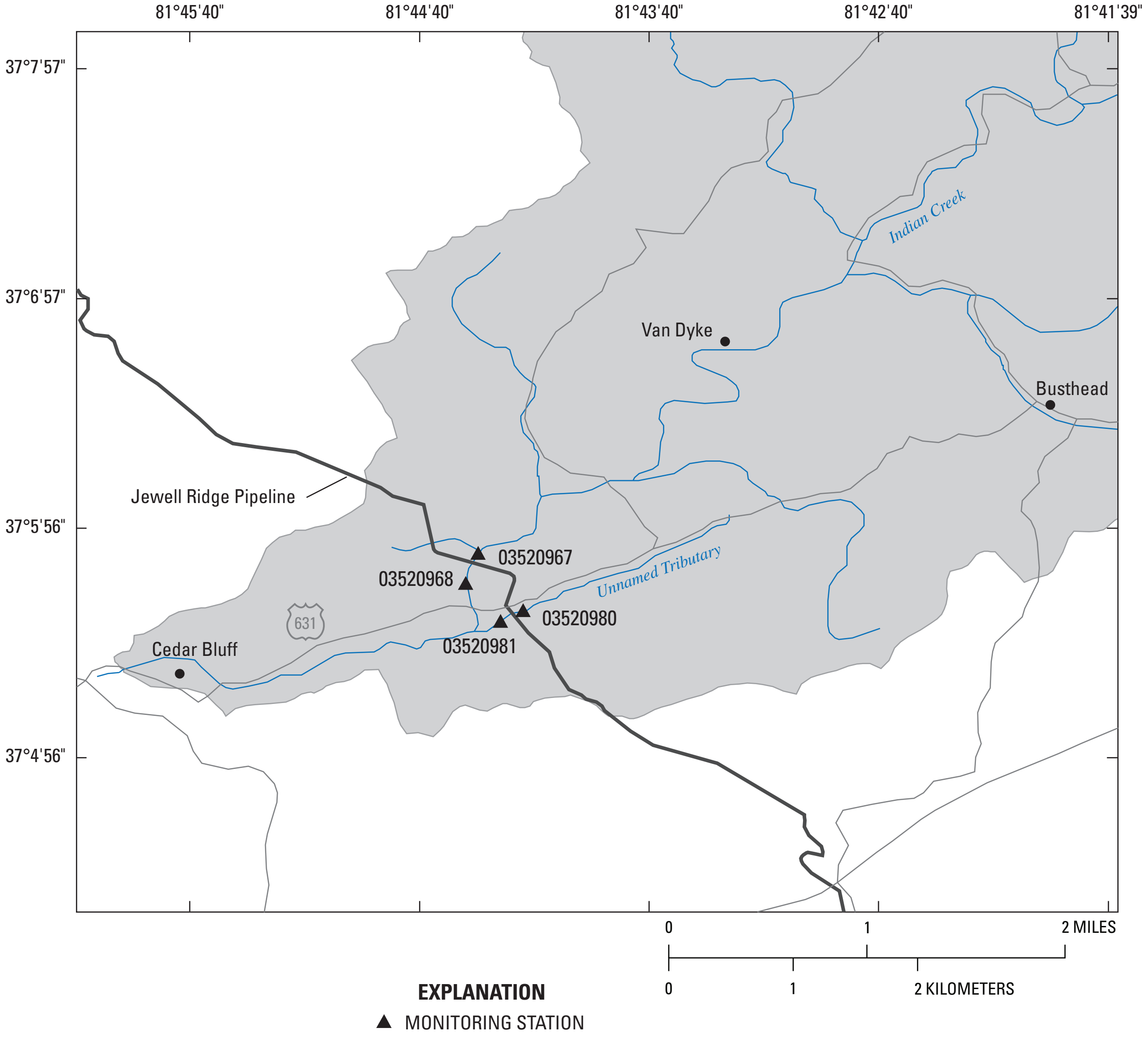

Figure 3. The Indian Creek and unnamed tributary monitoring network, Tazewell County, Virginia.

An additional water-quality-monitoring concern in Indian Creek was incomplete water-column mixing in the monitoring reach. To address this concern, two additional monitors were added so that the paired upstream and downstream monitors consisted of a near left-bank and near right-bank design. The use of dual upstream monitors located off each bank of the stream is appropriate for two reasons. First, the use of monitors located only a short distance off the streambank provided a dataset that was directly comparable to the dataset from the downstream monitors and used to determine how conditions change within the monitoring reach. Secondly, an ephemeral unnamed tributary to Indian Creek is located approximately 350 feet above the pipeline crossing; the potential sediment contributions from this unnamed tributary needed to be documented to ensure that the potential sediment contributions were not erroneously interpreted as sediment inputs from the pipeline crossing. The monitoring stations on both Indian Creek and the unnamed tributary were instrumented and activated 1 month prior to the initiation of the Jewell Ridge pipeline construction within the Indian Creek watershed. The monitoring allowed for the establishment of a brief baseline understanding of the differences in turbidity levels upstream and downstream from the pipeline crossings.

Indian Creek Network

The effect of the Indian Creek pipeline crossing on water-quality conditions was monitored by four continuous water-quality monitors installed pair-wise upstream and downstream from the pipeline crossing. Two monitors were installed 120 feet upstream (USGS station 03520967) from the pipeline crossing (fig. 3). These two upstream monitors were suspended from a boom so that one monitor was submersed 10 feet from the left bank and the second monitor was submersed 10 feet from the right bank (fig. 4*A*, table 1). The remaining two monitors were suspended from a boom 200 feet downstream (USGS station 03520968) from the pipeline crossing so that one monitor was submersed 10 feet from the left bank and the second monitor was submersed 10 feet from the right bank (fig. 4*B*, table 1). Each Indian Creek monitoring station was instrumented with a YSI Inc. Model 6920 multi-parameter sonde, which was outfitted with turbidity, pH, specific-conductance, and water-temperature sensors, and values for each of these water-quality properties were collected every 15 minutes. The water-quality values were stored and subsequently transmitted hourly using a Sutron SatLink2 GOES Satellite Transmitter and Logger. The hourly transmitted data were stored in and subsequently made publicly available via the USGS National Water Information System (NWIS) at *http://waterdata.usgs.gov/va/nwis*.

Unnamed Tributary Network

The effect of the unnamed tributary pipeline crossing on water-quality conditions was monitored by two continuous water-quality monitors installed upstream (USGS station 03520980) and downstream (USGS station 03520981) from the crossing (fig. 3). The upstream monitor was located approximately 100 feet above the pipeline crossing whereas the downstream monitor was located approximately 65 feet below the pipeline crossing (fig. 5, table 1). Each monitoring station was instrumented with a YSI Inc. Model 600 multi-parameter sonde. The YSI Inc. Model 600 multi-parameter sonde, which has a smaller diameter than the Model 6920 multi-parameter sonde, was selected for the unnamed tributary because of the shallow surface-water depths encountered. Each sonde was outfitted with turbidity, specific-conductance, water-temperature, and water-level sensors. Values for each of these constituents were collected every 15 minutes and then stored and subsequently transmitted hourly using a Sutron SatLink2 GOES Satellite Transmitter and Logger. These hourly transmitted data were stored in and subsequently made publicly available via NWIS at *http://waterdata.usgs.gov/va/nwis.*

Table 1. Water-quality monitoring stations, Indian Creek and unnamed tributary, Tazewell County, Virginia.

Station number	Station name	Latitude Longitude	Left- and right-bank water-quality monitors deployed
03520967	Indian Creek near Cedar Bluff, Va.	37°05'47" 81°44'27"	Yes
03520968	Indian Creek above Rt. 631 near Cedar Bluff, Va.	37°05'42" 81°44'28"	Yes
03520980	Indian Creek Tributary along Rt. 631 near Cedar Bluff, Va.	37°05'35" 81°44'13"	No
03520981	Indian Creek Tributary above mouth nr Cedar Bluff, Va.	37°05'32" 81°44'19"	No

Figure 4. Indian Creek water-quality monitoring stations located (*A*) upstream (Station number 03520967) and (*B*) downstream (Station number 03520968) from the Jewell Ridge Lateral natural gas pipeline crossing, Tazewell County, Virginia.

Figure 5. Water-quality monitors located on the unnamed tributary to Indian Creek, Tazewell County, Virginia. The monitoring station located in the foreground is the downstream monitor (Station number 03520980). The monitoring station in the background is the upstream monitor (Station number 03520981).

Continuous Water-Quality Monitor Maintenance

Approximately every 4 weeks, the water-quality monitors were serviced in the field to clean the equipment, evaluate the quality of the data being collected, and recalibrate the instrument (if necessary). This monitor servicing was performed using the methods described in the USGS guidelines for the operation and maintenance of continuous monitors (Wagner and others, 2000). A summary of the maintenance steps is presented here. In all cases, water-quality properties were measured before and after the instrument was cleaned of any algae or biofilm that may have developed. The differences before and after cleaning were used to evaluate whether the data needed to be corrected for instrument fouling. Following the fouling check, the calibration for pH, specific conductance, and turbidity were all checked using known standards. Discrepancies between the known values of the standards and the readings from the individual sondes were used to determine whether the data needed to be corrected for a drift in instrument calibration. Following the fouling and calibration checks, the instrument was re-calibrated if any of the measured water-quality properties were out of instrument tolerance (Wagner and others, 2000). Upon returning to the office from the field-maintenance visit, any necessary data corrections were applied to the data record and the data on the NWIS Web site were updated.

In addition to the monthly monitor maintenance, the entire water-quality record for each measured water-quality property was reviewed and finalized at the end of each water year. This annual review evaluated all the fouling and calibration drift checks, and screened the data for anomalous values, before the quality of the record was rated (either as excellent, good, fair, or poor). These ratings were determined on the basis of the corrections that had been applied to the record, and the criteria used for the ratings were those provided by Wagner and others (2000).

Continuous Stream Gage Operation

A standard USGS stream gage was installed, following established USGS procedures (Buchanan and Somers, 1968), at the upstream Indian Creek monitoring site (USGS station 03520967) (fig. 3) in October 2006 and maintained through April 2008 (table 1). Indian Creek water levels were measured at 15-minute intervals using a Keller-Pressure Systems, Incorporated (KPSI) pressure transducer. These water-level (stage) data were stored and subsequently transmitted hourly using a Sutron SatLink2 GOES Satellite Transmitter and Logger. The hourly transmitted data were stored in and subsequently made publicly available via NWIS at *http://waterdata.usgs.gov/va/nwis*. Stream discharge was measured routinely, during a variety of streamflow conditions, to establish a stage-discharge rating for Indian Creek. This stage-discharge rating was used to calculate stream discharge for each 15-minute interval of measured stage.

Data Analysis

The primary objective of the USGS monitoring effort was to identify whether the construction of the pipeline crossings would adversely impact the sediment-water quality in Indian Creek and the unnamed tributary. The specific study objectives were to (1) develop a continuous turbidity monitoring network that attempted to measure real-time changes in suspended-sediment conditions (using turbidity as a surrogate) downstream from the pipeline crossing in Indian Creek and the unnamed tributary to Indian Creek, and (2) provide continuous turbidity data that allow for the development of a turbidity-input warning system and assessment of long-term changes in turbidity conditions. The following sections document the approach that was used to monitor and evaluate water-quality conditions.

Continuous Water-Quality Data Collection

Turbidity, water temperature, specific conductance, and pH measurements were collected at the four water-quality monitoring stations on Indian Creek, and turbidity, water temperature, specific conductance, and water levels were collected at the two water-quality monitoring stations on the unnamed tributary. The primary objective for collecting these water-quality data was to enable East Tennessee Natural Gas, the USFWS, and the USGS to detect changes in water-quality conditions, more specifically sediment-water quality, immediately downstream from the pipeline crossings. These water-quality properties were collected during three phases of the pipeline construction: pre-construction, during construction, and post-construction. The time periods for these three phases were:

1. Pre-construction—April 28, 2006, through May 31, 2006;
2. Construction—June 1, 2006, through August 31, 2006; and
3. Post-construction—September 1, 2006, through April 9, 2008.

These data were essential for determining whether the construction of the Jewell Ridge pipeline crossing altered the short-term and long-term water quality in Indian Creek and the unnamed tributary.

Assessment of Long-Term Turbidity Patterns

The objective of the long-term water-quality assessment was to determine the influence of the pipeline crossing on downstream suspended-sediment conditions (using turbidity as a surrogate for suspended sediment) in Indian Creek and the unnamed tributary. Statistical analysis of the paired differences of the continuously collected upstream and downstream turbidity data is the most direct approach to determine whether turbidity conditions are changing downstream from the pipeline crossing. A signed-rank test (Helsel and Hirsch, 1992) was selected to test the null hypothesis for Indian Creek and the unnamed tributary. The signed-rank test was performed on the paired differences obtained from the following Indian Creek paired monitors: upstream minus downstream left bank (USLB and DSLB, respectively); upstream minus downstream right bank (USRB and DSRB, respectively); and upstream minus downstream monitors in the unnamed tributary (USTR and DSTR, respectively). The null hypothesis associated with an analysis of paired differences is that the median paired difference is equal to zero. This null hypothesis is true when the number of positive paired differences (upstream turbidity is greater than downstream turbidity) is approximately equal to the negative paired differences (upstream turbidity is less than downstream turbidity). The alternative hypothesis is that the median paired difference value is not equal to zero. A test was considered statistically different if the p-value was less than 0.05. These paired differences were calculated for each of the three time periods (pre-construction, construction, and post-construction).

In addition to the statistical analysis of paired differences, graphical presentations of turbidity data were used to visually determine differences between upstream and downstream values of turbidity. Monthly boxplots of paired differences, obtained from the upstream, right-bank, and left-bank monitors on Indian Creek and the upstream and downstream monitors on the unnamed tributary, were used to determine if the variability within the monthly paired differences was associated with the phase of pipeline construction. Each boxplot shows the distribution of the monthly paired differences by identifying the 10th, 25th, 50th, 75th, and 90th percentiles, where each percentile represents the percentage of samples that reside below that designated value. If the median (50th percentile) turbidity paired difference is 1.0 Formazin Nephelometric Units (FNU), for example, then 50 percent of monthly paired differences are greater than 1.0 FNU and 50 percent of the monthly paired differences are less than 1.0 FNU. Exceedance plots also were used to identify differences in turbidity conditions upstream and downstream from the pipeline crossing. Exceedance plots are similar to boxplots because they are used to relate a given turbidity value to the frequency of occurrence. The shape of the exceedance plot, however, can assist in identifying processes that may be controlling turbidity in Indian Creek and the unnamed tributary. For example, exceedance plots for the pre-construction turbidity values collected at the USLB (red line) and the USRB (blue line) monitor are shown in figure 6. These plots show that the USLB and USRB turbidity values have similar distributions with similar medians (50th percentile) of 3.0 and 3.2 FNU, respectively. The black line represents a hypothetical condition obtained by doubling all turbidity values collected at the USRB monitor, which shows that increases in turbidity cause the exceedance plot to shift to the right.

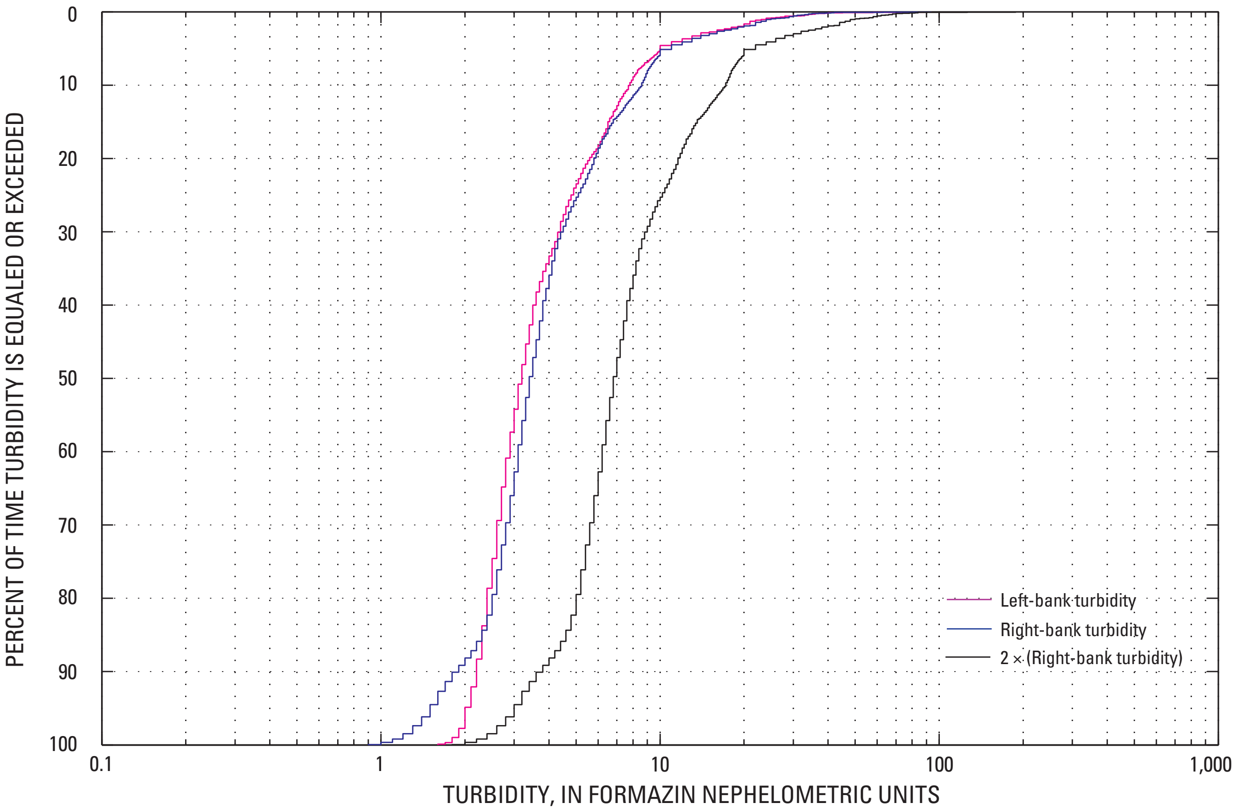

Figure 6. Exceedance plots for left-bank and right-bank turbidity collected at the upstream Indian Creek water-quality monitor (Station number 03520967) Tazewell County, Virginia. The black line represents the right-bank turbidity values multiplied by 2.

