Hydrological and Geophysical Investigation of Streamflow Losses and Restoration Strategies in an Abandoned Mine Lands Setting

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ABSTRACT

Longitudinal discharge and water-quality campaigns (seepage runs) were combined with surface geophysical surveys, hyporheic zone temperature profiling, and watershed-scale hydrological monitoring to evaluate the locations, magnitude, and impact of stream-water losses from the West Creek sub-basin of the West West Branch Schuylkill River into the underground Oak Hill Mine complex that extends beneath the watershed divide. Abandoned mine drainage, containing iron and other contaminants, from the Oak Hill Boreholes to the West Branch Schuylkill River was sustained during low-flow conditions and correlated to streamflow lost through the West Creek streambed. During high-flow conditions, streamflow was transmitted throughout West Creek; however, during low-flow conditions, all streamflow from the perennial headwaters was lost within the 300 to 600 m "upper reach," where an 1889 mine map indicated steeply dipping coalbeds underlie the channel. During low-flow conditions, the channel within the "intermediate reach," 700 to 1,650 m downstream, gained groundwater seepage with higher pH and specific conductance than upstream; however, all streamflow 1,650 to 2,050 m downstream was lost to underlying mines. Electrical resistivity and electromagnetic conductivity surveys indicated conductive zones beneath the upper reach, where flow loss occurred, and through the intermediate reach, where gains and losses occurred. Temperature probes at 0.06 to 0.10 m depth within the hyporheic zone of the intermediate reach indicated potential downward fluxes as high as 2.1 $\times$ 10^{-5} m/s. Cumulative streamflow lost from West Creek during seepage runs averaged 53.4 L/s, which equates to 19.3 percent of the daily average discharge of abandoned mine drainage from the Oak Hill Boreholes and a downward flux of 1.70 $\times$ 10^{-5} m/s across the 2.1 km by 1.5 m West Creek stream-channel area.

INTRODUCTION

Problem

The availability and quality of water are of global importance (WWAP, 2012) and can be severely limited in mined landscapes, where the natural hydrology and aquatic ecology can be extensively disturbed

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(Bernhardt et al., 2012; Feng et al., 2014). Dynamic hydrological variations commonly result in abandoned mine land (AML) watersheds because of rapid transfers of runoff, recharge, and discharge through the disturbed surface and subsurface combined with chemical interactions between the water and rock (Cifelli and Rauch, 1986; Dixon and Rauch, 1990; Carver and Rauch, 1994; and Cravotta et al., 2014). The formation and release of abandoned mine drainage (AMD), which is characterized by elevated concentrations of dissolved sulfate, iron, and other metals derived from the oxidation of pyrite and other sulfide minerals, can negatively impact aquatic environments and water supplies for decades after coal or metal mines have closed (Younger, 1997; Lambert et al., 2004; Cravotta, 2008; Mack et al., 2010; Nordstrom, 2011; and Burrows et al., 2015). Likewise, the loss of stream water to underlying mines can decrease the supply of clean, potable water while adding to the AMD volume and pollution loads further downstream in a watershed (Younger and Wolkersdorfer, 2004; Goode et al., 2011; and Cravotta et al., 2014).

An understanding of the inter-relations and aquatic impacts of streamflow losses and the associated AMD is needed to identify remediation priorities and watershed restoration strategies in AML areas. Specific information on plausible recharge and discharge locations and, particularly, the locations of stream leakage to underground mines can be used to design and implement stream restoration to abate streamflow losses (Ackman and Jones, 1991). If the streamflow can be transmitted from headwaters downstream, bypassing the mines, the stream habitat can be improved, the total volume of water that flows through the mines and emerges as AMD can be decreased, and pollutant transport within the watershed may be decreased. However, the locations and quantities of stream-water losses can be difficult to identify because streamflow can be gained or lost at numerous locations within a stream channel, or it can vary from gains to losses at a given location, depending on streamflow volume and other factors.