Turbidity-Input Warning System

The ability to detect real-time sediment input (using turbidity as a surrogate) downstream from the Indian Creek and unnamed tributary pipeline crossings was a primary requirement of the USFWS Biological Opinion (U.S. Fish and Wildlife Service, 2006). East Tennessee Natural Gas developed a real-time turbidity-input warning system in order to ensure that the water-quality requirement established by the USFWS was met. The thresholds for detecting changes in turbidity downstream from the pipeline crossing were:

1. For turbidity values less than 40 FNU, a 6-FNU increase in turbidity detected downstream from the pipeline crossing, relative to the associated turbidity value upstream from the pipeline crossing, sustained for no less than 1 hour, or

2. For turbidity values greater than or equal to 40 FNU, a 15-percent increase in turbidity detected downstream from the pipeline crossing, relative to the associated turbidity value upstream from the pipeline crossing, sustained for no less than 1 hour.

The real-time turbidity-input warning system used continuous turbidity data collected by the USGS at the paired upstream and downstream monitors on Indian Creek and the unnamed tributary. Turbidity data were collected every 15 minutes and transmitted hourly to the USGS NWIS Web site. East Tennessee Natural Gas automatically retrieved these turbidity data and compared them to the established thresholds. If a threshold was violated for four consecutive turbidity observations (1 hour), then the on-site manager, overseeing the pipeline construction, received a warning that a potential sediment input was detected downstream from the pipeline crossing. The on-site manager was required to (1) investigate the cause of the threshold exceedence, (2) document whether instream turbidity (sediment derived from the pipeline crossing construction) was the cause of the threshold exceedence, and (3) cease construction activities until the sediment input was corrected. This warning system also was subject to false-positive warnings. A false-positive warning is one that is not caused by sediment input from the pipeline crossing but is caused by a variety of sources that include: instream debris such as leaves and trash that get caught on the downstream turbidity probe; bio-fouling on the downstream turbidity probe; or mechanical malfunction of the downstream turbidity probe.

Water-Quality Patterns in Indian Creek and the Unnamed Tributary

Water-quality data collected during pre-construction, construction, and post-construction phases of the pipeline crossings beneath Indian Creek and through an unnamed tributary are summarized in table 2. Water-quality data include the median and the range (minimum and maximum) for turbidity, pH, specific conductance, and water temperature collected during the three phases of construction. Median values of pH ranged from 8.0 to 9.4 during the duration of the study. The highest median pH values occurred during the construction phase at both the Indian Creek left-bank and right-bank downstream monitors 9.4 and 8.4, respectively. Median values of specific conductance observed in Indian Creek ranged from 198 to 244 microsiemens per centimeter (µS/cm) whereas median values of specific conductance observed in the unnamed tributary ranged from 394 to 499 µS/cm. Specific-conductance values in the unnamed tributary were typically double the values observed in Indian Creek. Water temperature was similar in Indian Creek and the unnamed tributary and reflected the phase of construction during which temperature was measured. The highest water-temperature values were observed during the construction period, for example, which took place during the summer months. Time-series plots for pH, specific conductance, and water temperature collected from Indian Creek and specific conductance and water temperature collected from the unnamed tributary are provided for each monitoring station in Appendixes 1 through 6.

Indian Creek Streamflow

Continuous streamflow data were collected from Indian Creek at the upstream monitoring station (USGS station 03520967) from October 2006 through April 2008 (fig. 7). Given the October 2006 start date, streamflow data were only available during the post-construction phase of the study. Monthly summary statistics for streamflow conditions in Indian Creek, which include the minimum, 25th percentile, median, 75th percentile, and maximum, are presented in table 3. Monthly median values of streamflow in Indian Creek ranged from 0.39 to 61.66 cubic feet per second (ft^3/s) in October 2007 and April 2008, respectively. The extensive drought that affected much of southeastern and mid-Atlantic United States is evident in the Indian Creek streamflow data, with diminished values of streamflow measured from July 2007 through January 2008.

Table 2. Statistical summaries of water-quality data collected at Indian Creek and unnamed tributary water-quality monitoring stations during pre-construction, construction, and post-construction of the Jewell Ridge Lateral natural gas pipeline, Tazewell County, Virginia.

[Values presented are the median and range (minimum and maximum) for each construction period; FNU, Formazin Nephelometric Units; µS/cm at 25 ºC, microsiemens per centimeter at 25 degrees Celsius; ºC, degrees Celsius; US, upstream; DS, downstream; —, no data]

	Turbidity, FNU	pH, standard units	Specific conductance, µS/cm at 25 ºC	Water temperature, ºC
Indian Creek, Pre-Construction				
US left bank	3.2	8.1	198	13.9
	(1.6–94)	(7.8–9.1)	(146–231)	(9.8–24.1)
US right bank	3.0	8.1	202	13.0
	(1.4–89)	(7.8–9.0)	(146–236)	(9.9–23.0)
DS left bank	3.4	8.2	199	13.9
	(0.9 – 94)	(7.9 – 9.2)	(144–240)	(9.8–24.0)
DS right bank	3.6	8.1	200	13.0
	(1.8–86)	(7.7–9.0)	(146–233)	(9.8–23.0)
Unnamed Tributary, Pre-Construction Period				
US	13.0	—	394	13.1
	(0.1–1,060)		(229–475)	(9.0–24.1)
DS	14.0	—	401	13.2
	(3.4–1,130)		(250–467)	(9.0–25.0)
Indian Creek, Construction Period				
US left bank	4.0	8.1	228	20.0
	(1.8–540)	(7.7–8.8)	(93–335)	(13.8–26.2)
US right bank	3.9	8.1	231	20.8
	(1.4–440)	(7.6–8.7)	(77–331)	(13.0–25.0)
DS left bank	5.5	9.4	228	20.7
	(1.8–300)	(7.9–10.2)	(83–333)	(13.8–26.0)
DS right bank	4.5	8.4	231	20.0
	(1.3–290)	(7.8–9.1)	(80–336)	(13.0–26.2)
Unnamed Tributary, Construction Period				
US	11.0	—	499	19.2
	(4.0–1,250)		(161–556)	(12.2–26.2)
DS	8.3	—	487	19.4
	(1.5–1,290)		(178–537)	(12.3–26.6)
Indian Creek, Post-Construction Period				
US left bank	2.7	8.0	240	10.5
	(0.0–970)	(6.8–9.3)	(26–441)	(0.1–26.3)
US right bank	2.6	8.1	239	10.5
	(0.1–1030)	(6.6–9.5)	(84–437)	(0.2–26.1)
DS left bank	2.5	8.1	239	10.5
	(0.0–740)	(6.2–10.6)	(83–445)	(0.1–27.2)
DS right bank	2.7	8.1	244	10.4
	(0.1–720)	(7.3–9.4)	(54–439)	(0.1–27.2)
Unnamed Tributary, Post-Construction Period				
US	10.0	—	472	10.5
	(0.4–2,340)		(188–905)	(0.1–25.6)
DS	9.9	—	471	10.5
	(0.4–1,780)		(188–862)	(0.1–26.4)

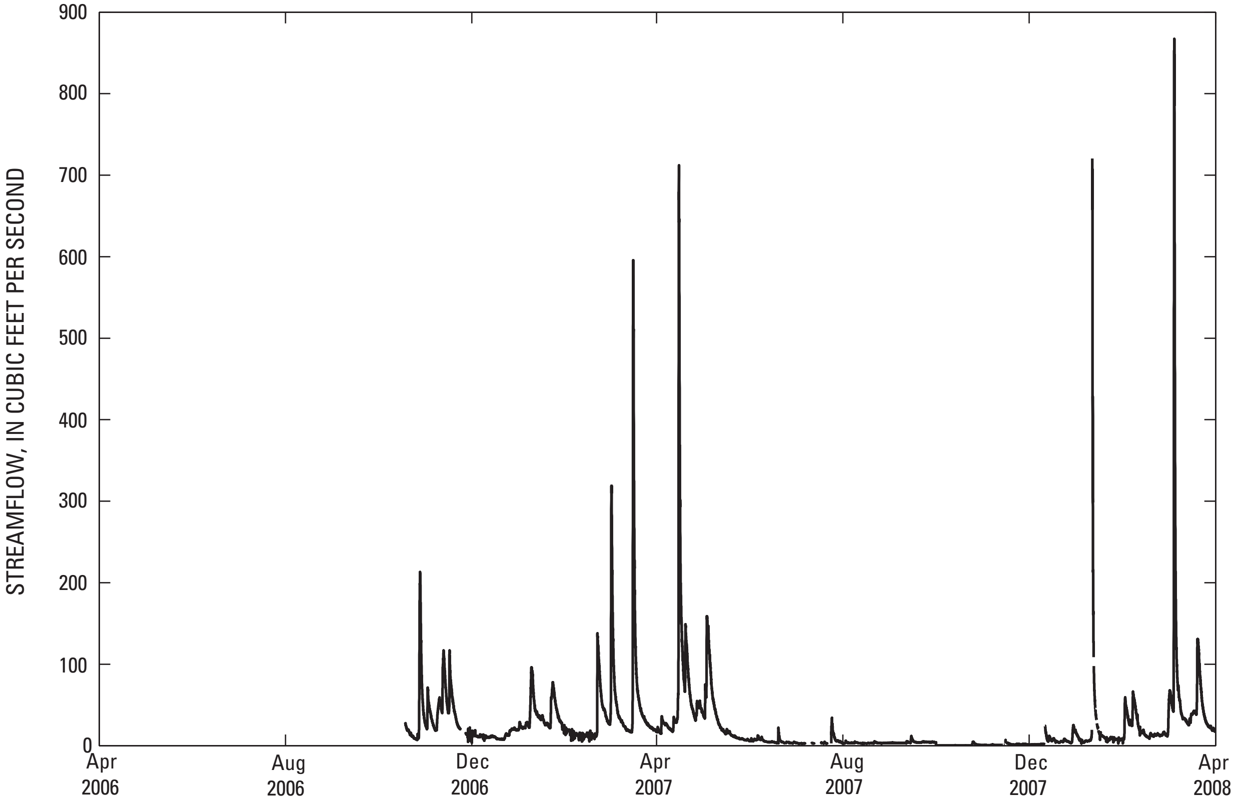

Figure 7. Computed unit values (15-minute) of streamflow collected from Indian Creek near Cedar Bluff, Virginia (Station number 03520967).

Table 3. Statistical summaries of monthly streamflow conditions in Indian Creek near Cedar Bluff, Virginia (Station number 03520967).

[Streamflow is in cubic feet per second]

Date (month/year)	Minimum	25th Percentile	Median	75th Percentile	Maximum
10/2006	7.25	10.00	18.38	32.53	213.10
11/2006	4.73	22.33	39.90	53.81	116.82
12/2006	3.70	10.00	11.81	14.34	22.33
1/2007	13.29	23.75	29.97	42.69	96.23
2/2007	5.01	11.34	14.34	29.97	137.86
3/2007	16.57	22.33	29.97	53.81	595.51
4/2007	14.88	25.23	37.08	66.42	711.91
5/2007	5.60	9.57	17.16	39.00	158.90
6/2007	2.80	3.95	4.73	7.25	22.33
7/2007	2.80	3.01	3.70	5.91	34.31
8/2007	2.80	3.01	3.23	3.46	6.23
9/2007	2.80	3.46	3.95	4.46	11.81
10/2007	0.23	0.33	0.39	0.64	4.96
11/2007	0.53	0.97	1.32	1.90	6.84
12/2007	1.20	1.90	4.96	7.55	25.17
1/2008	3.00	6.17	7.92	11.27	720.34
2/2008	7.55	12.71	14.26	28.29	66.42
3/2008	17.69	28.29	39.00	59.36	867.04
4/2008	14.26	17.69	61.66	102.32	561.61

Instream Turbidity Conditions

Turbidity was the primary water-quality property used to determine if instream water-quality conditions were altered as a result of the Jewell Ridge pipeline crossing beneath Indian Creek and through the unnamed tributary. Turbidity data were collected from each of the six water-quality monitors deployed in Indian Creek and the unnamed tributary and were used to evaluate instream water-quality conditions at various time spans that included: (1) full period of record; (2) the three phases of construction; (3) monthly; and (4) hourly. Results from all time spans were used to formulate a conceptual model for turbidity patterns observed in Indian Creek.

Turbidity values collected during the nearly 24-month period from Indian Creek showed four periods of elevated turbidity: June 2006 through July 2006; September 2006 through November 2006; April 2007 through July 2007; and February 2008 through March 2008 (figs. 8 and 9). These elevated turbidity periods were primarily related to periods of wet weather and increased streamflow, and are fairly consistent between the paired upstream and downstream monitors as well as the left-bank and right-bank monitors. The elevated turbidity observed during March and April 2007, for example, corresponded with the increased streamflow that was measured in Indian Creek during this same period (fig. 7).

Patterns of turbidity measured in the unnamed tributary were much more variable during the 24-month monitoring period (fig. 10), compared with the patterns of turbidity measured in Indian Creek. Turbidity values, measured in the unnamed tributary, were routinely at 1,000 FNU at both the upstream and downstream monitors (fig. 10). Turbidity values measured in the unnamed tributary were two to four times greater than turbidity values measured in Indian Creek (table 2). Turbidity in the unnamed tributary seems to be influenced by other watershed factors, in addition to streamflow, which may potentially include unregulated discharges from local residential and commercial properties as well as the local community working in and around this tributary.

Long-Term Patterns of Turbidity in Indian Creek and the Unnamed Tributary

Exeedance plots were used to graphically compare the turbidity values measured during the pre-construction, construction, and post-construction phases of the pipeline crossing beneath Indian Creek and through the unnamed tributary. Exceedance plots show integrated turbidity data, collected during each phase of construction, as a function of the frequency of occurrence. Indian Creek turbidity values, collected during the three phases of construction, are shown in figures 11 and 12. The initial turbidity patterns from both the left- and right-bank monitors that can be identified from these exceedance plots show that turbidity measured during the construction phase was greater (shifted to the right on the exceedance plot), than turbidity measured during the pre- and post-construction phases. This pattern of elevated turbidity during the construction phase was consistent at the upstream and downstream monitors; however, the range of turbidity values between the three construction phases was greatest at the downstream monitors (figs. 11 and 12, table 2). These patterns indicate that there was likely a suspended-sediment input (using turbidity as a surrogate) to Indian Creek between the upstream and downstream monitors during the construction period, however, the magnitude of the sediment input between these monitors is relatively small. The observed range in median values, for example, for the three pipeline construction phases at the upstream monitors was 1.3 FNU for each. The range in median values for the construction phases at the downstream monitors increased to 3.0 and 1.8 FNU for the left- and right-bank monitors, respectively. The range in median turbidity values, between the three phases of construction, would be identical for the upstream and downstream monitors if a source of turbidity was not present between the two locations. The input of turbidity, during the active construction phase, is more pronounced at the downstream left-bank monitor compared to the downstream right-bank monitor. The source of the turbidity input between the upstream and downstream monitoring sites during the construction period may be related to the pipeline crossing activities, but other potential turbidity sources between the two monitors such as bank erosion, upstream sediment sources, algal growth, and point inputs from adjoining residential properties cannot be excluded. The discrepancy between the downstream left- and right-bank monitors is discussed further in the “Conceptual Model for Indian Creek Turbidity Patterns” section of this report.

The exceedance plots for turbidity values collected upstream and downstream from the pipeline crossing in the unnamed tributary (fig. 13) exhibit a considerably different pattern than the one observed in Indian Creek (figs. 11 and 12). The major difference is that turbidity values measured during the construction period were generally less than those measured during the pre- and post-construction phases. This pattern also was consistent at both the upstream and downstream monitors. The decrease in turbidity during the construction phase may be related to the diversion of streamflow away from the trenching activity within the active channel. As with Indian Creek, the range of turbidity values between the three construction phases was greatest at the downstream monitors; however, this increased range was directly related to discrepancies between turbidity values at the upstream and downstream monitors collected during the pre-construction phase, not the construction phase. The observed range in median values for the construction phases at the upstream monitor was 3.0 FNU; the range in median values for the construction phases at the downstream monitor was 5.7 FNU (fig. 13, table 2).

The exceedance plots of turbidity data from the unnamed tributary, overall, show that the pipeline crossing was not a substantial source of suspended sediment (using turbidity as a surrogate). A closer look at the turbidity data collected during

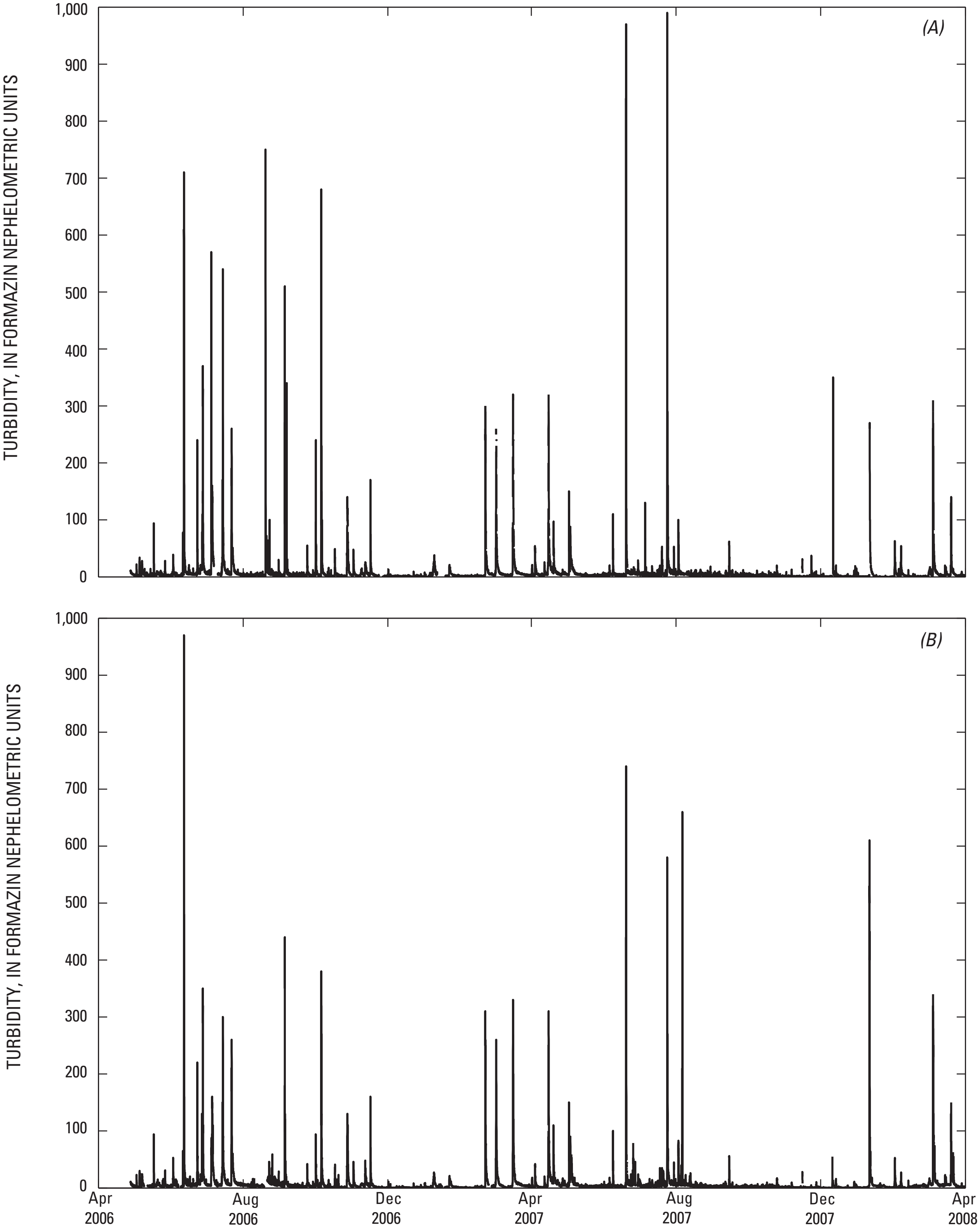

Figure 8. Turbidity data (15-minute interval) collected from Indian Creek, Tazewell County, Virginia, at the (*A*) upstream (Station number 03520967) and (*B*) downstream (Station number 03520968) left-bank water-quality monitors.

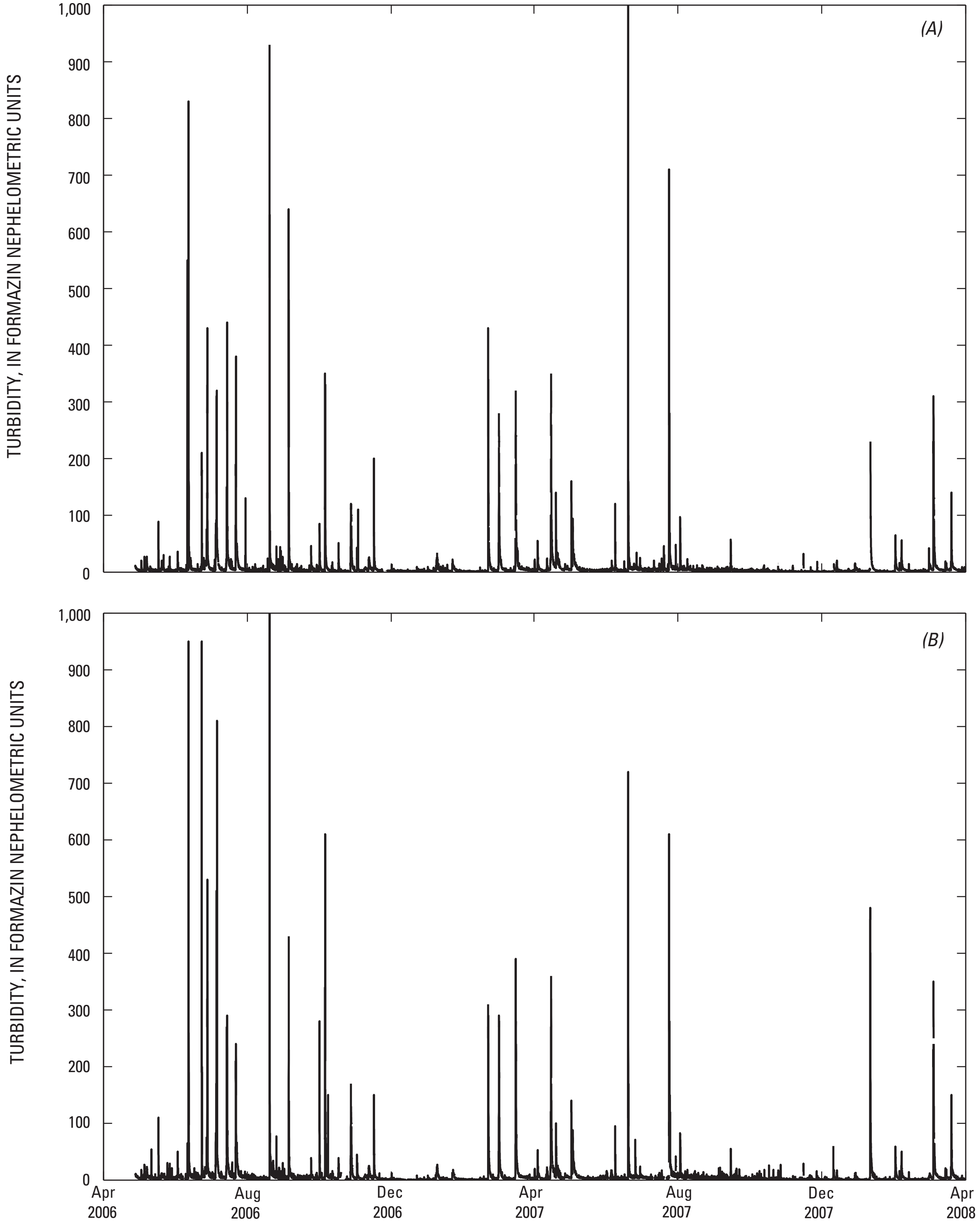

Figure 9. Turbidity data (15-minute interval) collected from Indian Creek, Tazewell County, Virginia, at the (*A*) upstream (Station number 03520967) and (*B*) downstream (Station number 03520968) right-bank water-quality monitors.

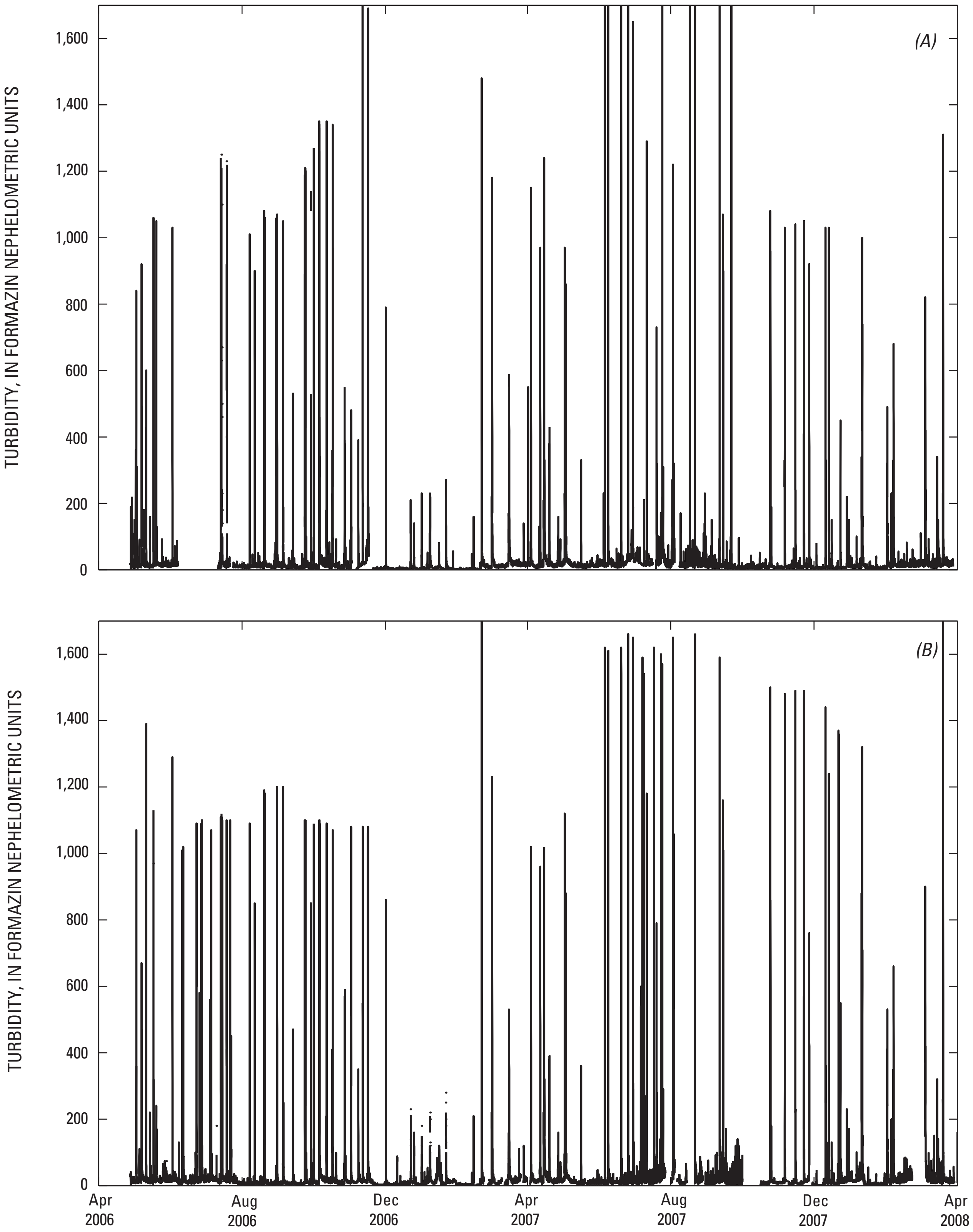

Figure 10. Turbidity data (15-minute interval) collected from the unnamed tributary at the (*A*) upstream (Station number 03520980) and (*B*) downstream (Station number 03520981) water-quality monitors, Tazewell County, Virginia.

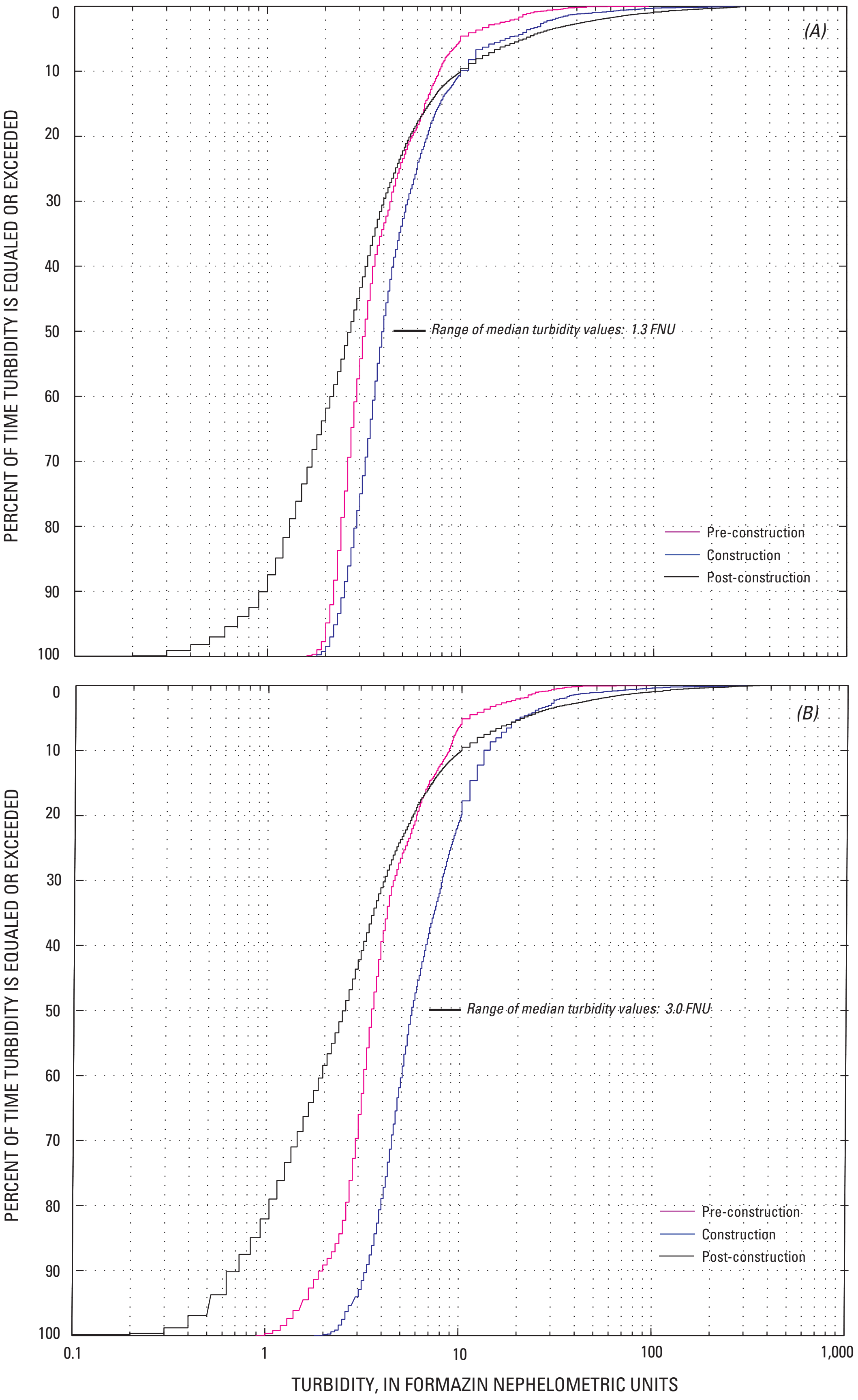

Figure 11. Exceedance plots for left-bank turbidity collected at the (*A*) upstream Indian Creek water-quality monitor (Station number 03520967) and (*B*) downstream Indian Creek water-quality monitor (Station number 03520968) during the pre-construction, construction, and post-construction phases, Tazewell County, Virginia.

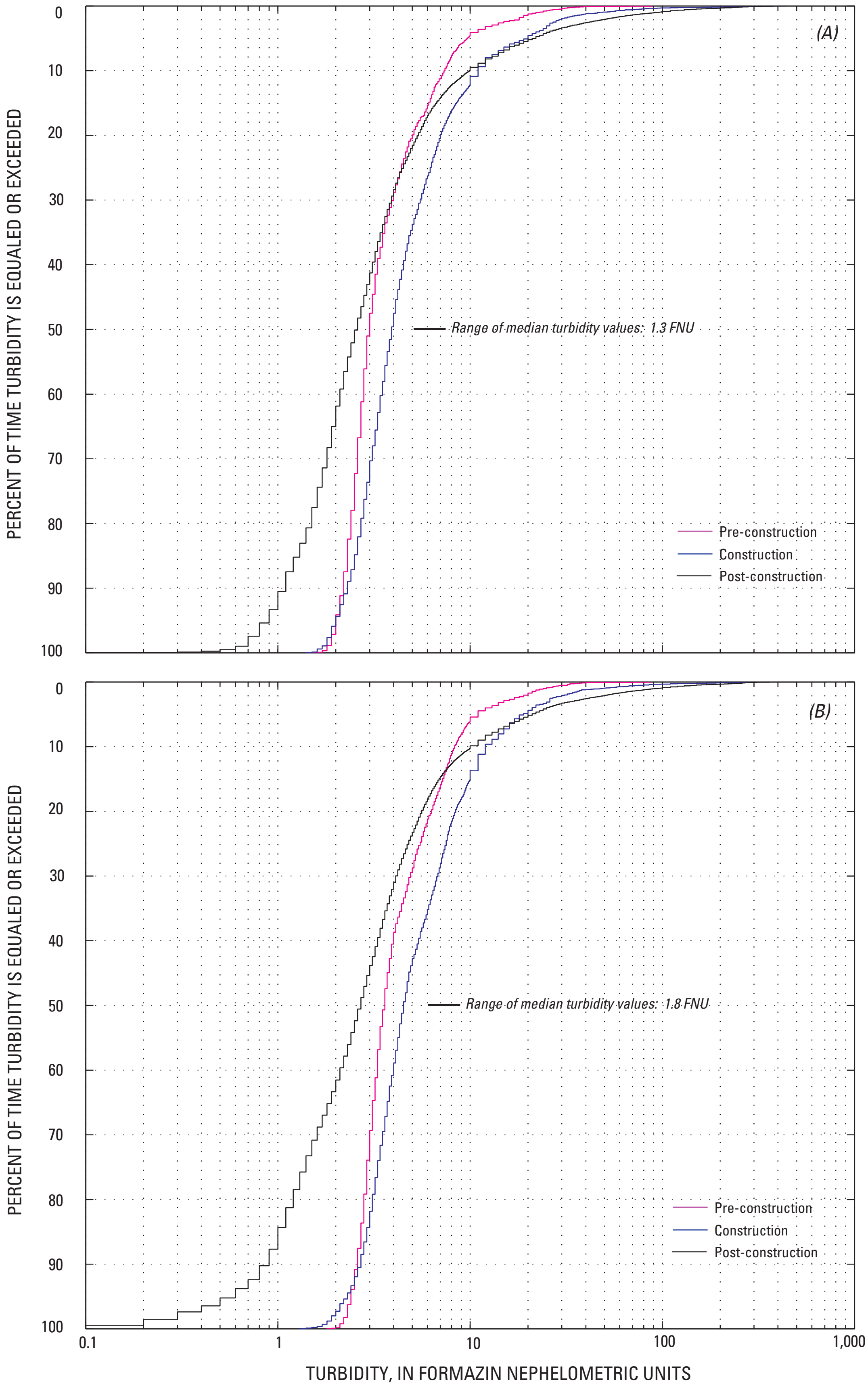

Figure 12. Exceedance plots for right-bank turbidity collected at the (*A*) upstream Indian Creek water-quality monitor (Station number 03520967) and (*B*) downstream Indian Creek water-quality monitor (Station number 03520968) during the pre-construction, construction, and post-construction phases, Tazewell County, Virginia.

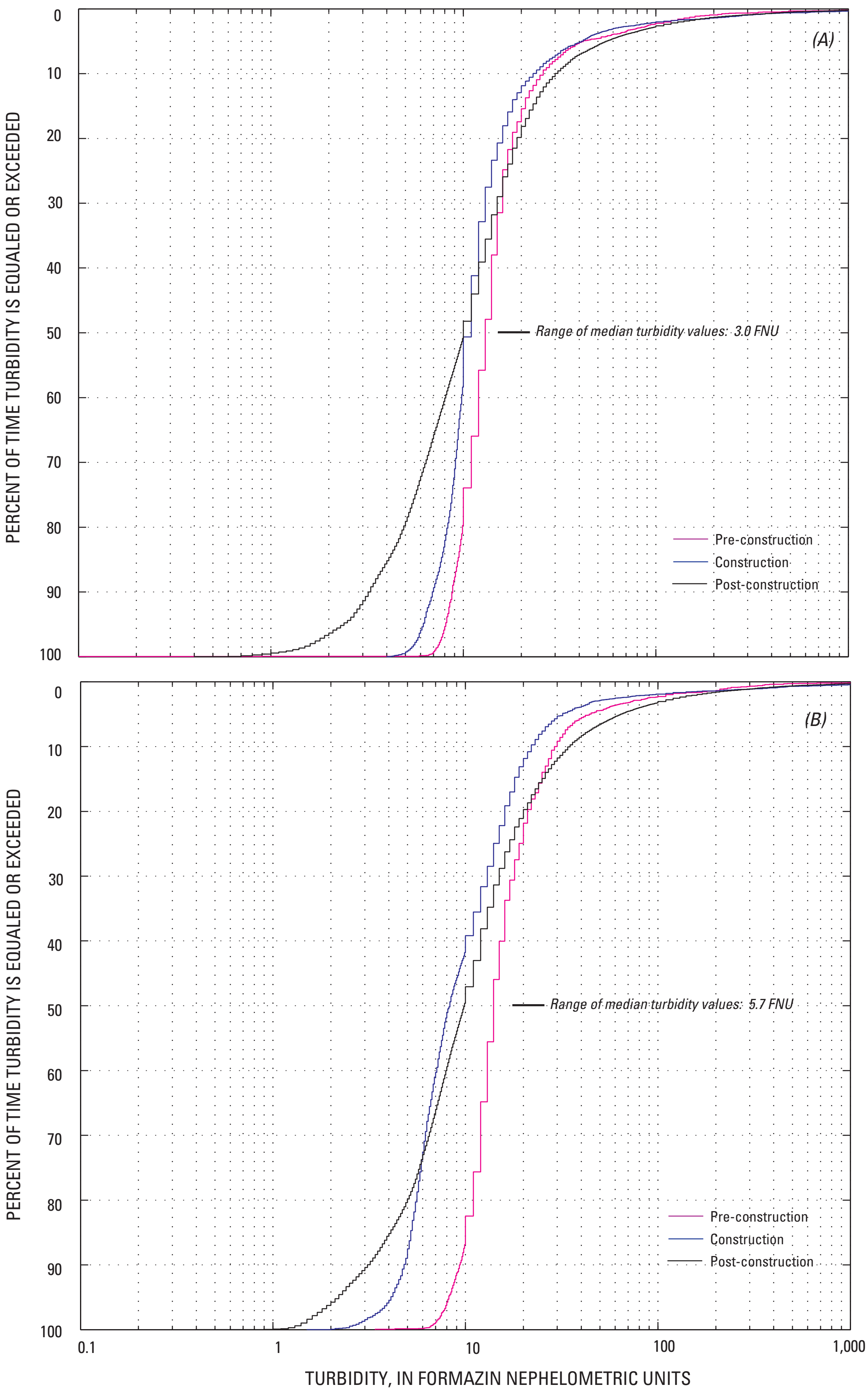

Figure 13. Exceedance plots for turbidity collected at the (*A*) upstream unnamed tributary water-quality monitor (Station number 03520980) and (*B*) downstream unnamed tributary water-quality monitor (Station number 03520981) during the pre-construction, construction, and post-construction phases, Tazewell County, Virginia.

the pipeline crossing activities, (August 4, 2006, through August 7, 2006), however, reveals that turbidity conditions did increase for a short time (fig. 14). On August 4, 2006, the pipeline crossing activities included the installation of flow-control measures and blasting of the pipeline crossing. The installation of the flow-control measures and subsequent channel blasting resulted in one elevated turbidity measurement of 460 FNU and several slightly elevated turbidity values relative to upstream conditions (fig. 14). The channel trenching, pipeline installation, backfilling of the trench, and removal of flow-control measures resulted in the turbidity measurements collected on August 5, 2006 (fig. 14). The elevated turbidity conditions observed following the removal of the flow-control measures were consistent with the literature accounts of the dry-cut pipeline crossing technique (Reid and others, 2002). Although turbidity (suspended sediment) was generated during the construction of the unnamed tributary pipeline crossing, the turbidity values were significantly lower than the turbidity values generated during natural rainfall-runoff events within this tributary (fig. 15). The turbidity values associated with the rainfall-runoff event that occurred on August 7, 2006 are (1) consistent both upstream and downstream, indicating that the freshly constructed crossing was not a substantial source of sediment during this runoff event, and (2) representative of turbidity values routinely generated during runoff-events.

A signed-rank test was used to directly compare upstream and downstream turbidity values measured during the three phases of pipeline construction. The signed-rank test determines whether the median value of the paired differences of upstream and downstream turbidity values is equal to zero. The results of the signed-rank test are presented in table 4. The signed-rank test on the pre-construction paired differences revealed that the median paired differences for Indian Creek (left bank and right bank) and the unnamed tributary were all significantly different from zero ($p < 0.001$). The median pre-construction paired differences were –0.3, –0.5, and –1.0 FNU for the Indian Creek left bank and right bank and the unnamed tributary, respectively. The results from the pre-construction paired differences indicate that there is typically a slight increase (1 FNU or less) in turbidity as water passes from the upstream monitors to the downstream monitors. The signed-rank test on the construction paired differences revealed that

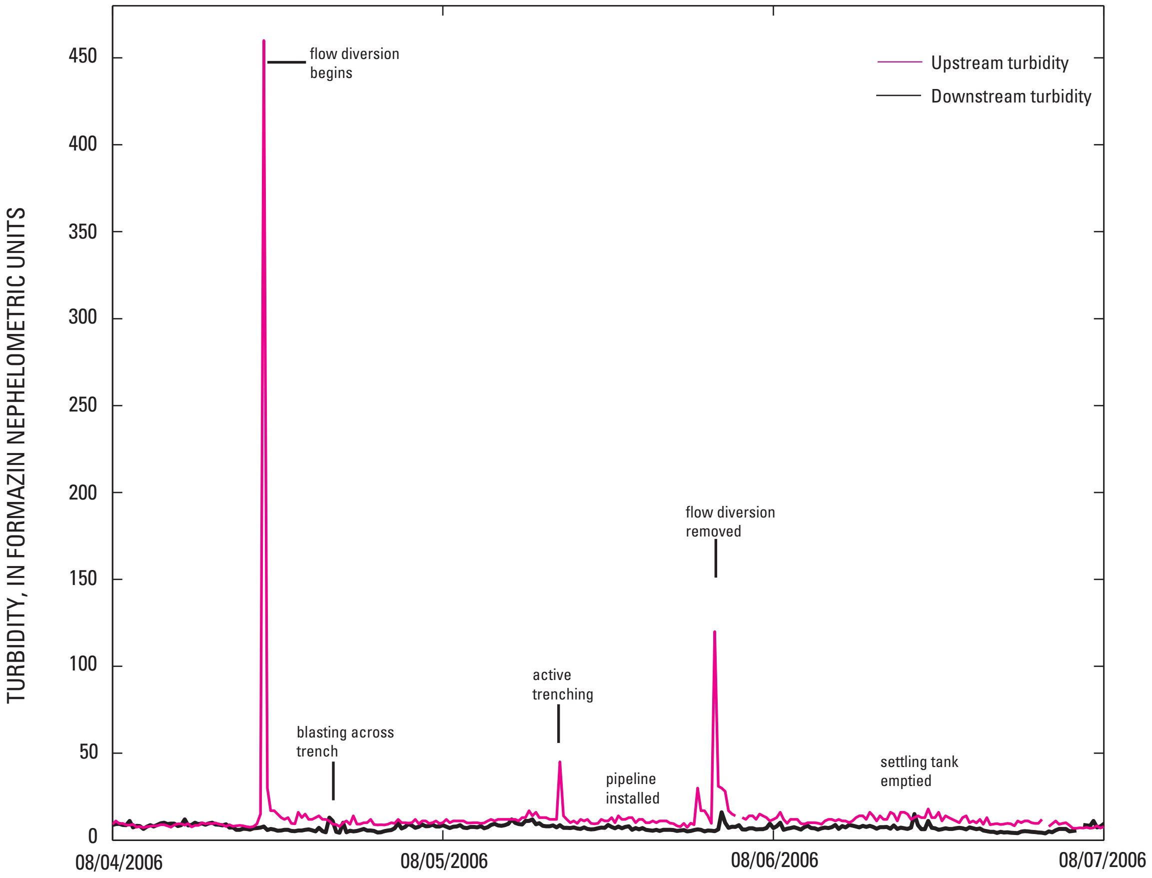

Figure 14. Turbidity data (15-minute interval) collected from the unnamed tributary at the upstream (Station number 03520980) and downstream (Station number 03520981) water-quality monitors during active pipeline construction August 4–7, 2006, Tazewell County, Virginia.

Table 4. Signed-rank test results for turbidity differences from paired upstream and downstream turbidity values from Indian Creek and unnamed tributary.

[Values presented are the median paired difference in upstream and downstream turbidity, in Formazin Nephelometric Units, and the associated signed-rank test p-value in parentheses]

	Indian Creek left bank	Indian Creek right bank	Unnamed tributary
Pre-Construction	–0.3	–0.5	–1.0
	(< 0.001)	(< 0.001)	(< 0.001)
Construction	–1.3	–0.7	1.7
	(< 0.001)	(< 0.001)	(< 0.001)
Post-Construction	0.2	0.1	0
	(< 0.001)	(< 0.001)	(0.055)

the median percent differences for Indian Creek (left bank and right bank) and the unnamed tributary were all significantly different from zero ($p < 0.001$). The median construction paired differences values were –1.3, –0.7, and 1.7 FNU for the Indian Creek left bank and right bank and the unnamed tributary, respectively. The result from the construction period paired differences from the Indian Creek left-bank monitors indicates that turbidity values increased 1 FNU as water moved below the pipeline construction. This same pattern in construction paired differences from the right-bank monitors was observed; however, the difference relative to the pre-construction median paired difference was only 0.2 FNU. Conversely, the signed-rank test results for the unnamed tributary indicate that turbidity values decreased 1.7 FNU downstream from the upstream monitor, which is a shift of 2.7 FNU relative to pre-construction conditions. The signed-rank test on the post-construction paired differences revealed that the median of the paired differences for Indian Creek (left bank and right bank) were all significantly different from zero. The median post-construction paired differences were 0.2 and 0.1 FNU for the Indian Creek left bank and right bank, respectively. The signed-rank test on the unnamed tributary post-construction paired differences revealed that the median of the paired differences was not significantly different from zero. The median post-construction paired difference was 0.0 FNU for the unnamed tributary. These post-construction turbidity conditions were similar to the observed pre-construction conditions.

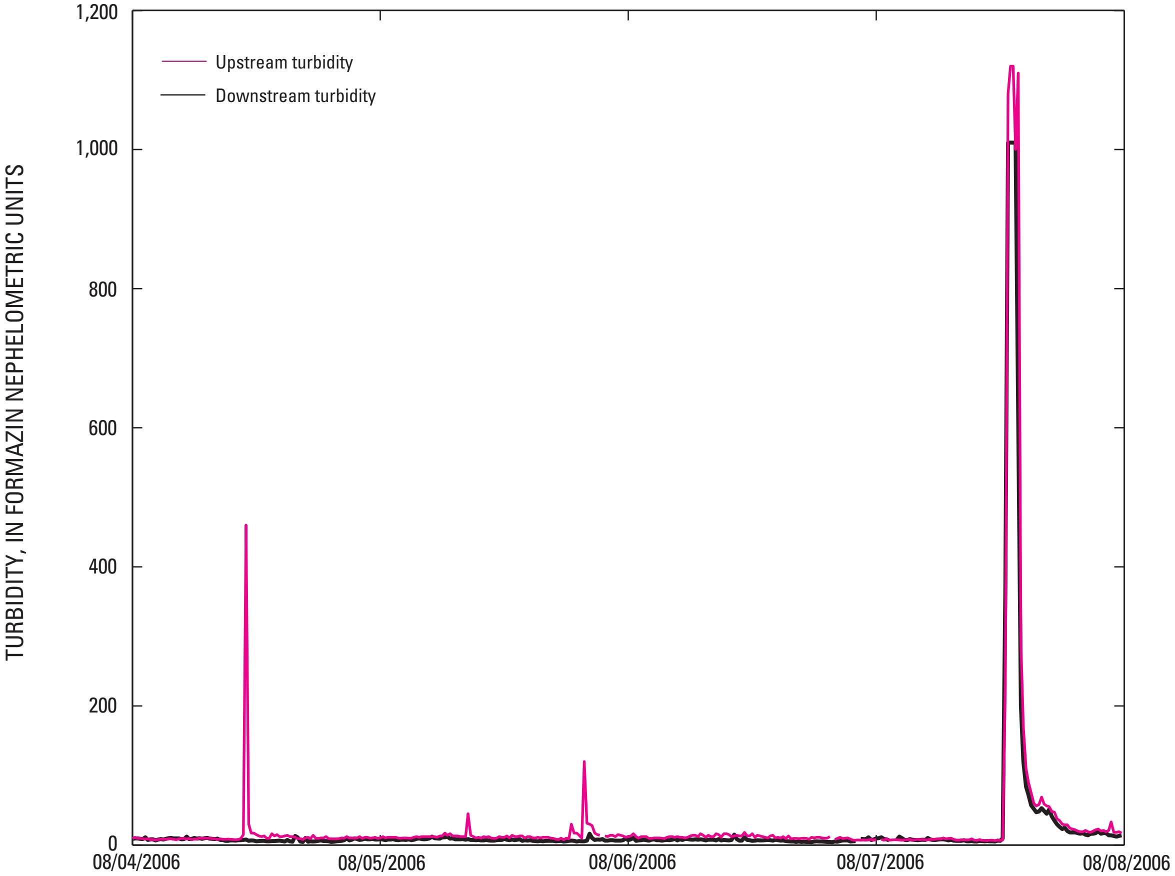

Figure 15. Turbidity data (15-minute interval) collected from the unnamed tributary at the upstream (Station number 03520980) and downstream (Station number 03520981) water-quality monitors during active pipeline construction August 4–8, 2006, Tazewell County, Virginia.

The results from the signed-rank test analysis help to determine whether the pipeline crossing affected downstream sediment conditions in Indian Creek and the unnamed tributary. In Indian Creek, the paired differences of upstream and downstream turbidity values and the associated signed-rank test all indicate that more sediment entered the study reach during the construction phase than during the pre-construction and post-construction phases. The signed-rank test results also indicate that a more pronounced sediment source exists between the upstream and downstream left-bank monitors. Although this result is significant, the magnitude of the difference is small. The discrepancy between the downstream left- and right-bank monitors is discussed further in the “Conceptual Model for Indian Creek Turbidity Patterns” section of this report. In the unnamed tributary, the pipeline crossing did not increase turbidity conditions downstream from the pipeline crossing on the basis of the signed-rank test analysis of the three construction periods.

Boxplots of the paired differences for each month of the study were generated for the Indian Creek and unnamed tributary monitors. These boxplots show the distribution of the monthly paired differences (represented by the 10th, 25th, 50th, 75th, and 90th percentiles). For comparison, the monthly differences for the paired turbidity values collected at the two upstream Indian Creek monitors (left and right bank) are presented in figure 16. The black horizontal line that passes through all of the monthly boxplots is the locally weighted scatterplot smoothing (LOWESS) (Helsel and Hirsch, 1992) best fit of the monthly medians. The LOWESS best-fit line was used to identify temporal patterns between the monthly medians. This boxplot of the upstream paired differences indicates that the majority of the monthly paired differences, for the entire study period, occurred between 2.0 and –2.0 FNU. This result strongly indicates that the combination of variability between the instruments and the natural variability in the channel accounts for ± 2 FNU. Paired differences within the ± 2 FNU range should be considered environmental and instrument noise, whereas values outside of this range may indicate a measurable change in turbidity. The boxplot of monthly paired differences for the Indian Creek left bank (upstream minus downstream) shows that most of the paired differences occur within the ± 2 FNU range; however, June 2006 through August 2006 had paired differences that exceeded this –2.0 FNU, indicating a sustained sediment input downstream from the upstream Indian Creek monitors (fig. 17*A*). This pattern of sediment input from June 2006 through August 2006 was observed in the paired differences from the upstream and downstream right-bank monitors (fig. 17*B*). The vast majority of the right-bank turbidity paired differences are within the ± 2 FNU range. The boxplot of

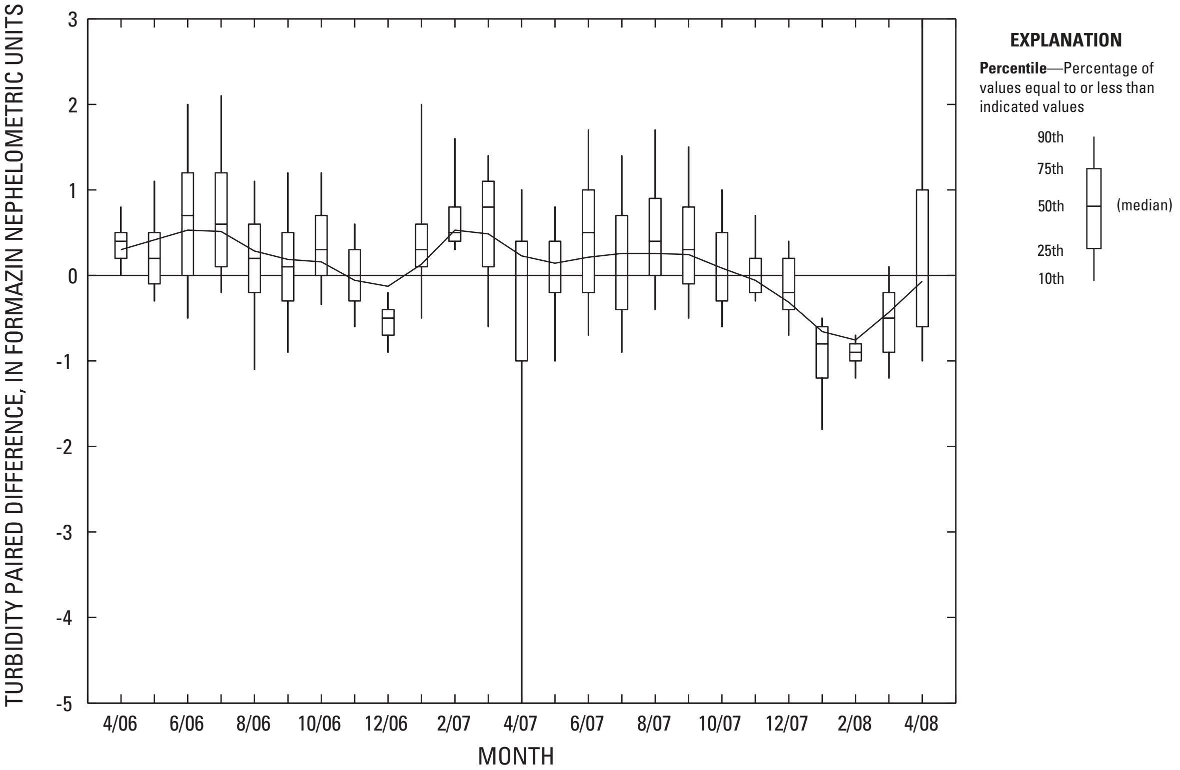

Figure 16. Monthly differences for paired turbidity values collected at the left-bank and right-bank upstream Indian Creek water-quality monitors (Station number 03520967, fig. 3), Tazewell County, Virginia. Turbidity paired difference equals left-bank turbidity minus right-bank turbidity. The black line represents the LOWESS smoothed fit line through the monthly medians.

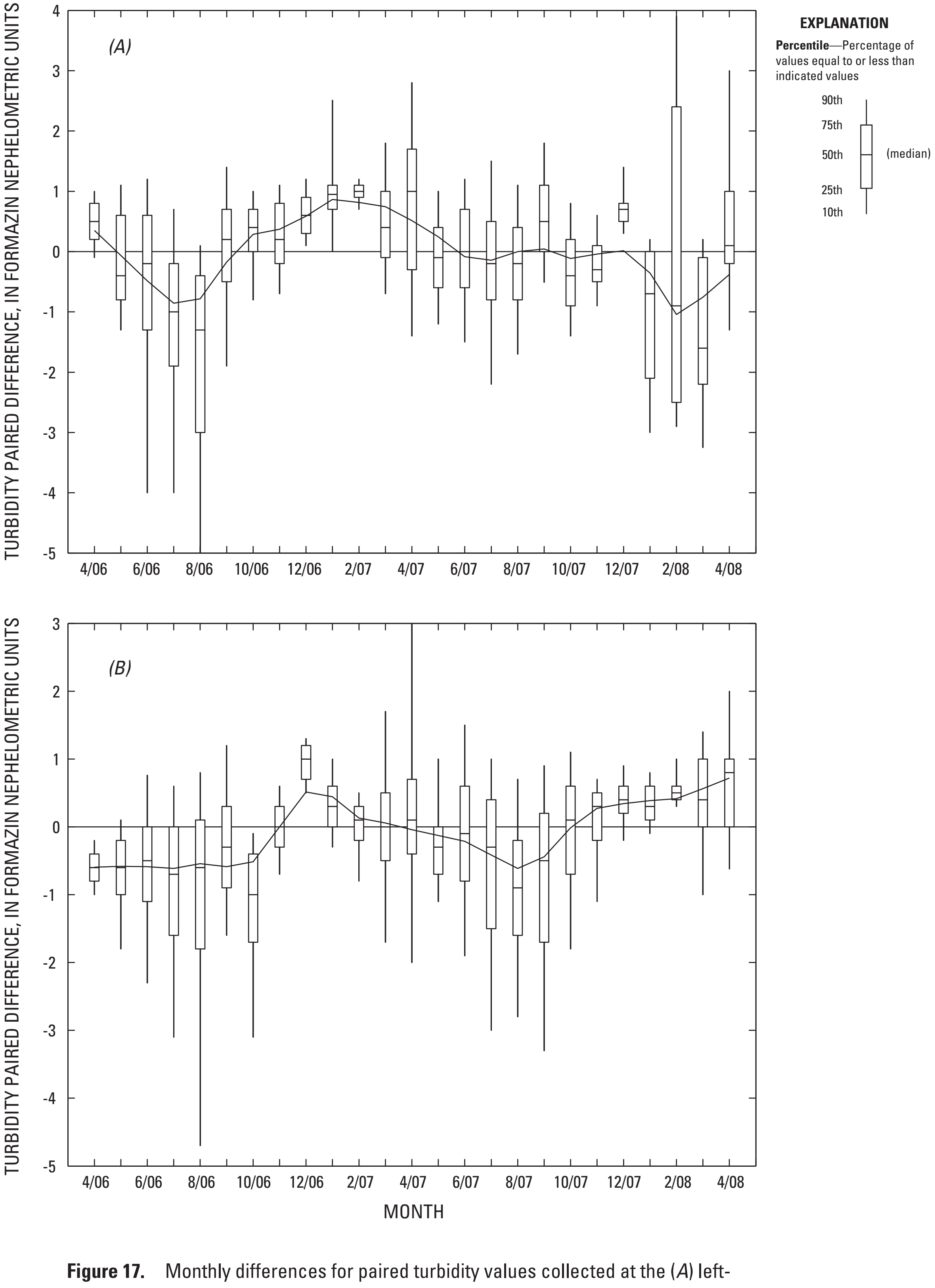

Figure 17. Monthly differences for paired turbidity values collected at the (*A*) left-bank and (*B*) right-bank monitors located upstream (Station number 03520967, fig. 3) and downstream (Station number 03520968) of the pipeline crossing under Indian Creek, Tazewell County, Virginia. Turbidity paried difference equals left-bank upstream turbidity minus left-bank downstream turbidity. The black line represents the LOWESS smoothed fit line through the monthly medians.

monthly paired differences for the unnamed tributary show that turbidity in the tributary is highly variable compared to turbidity paired differences for Indian Creek, with a range that typically extends ± 10 FNU (fig. 18). The monthly paired differences indicate that turbidity conditions improved (that is, turbidity decreased at the downstream monitor) during the pipeline construction and that the construction paired differences are indistinguishable from the remaining monthly paired differences.

As part of the assessment of long-term turbidity patterns, exceedance plots of measured turbidity values, signed-rank test of turbidity paired differences, and monthly boxplots of turbidity paired differences were used to determine whether the Indian Creek and unnamed tributary pipeline crossings resulted in increased turbidity levels downstream from the crossings. These three analytical evaluations of the measured turbidity patterns provided consistent results for turbidity conditions for both Indian Creek and the unnamed tributary. In Indian Creek, turbidity significantly increased downstream from the pipeline crossing. The greatest increase in downstream turbidity occurred during the construction phase. Although the results for left- and right-bank turbidity patterns were consistent, the turbidity patterns were most pronounced along the left bank. This discrepancy between the left- and right-bank turbidity patterns is discussed further in the “Conceptual Model for Indian Creek Turbidity Patterns” section of this report. In the unnamed tributary, turbidity values downstream from the pipeline crossing were measurably elevated for short durations during active pipeline-crossing construction, August 4–6, 2006; however, the sediment generated during this period, as indicated by the increase in turbidity, was substantially lower than the turbidity levels that are generated during typical runoff events. On the unnamed tributary, the long-term patterns in turbidity, collected during the construction phase, indicate that turbidity significantly decreased downstream from the pipeline crossing.

Utility of the Turbidity-Input Warning System

The turbidity-input warning system required by the USFWS and subsequently established by East Tennessee Natural Gas and the USGS was instrumental in ensuring the integrity of the ecology of Indian Creek and the unnamed tributary. A turbidity warning occurred when downstream turbidity was either 6 FNU, or 15 percent (see “Turbidity-Input Warning System” section for additional details) greater than the corresponding upstream turbidity value, sustained for

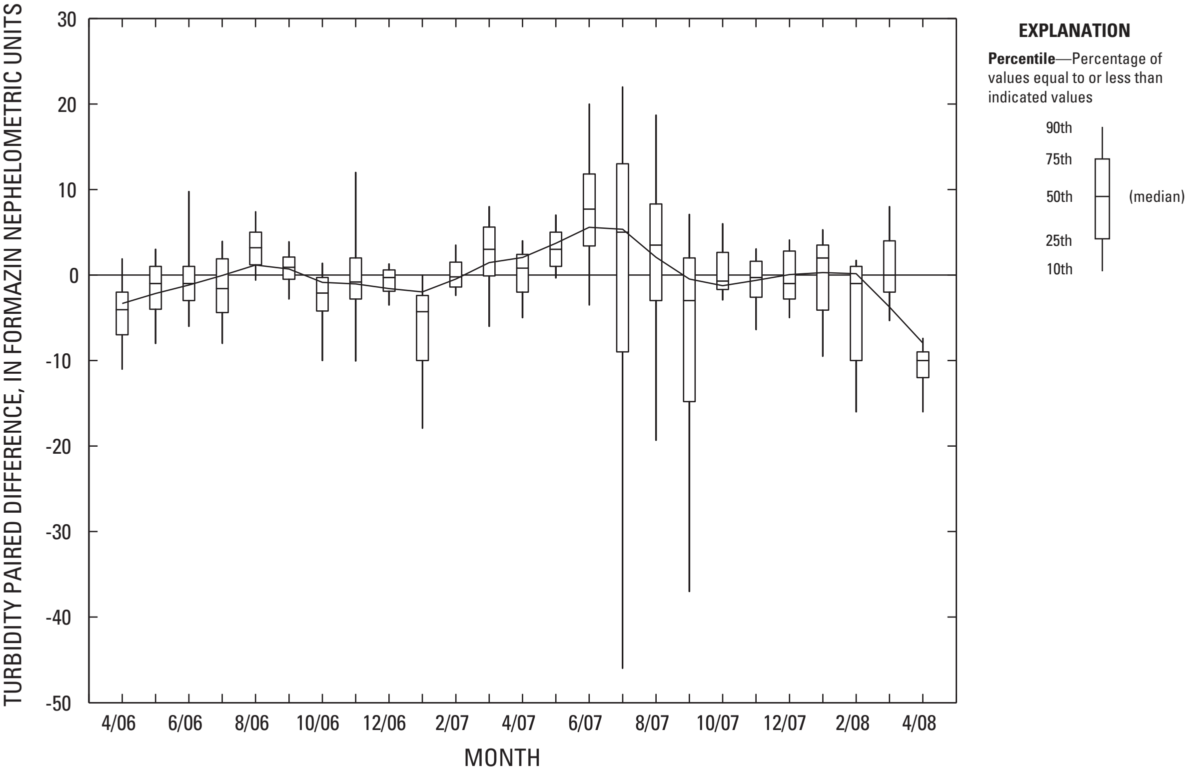

Figure 18. Monthly differences for paired turbidity values collected at the upstream (Station number 03520980) and downstream (Station number 03520981, fig. 3) unnamed tributary water-quality monitors, Tazewell County, Virginia. Turbidity paired difference equals upstream turbidity minus downstream turbidity. The black line represents the LOWESS smoothed fit line through the monthly medians.

a period of 1 hour. Once a threshold was exceeded, the on-site manager for East Tennessee Natural Gas would investigate Indian Creek below the upstream monitors for incoming sediment. If incoming sediment was not present, then East Tennessee Natural Gas would contact the USGS to check for turbidity-equipment problems such as fouling from the accumulation of debris on the water-quality monitoring sonde. An example of the warnings received each month for exceeding the downstream-turbidity thresholds is provided in figure 19. This figure shows that during each month, between 0 and 38 warnings (0 to 1.45 percent of the collected turbidity unit values) occurred throughout the period of study. During the construction phase, 16 to 38 alarms occurred each month, and were subsequently investigated. Most of the warnings were determined to be caused by fouling of the turbidity probe.

On August 19, 2006, the turbidity-input warning system captured a substantial sediment-input event. An intensive rainfall event in the Indian Creek watershed caused upland surface-water runoff and associated sediment transport from the Jewell Ridge pipeline right-of-way. Although sediment- and erosion-control measures were in place, this runoff and sediment transport overwhelmed the existing controls and entered an ephemeral unnamed tributary approximately 350 feet upstream from the right-bank monitor on Indian Creek. This runoff event delivered substantial amounts of suspended sediment into Indian Creek. Turbidity values measured at the upstream left- and right-bank monitors peaked at 930 and 750 FNU, respectively, whereas turbidity reached 1,220 FNU at the downstream right-bank monitor. The downstream left-bank monitor was not functioning during this sediment-input event.

The turbidity-warning system allowed real-time detection of sediment/turbidity input within the study reach. The ability for watershed managers to detect sediment input as it happened allowed for rapid-response corrective actions. The turbidity-input warning system successfully detected episodic exceedences of the established turbidity threshold, and helped to prevent occurrences of chronic long-term input of turbidity. One limitation of the turbidity-input warning system is that the conservative nature of the turbidity thresholds make the system highly susceptible to false-positive warnings.

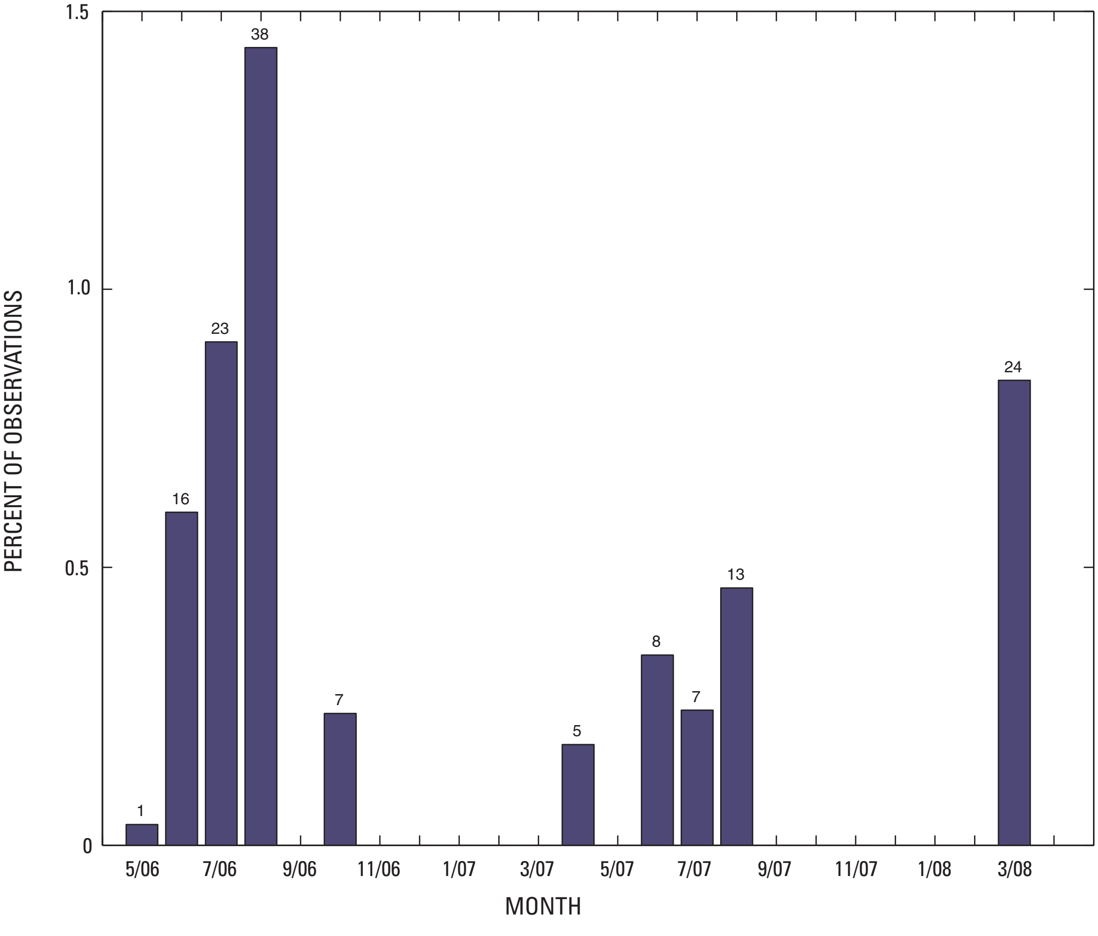

Figure 19. Monthly bar plot showing the percentage of turbidity paired differences that resulted in a warning for exceeding the turbidity threshold along the left bank of Indian Creek, Tazewell County, Virginia. The number above each bar plot represents the actual number of warnings.

Conceptual Model for Indian Creek Turbidity Patterns

This study was designed to evaluate whether the Jewell Ridge pipeline crossing and associated pipeline construction resulted in increased turbidity levels, thus increasing suspended-sediment concentrations during the construction phase, and to detect both real-time and long-term changes in turbidity conditions within the pipeline-crossing easement. Results obtained from all statistical and graphical analyses indicate that turbidity levels increased within the Indian Creek pipeline-crossing easement, and that these increases in turbidity were small in magnitude but occurred over a prolonged time period. Although these results were consistent for all upstream to downstream analyses, the pattern of increased turbidity was always more pronounced along the left side of the channel compared to the right side of the channel. An investigation into these left- and right-channel inconsistencies, coupled with the occurrence of the August 19, 2006, right-of-way slope failure and subsequent sediment transport, led to the development of an alternative conceptual model for turbidity patterns measured during the construction phase. The initial conceptual model, which was tested during this study, was that the pipeline crossing and nearby adjacent trenching activities would transport sediment directly into the Indian Creek monitoring reach. The alternative conceptual model was that transport of sediment from the pipeline construction right-of-way into an ephemeral unnamed tributary and subsequently into Indian Creek served as the primary source of turbidity/sediment detected during the construction phase. For the remainder of this section, data are presented that support the development of this alternative conceptual model.

The ephemeral unnamed tributary (which should not be confused with the unnamed tributary monitored as part of this study) discharges into Indian Creek along the right bank, approximately 350 feet above the upstream water-quality monitors (fig. 20). The path of the Jewell Ridge pipeline crosses the headwaters of the ephemeral unnamed tributary (fig. 20). The effects of this ephemeral unnamed tributary on sediment delivery to Indian Creek were considered during the development phase of this study; however, the study was designed to focus on the Indian Creek pipeline crossing and it was anticipated that this ephemeral unnamed tributary would not be a source of construction sediment. The design of the monitoring network (paired upstream, downstream, left-bank, and right-bank monitors) was chosen to isolate the Indian Creek pipeline crossing and to account for incoming sediment from this ephemeral unnamed tributary; however, the August 19, 2006, sediment transport event showed that the pipeline construction activity was a substantial source of sediment in the ephemeral unnamed tributary. The design of the water-quality network that was implemented and associated data analyses allowed for the determination that sediment derived from this ephemeral unnamed tributary may in fact be the primary source of sediment that was detected within the Indian Creek pipeline-crossing easement.

Analysis of turbidity data collected at the upstream Indian Creek monitors revealed that variability between turbidity data collected at the left- and right-bank monitors increased during pipeline construction. Results from a paired differences analysis (left-bank minus right-bank turbidity value) of the 50th, 75th, 80th, 90th, 95th, and 99th percentiles for turbidity data collected at both upstream Indian Creek turbidity monitors are presented in figure 21. The 50th though the 99th percentiles represent turbidity values that ranged from 3 to 100 FNU during the entire period of study. During pre-construction, paired differences from these specified percentiles ranged from 0.2 to 1.4 FNU, which indicates that turbidity values were slightly greater at the left-bank monitor. This pre-construction result shifted during the construction phase to a range of 1.0 to –3.0 FNU. The paired differences for the 75th, 80th, 90th, and 95th percentiles were all negative, indicating that turbidity values were greater at the right-bank monitor. This result indicates that during elevated turbidity conditions within the construction period, which were typically associated with runoff events, the right side of the Indian Creek channel was more turbid than the left side of the channel. Also, this shift from positive paired differences during the pre-construction phase to negative paired differences during the construction phase indicates that a new sediment source was contributing to Indian Creek turbidity. The ephemeral unnamed tributary discharges to the right bank of Indian Creek 350 feet above the upstream monitors thereby allowing very little distance for mixing, which would generate the negative paired differences that were observed. Additionally, Indian Creek is considered completely mixed upstream from the confluence with the ephemeral unnamed tributary. The paired differences returned to all positive values during the post-construction phase. The post-construction paired differences ranged from 0 to 4 FNU, and the observed range for the 50th to 95th percentiles was 0.0 to 0.1 FNU. The consistent and small observed ranges in pre- and post-construction paired differences indicate that Indian Creek is well mixed as it flows by the upstream monitors. Conversely, the negative paired differences observed during the construction phase indicate that sediment delivered from the ephemeral unnamed tributary primarily was detected by the right-bank monitor, and that the contributions from this tributary dissipated during the post-construction phase.

The results of the paired differences analysis performed on the paired upstream left- and right-bank turbidity percentiles explain the discrepancy observed in the long-term analysis of left- and right-bank paired upstream and downstream data. The long-term analysis of these paired differences indicates that turbidity increased within the pipeline-crossing easement during construction; however, these results were more pronounced along the left channel compared to the results for the right side of the channel. This discrepancy is explained by the turbidity patterns observed at the upstream monitors during the construction phase. Most of the long-term analyses relied on paired differences of upstream and downstream turbidity data to detect change. Because turbidity

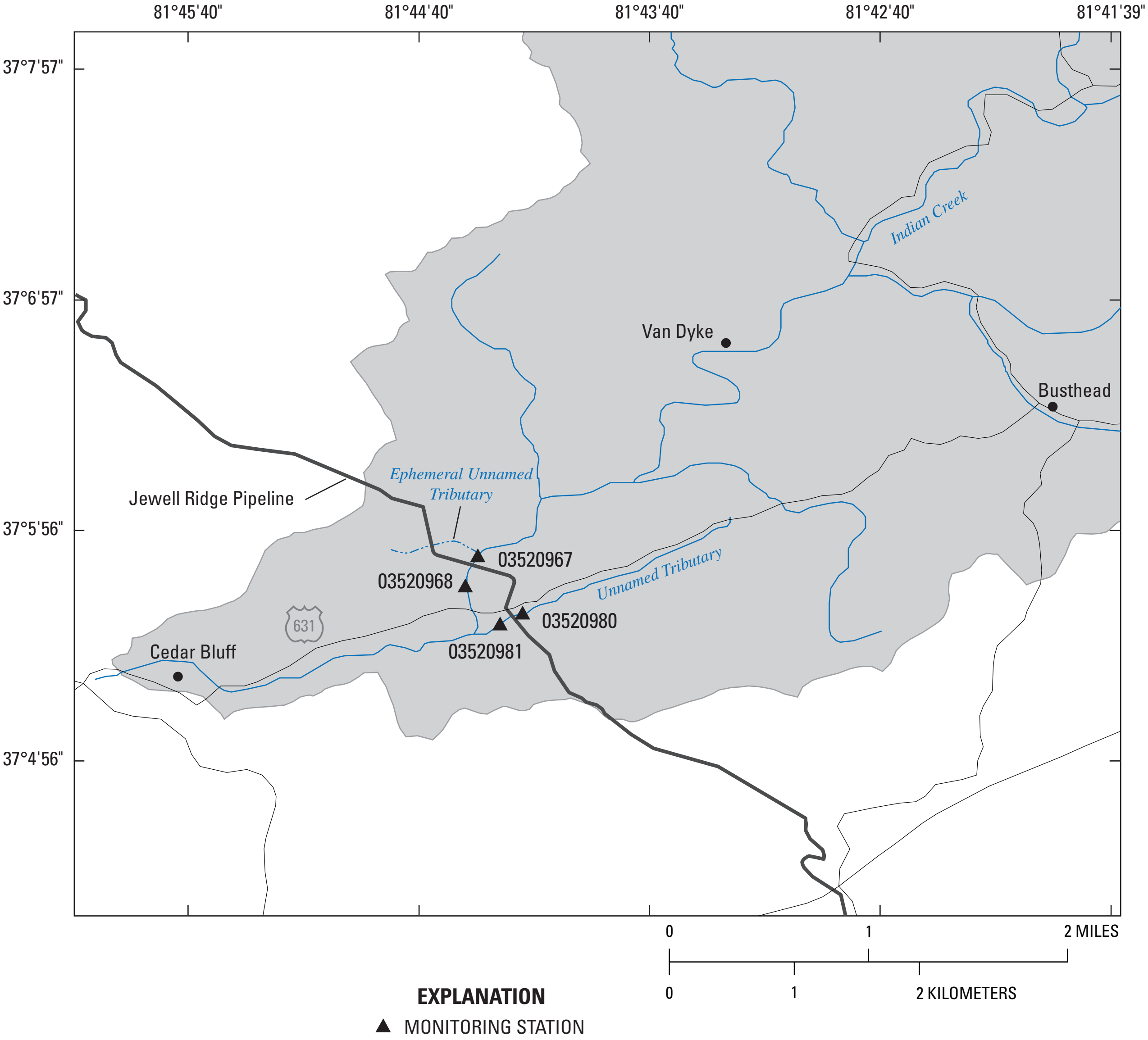

Figure 20. The Indian Creek and unnamed tributary monitoring network as well as the ephemeral unnamed tributary, Tazewell County, Virginia.

at the upstream right-bank monitor was elevated during the construction phase, the difference between the upstream and downstream right-bank monitors was minimized. Essentially, the turbidity that was detected by the upstream right-bank monitor was detected by the downstream right-bank monitor. Additionally, the turbidity that passed the upstream right-bank monitor was transported and subsequently mixed across the channel so that the downstream left-bank monitor also detected this turbidity. As the upstream left-bank monitor did not fully detect this incoming turbidity from the ephemeral unnamed tributary, a pronounced and statistically significant result was obtained, which indicated that a sediment input occurred along the left bank.

The following conclusions can be drawn from the alternative conceptual model:

1. Turbidity values significantly increased within the pipeline-crossing easement during the construction phase;
2. The primary source of this turbidity increase can be linked to sediment delivered from the ephemeral unnamed tributary; and
3. The bored pipeline crossing had little to no effect on sediment conditions in Indian Creek, and sediment transport from the upland pipeline right-of-way into the ephemeral unnamed tributary was the primary source for the turbidity increases observed in the pipeline-crossing easement.

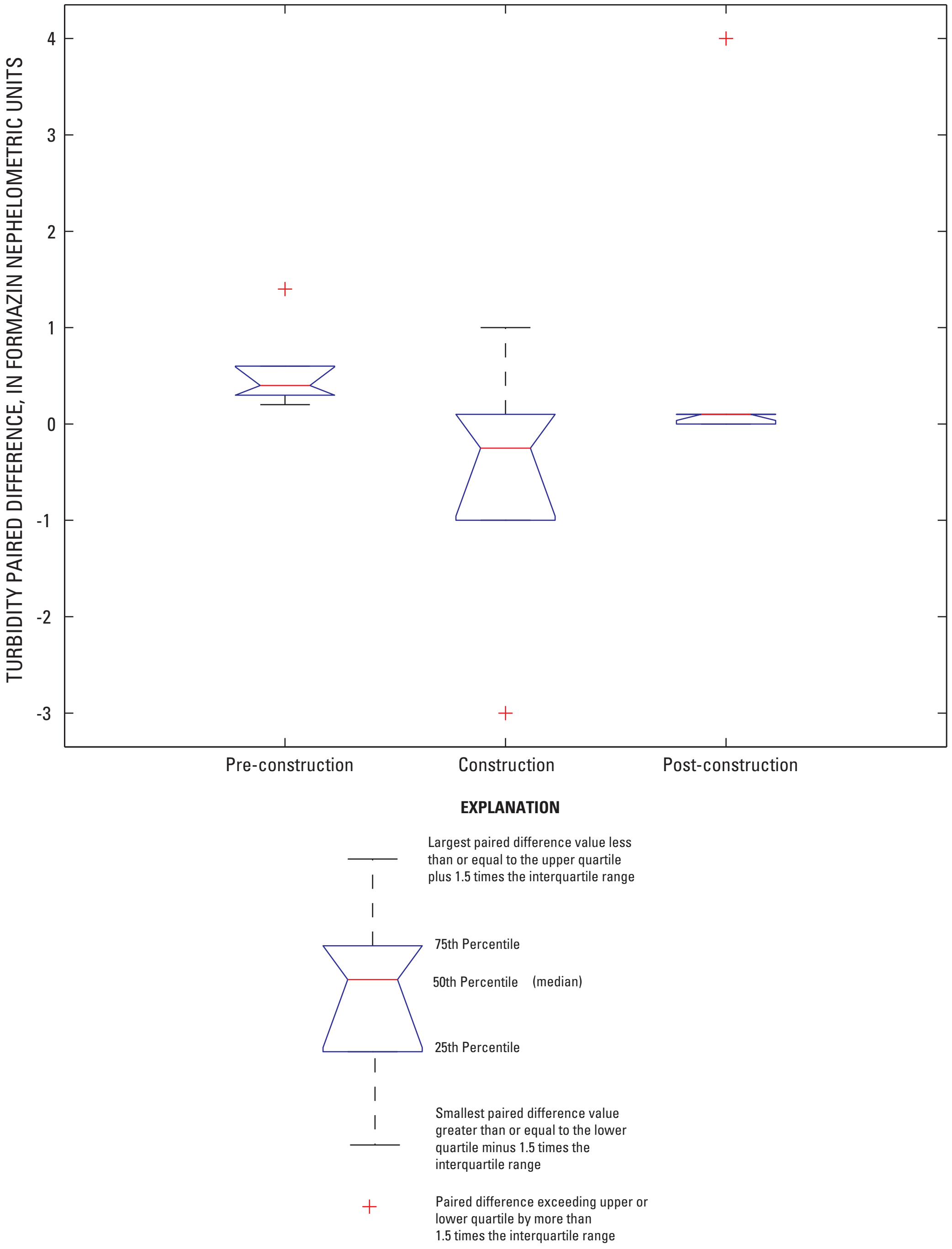

Figure 21. Boxplots of turbidity paired differences for turbidity collected at the left-bank and right-bank upstream Indian Creek water-quality monitors (Station number 03520967), Tazewell County, Virginia. Turbidity paired difference equals left-bank turbidity minus right-bank turbidity for values at the 50th, 75th, 80th, 90th, 95th, and 99th percentiles.

These conclusions are consistent with those in the literature regarding the effect of the HDD technique on downstream suspended-sediment conditions. The HDD technique has been shown to have little to no impact on downstream suspended-sediment conditions (Reid and others, 2002; Lévesque and Dubé, 2007). The HDD technique bores a pipeline crossing at least 5 feet beneath the bottom of the stream. The area of the boring is bordered by extensive silt fencing and hay bails, which also reduce the likelihood that sediment will be transported into the crossing. No sediments were ever observed to directly wash off the Indian Creek pipeline crossing construction site. Conversely, it has been shown that the greatest risk associated with sediment transport during the application of HDD is the runoff and associated sediment transport from the upland pipeline right-of-way into nearby drainages (Reid and others, 2002; Lévesque and Dubé, 2007).

Study Limitations

Although the establishment of the turbidity-monitoring network enabled short-term and long-term evaluation of the pipeline crossing beneath Indian Creek and through the unnamed tributary, several confounding factors affected the statistical analysis to identify changes in turbidity conditions. These factors include (1) an abbreviated pre-construction monitoring period, (2) loss of turbidity data through fouling, (3) uncontrolled sediment sources upstream from the monitoring reach, and (4) routing of extracted bore water downstream from the monitoring reach.

Pre-construction monitoring was a critical component in determining the overall influence of the pipeline crossing on downstream water-quality conditions. The objective of the pre-construction monitoring period was to quantify the extent of environmental and instrument variability in instream water-quality properties. Ideally, the pre-construction monitoring period would have been long enough to capture a wide range of hydrologic conditions. The pre-construction monitoring period was limited to 34 days, however, during which no substantial runoff event occurred within the Indian Creek Basin. As a result, the natural and instrument variability associated with turbidity in Indian Creek is representative of the 34-day pre-construction monitoring period but underrepresents the complete range of conditions.

The use of continuously collected turbidity data was essential to the real-time monitoring of water-quality conditions in Indian Creek and the unnamed tributary. During the study period, turbidity conditions were intensively monitored at an average rate of 2,600 and 2,400 turbidity observations per month from Indian Creek and the unnamed tributary, respectively. The turbidity monitoring instrument, however, was prone to fouling caused by several factors including instream debris (leaves and sediment), biofouling (algal growth and presence of macro-invertebrates), and electronic drift. Fouling of the Indian Creek and the unnamed tributary monitors resulted in an average monthly loss of turbidity data of 10 and 20 percent, respectively. The USGS, in response to the elevated rate of fouling on the unnamed tributary monitors, increased the maintenance to once every 2 weeks instead of once every 4 weeks. Additionally, the occurrence of turbidity-instrumentation fouling typically resulted in an exceedence of the established turbidity threshold, which had to be investigated to ensure the warning was not a result of sediment input.

On August 19, 2006, excessive runoff and associated sediment transport from the upland Jewell Ridge pipeline construction right-of-way overwhelmed the upland slope and entered an ephemeral unnamed tributary, which brought substantial amounts of suspended sediment into Indian Creek 350 feet upstream from the monitoring site. The primary concern regarding the influence of this sediment input on the success of the monitoring effort is that it occurred upstream from the upstream turbidity monitors. The Indian Creek monitoring network was designed to evaluate the effects of the pipeline crossing on downstream values of turbidity; the upstream monitors were intended to represent non-pipeline-derived turbidity. There is no way to determine how long this sediment-input event influenced the analysis of the differences of paired-turbidity values.

During the construction of the Indian Creek pipeline crossing, HDD was used to drill under Indian Creek. As part of the drilling, water and associated sediment were pumped from the drill site and stored in a series of two on-site settling tanks. Most of the suspended material settled out within the first settling tank. This water was then passed to a second settling tank where additional deposition of particulate constituents occurred. The stored water was then released through a filter bag onto a grassy field that drained into Indian Creek. The discharge location selected for the release in the grassy field caused the release water to flow into Indian Creek downstream from the downstream monitor. Thus, it cannot be determined whether this activity affected water-quality conditions in Indian Creek.

Summary and Conclusions

In 2006, the USGS, in cooperation with East Tennessee Natural Gas and USFWS, began a study to monitor the effects of construction of the Jewell Ridge Lateral natural gas pipeline on suspended-sediment concentrations below the pipeline crossing beneath Indian Creek and through an unnamed tributary to Indian Creek in Tazewell County, Virginia. The Biological Opinion, prepared by the USFWS, required that turbidity conditions be intensively monitored below the pipeline crossings because of the presence of threatened and endangered mussel species. Indian Creek is listed as one of the Virginia Department of Game and Inland Fisheries' designated Threatened and Endangered Species Waters and contains federally designated critical habitat for two endangered freshwater mussel species, purple bean (*Villosa perpurpurea*) and rough rabbitsfoot (*Quadrula cylindrical strigillata*).

Additionally, Indian Creek contains the last known reproducing population of the tan riffleshell (*Epioblasma florentina walkeri*). The primary objective of the USGS monitoring effort was to identify whether the construction of the Indian Creek pipeline crossing would adversely impact the suspended-sediment concentrations, using turbidity as a surrogate. The specific study objectives were to (1) develop a continuous turbidity monitoring network that attempted to measure real-time changes in suspended-sediment conditions (using turbidity as a surrogate) downstream from the pipeline crossing in Indian Creek and the unnamed tributary to Indian Creek, and (2) provide continuous turbidity data that allow for the development of a turbidity-input warning system and assessment of long-term changes in turbidity conditions.

Water-quality conditions were assessed using continuous water-quality monitors deployed upstream and downstream from the pipeline crossings in Indian Creek and the unnamed tributary. In Indian Creek, two water-quality monitoring sondes were suspended from a boom upstream from the pipeline crossing so that one monitor was submersed near the left bank and the second monitor was submersed near the right bank. Two additional water-quality monitoring sondes were suspended from a boom downstream from the pipeline crossing so that one monitor was submersed near the left bank and the second monitor was submersed near the right bank. These paired upstream and downstream monitors were outfitted with turbidity, pH, specific conductance, and water-temperature sensors. In the unnamed tributary, two water-quality monitoring sondes were deployed upstream and downstream from the pipeline crossing. The paired upstream and downstream monitors were outfitted with turbidity, specific-conductance, water-temperature, and water-level sensors. Water-quality data were collected continuously (every 15 minutes) during three phases of the pipeline construction: pre-construction (April 28, 2006, through May 31, 2006), during construction (June 1, 2006, through August 31, 2006), and post-construction (September 1, 2006, through April 9, 2008), transmitted hourly via satellite transmission, and made publicly available on the USGS NWIS Web page (*http://waterdata.usgs.gov/va/nwis/nwis*).

Continuous turbidity data were evaluated at various time steps to determine if the construction of the pipeline crossings had an effect on downstream suspended-sediment conditions in Indian Creek and the unnamed tributary. Hourly evaluations of paired upstream- and downstream-turbidity data were performed by the on-site managers from East Tennessee Natural Gas to ensure that the difference in the paired turbidity values was within the established threshold. This threshold required that downstream turbidity values could not be 6 FNU, or 15 percent greater than the paired upstream turbidity value. If the established threshold was exceeded for a sustained period of 1 hour, then an on-site inspection was required to ensure sediment was not actively being transported from the construction site. At the monthly and phase-of-construction time step, a signed-rank test was performed on the paired differences of the upstream and downstream turbidity values to test the null hypothesis that the median paired difference value was equal to zero. If the null hypothesis was accepted, then the construction of pipeline crossing had no effect on downstream sediment conditions; conversely, if the null hypothesis was rejected, then it would be concluded that pipeline construction did affect downstream sediment conditions.

The results of this intensive water-quality monitoring effort indicate that values of turbidity in Indian Creek increased significantly between the upstream and downstream water-quality monitors during the construction of the Jewell Ridge pipeline. The magnitude of the turbidity increase, however, is small (less than 2 FNU). The results from this study indicate that the source of the increased turbidity, detected within the pipeline-crossing easement during construction, primarily can be linked to sediment delivered to Indian Creek from an ephemeral unnamed tributary. The primary source of the sediment in the ephemeral unnamed tributary is from runoff from the upland pipeline construction right-of-way. Conversely, turbidity conditions in the unnamed tributary were not adversely altered during the construction of the pipeline crossing. Turbidity data collected during the active construction of the dry-cut pipeline crossing through the unnamed tributary indicated that turbidity increased downstream; however, the increase in turbidity values was shown to be minimal compared to the turbidity values obtained during natural runoff events.

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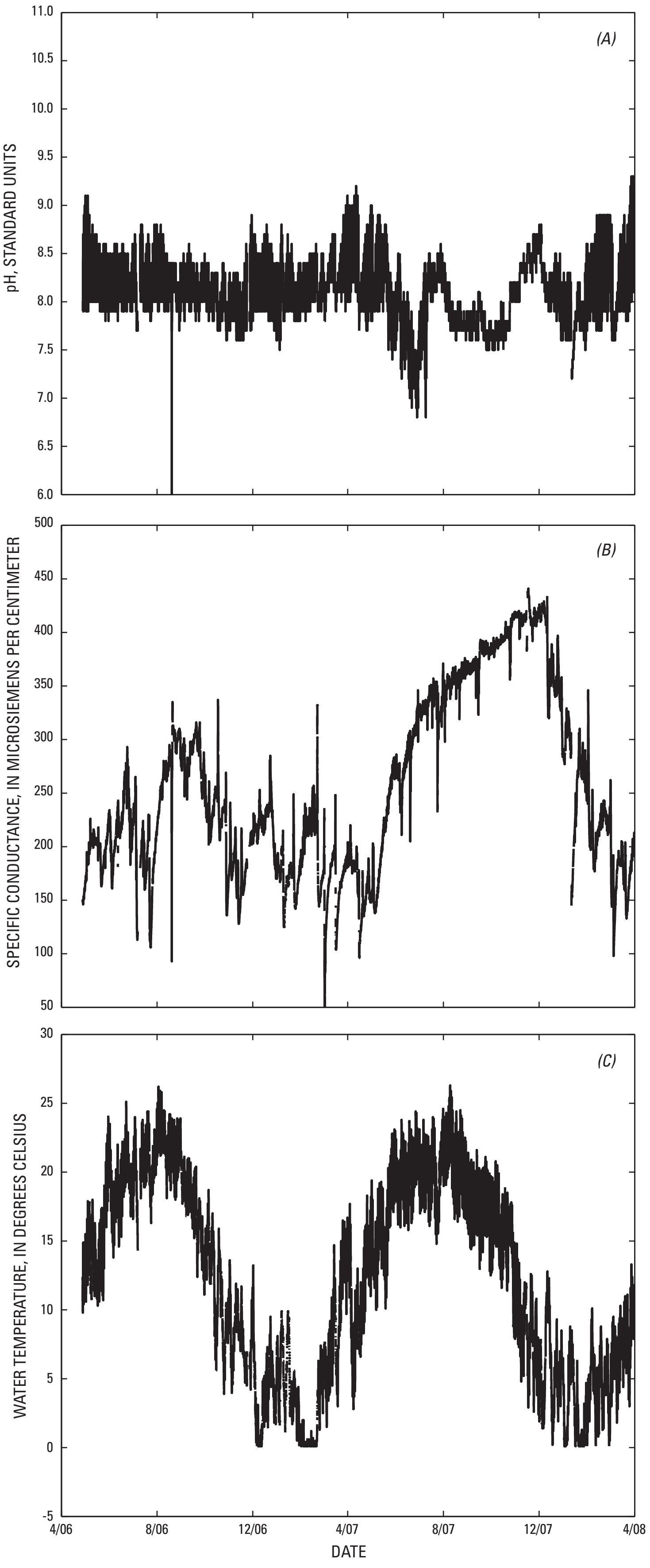
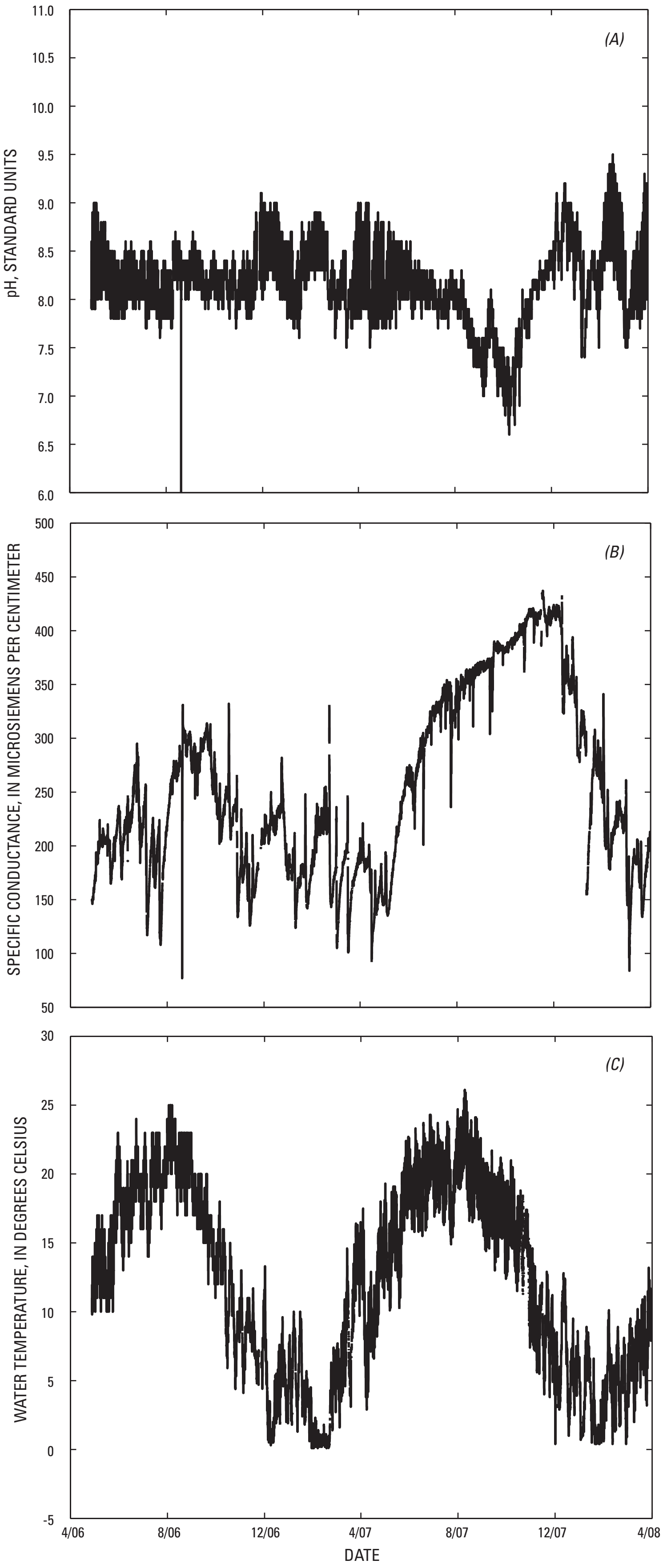
Appendixes 1–6

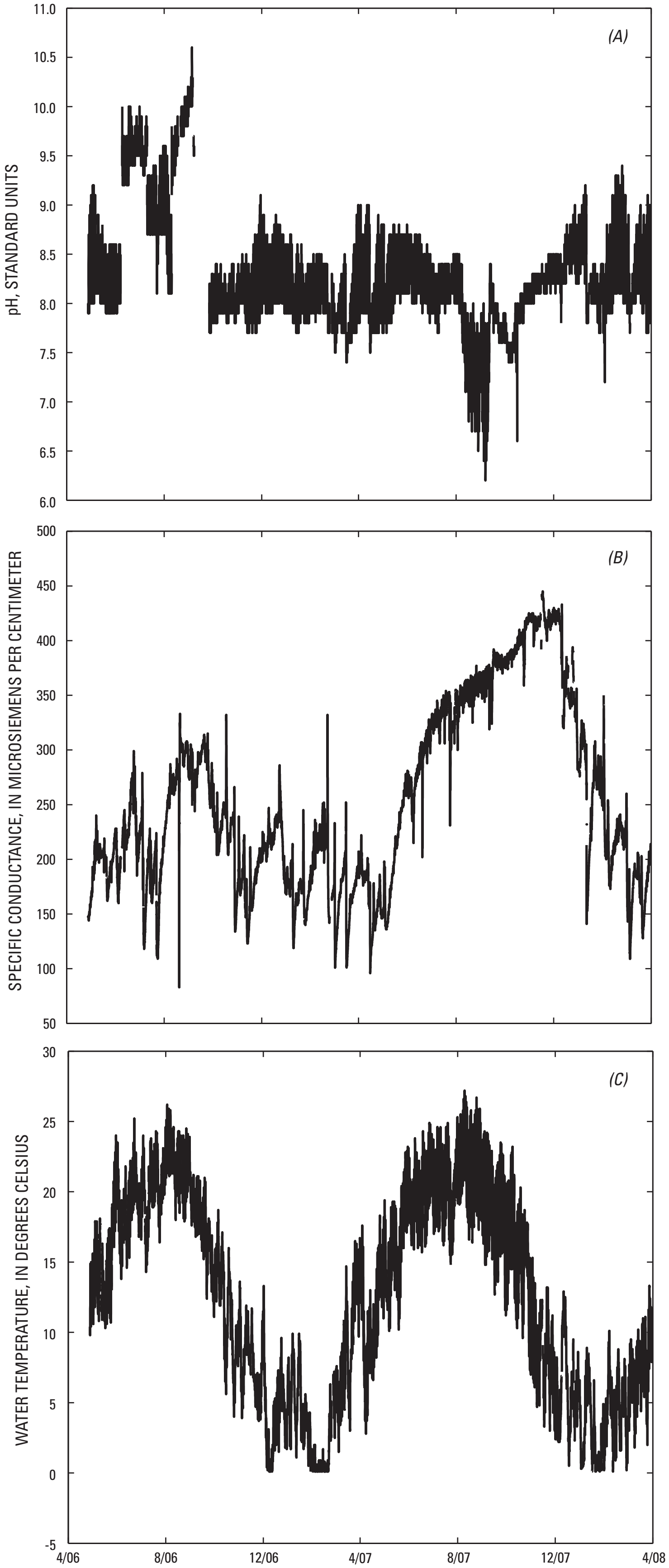
The following appendixes provide graphs showing continuous water-quality data collected from Indian Creek and an unnamed tributary, Tazewell County, Virginia.



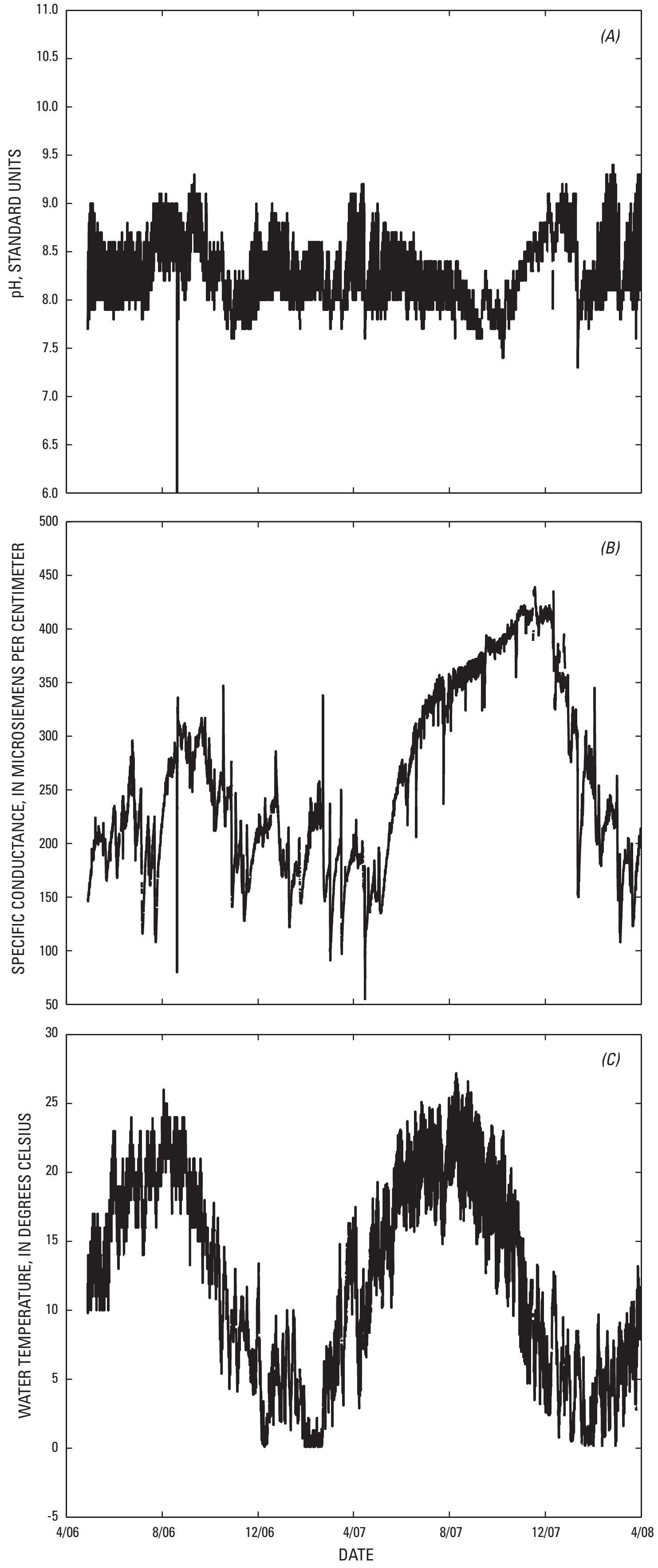
Appendix 1. Continuous water-quality data (15-minute interval) collected from Indian Creek, Tazewell County, Virginia, at the upstream (Station number 03520967) left-bank water-quality monitor: (*A*) pH, (*B*) specific conductance, and (*C*) water temperature.



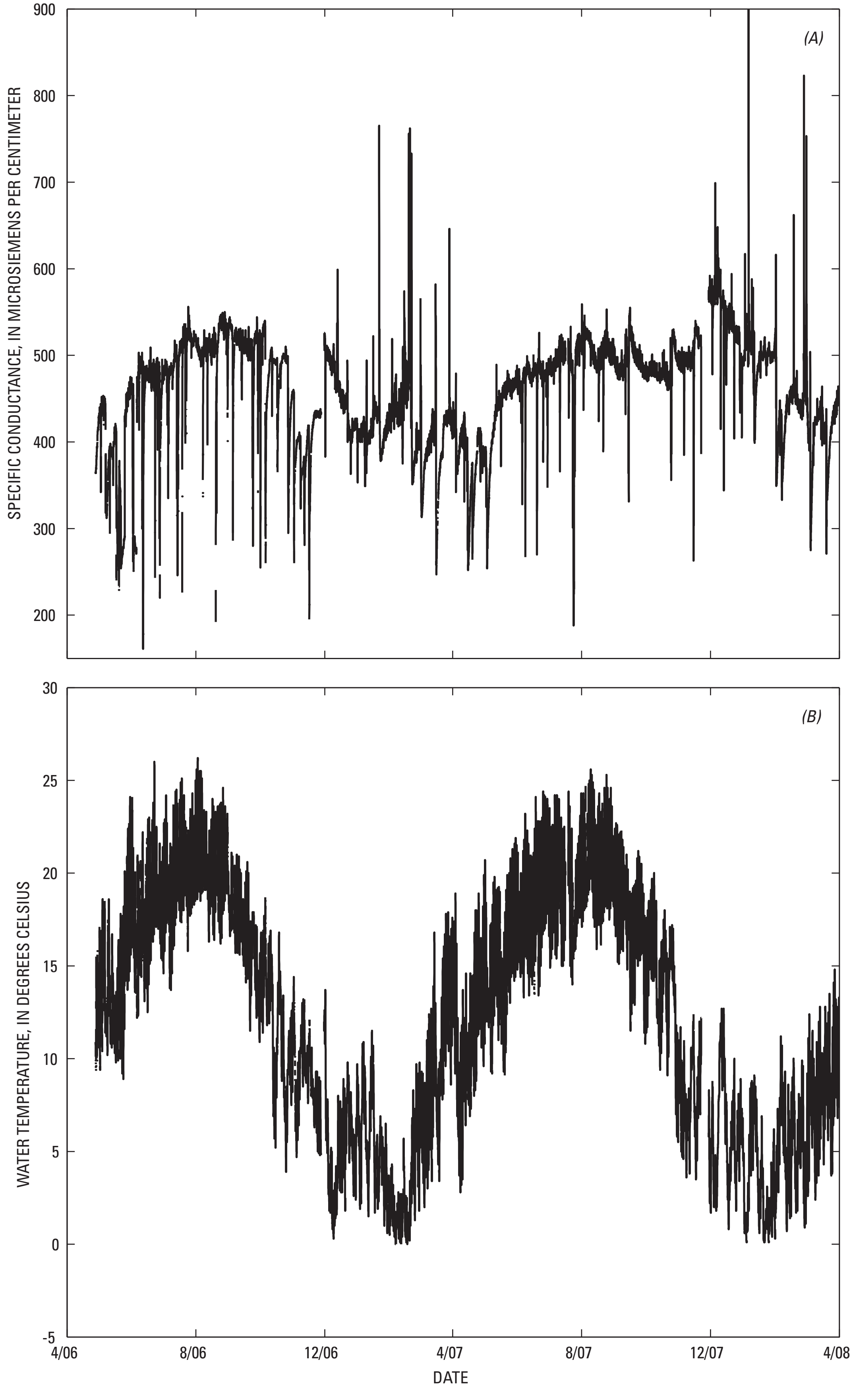
Appendix 2. Continuous water-quality data (15-minute interval) collected from Indian Creek, Tazewell County, Virginia, at the upstream (Station number 03520967) right-bank water-quality monitor: (*A*) pH, (*B*) specific conductance, and (*C*) water temperature.



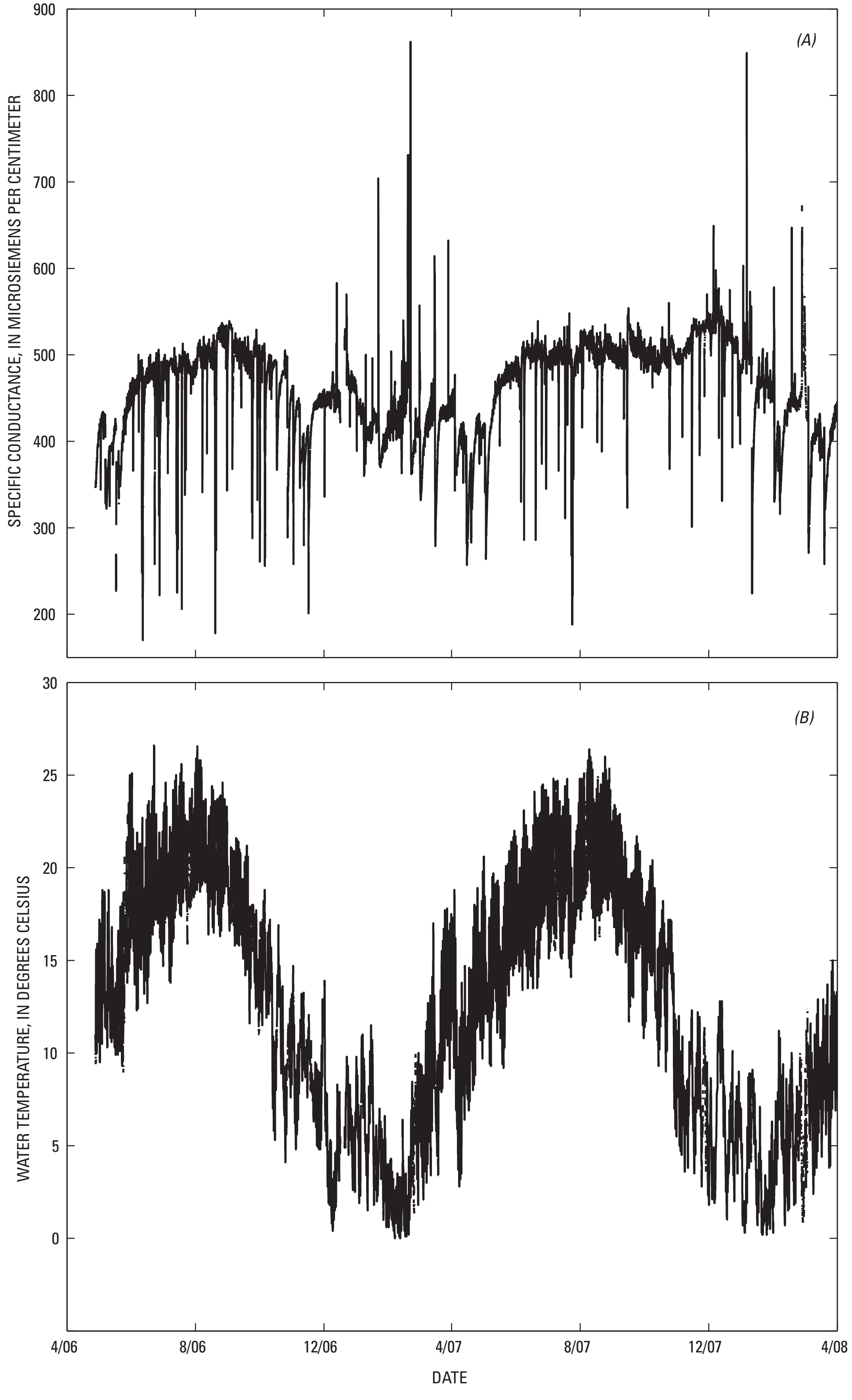
Appendix 3. Continuous water-quality data (15-minute interval) collected from Indian Creek, Tazewell County, Virginia, at the downstream (Station number 03520968) left-bank water-quality monitor: (*A*) pH, (*B*) specific conductance, and (*C*) water temperature.



Appendix 4. Continuous water-quality data (15-minute interval) collected from Indian Creek, Tazewell County, Virginia, at the downstream (Station number 03520968) right-bank water-quality monitor: (*A*) pH, (*B*) specific conductance, and (*C*) water temperature.



Appendix 5. Continuous water-quality data (15-minute interval) collected from the unnamed tributary, Tazewell County, Virginia, at the upstream (Station number 03520980) water-quality monitor: (*A*) specific conductance and (*B*) water temperature.



Appendix 6. Continuous water-quality data (15-minute interval) collected from the unnamed tributary, Tazewell County, Virginia, at the downstream (Station number 03520981) water-quality monitor: (*A*) specific conductance and (*B*) water temperature.

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