This paper reports on the use of hydrological and geophysical methods of investigation in an AML area (1) to identify the primary locations, quantities, and effects of streambed leakage on the streamflow and aquatic habitat and (2) to document quantitative and qualitative relations between the streamflow losses to inter-basin transfer as groundwater and the subsequent discharge of AMD in an adjacent watershed.

Background

Instantaneous stream discharge and water-quality measurements during stable flow conditions along a defined length of a stream channel can be used to indicate spatial variations in stream characteristics. These longitudinal discharge surveys are commonly referred to as seepage runs and are typically used to document the magnitude and locations of streamflow loss or gain due to groundwater seepage (e.g., Risser, 2006). The stream discharge at each station along the stream is the product of the measured cross-sectional area and the mean water velocity at that station (Rantz et al., 1982). Nonuniform geometry of the stream channel, irregularities and obstructions on the streambed, coarse or porous substrate that transmits a large fraction of flow through the hyporheic zone, and/or slow flow velocity or shallow water depth are common factors that contribute to errors in the area-velocity measurement of discharge in small streams. Although alternative methods, such as weirs and flumes, generally can improve the accuracy of discharge measurement (e.g., Rantz et al., 1982), these methods may be impractical for short-duration investigations or where channel or flow conditions are unstable or difficult to contain.

Chemical (tracer) dilution and natural water chemistry can be used to quantify inflows by groundwater or small tributaries to streams with complex channel characteristics (Schemel et al., 2006; Kimball et al., 2007; and Runkel et al., 2012). Groundwater entering a stream channel commonly has higher or lower specific conductance attributed to concentrations of specific dissolved ions, such as bicarbonate or sulfate, and/or may have different temperature than the stream water flowing down a channel from upstream locations. Thus, groundwater inflows can dilute artificial tracers (if added) from upstream inputs while also affecting the temperature, specific conductance, and concentrations of certain solutes. However, where streamflow gains *and* losses take place along the flow path, spatial variations in chemical tracers may be difficult to interpret because a decrease in tracer concentration could result from dilution (inflow) as well as a loss of mass (outflow from the channel). Measurement of all the inflows and outflows along the flow path generally is not feasible. Thus, changes in the natural chemistry of surface water compared to groundwater at various locations and times can be instrumental in determining the amount of exchange among the stream, hyporheic zone, and groundwater (Cardenas, 2009; Bianchin et al., 2011), particularly when longitudinal streamflow measurements are conducted to quantify the gains and losses.

Surface geophysical techniques, such as electrical resistivity and electromagnetic surveys, can be used to characterize the subsurface stratigraphy, saturation state, and grain-size variations within hydrologic systems. Electrical resistivity methods are particularly useful for monitoring changes in saturation state because there is a direct correlation between the percent saturation and the bulk resistivity (Archie, 1942). Thus, resistivity surveys have been successfully used to locate the water table (Reed et al., 1983), to record temporal and spatial variations in saturation and flow through the hyporheic zone and deeper subsurface (Nyquist et al., 2008; Clifford and Binley, 2010; Sherrod et al., 2012; Toran et al., 2012, 2013; and Ward et al., 2012), to identify groundwater seepage zones in streambed and lakebed sediments (Ackman and Jones 1991; Nyquist et al., 2008; and Toran et al., 2015), and to delineate preferential subsurface flow paths (Hagrey and Michaelsen, 1999; Yang et al., 2000). Likewise, electromagnetic conductivity measurements have proven useful to delineate zones of streambed leakage and shallow subsurface flow paths (Ackman and Jones, 1991; Grgich et al., 2004). Although surface geophysical methods can be used to estimate quantitative hydrologic properties (Binley et al., 2002a, 2002b; Vanderborght et al., 2005; Linde et al., 2006; and Johnson et al., 2009), it is often possible to glean useful qualitative information from results (Sherrod et al., 2012).

Time-series measurements of temperature within the hyporheic zone can indicate when the streambed becomes dry or water saturated and can be used to estimate the potential flux of water through streambed sediments (Constantz et al., 2001; Burkholder et al., 2008; Hyun et al., 2011; Briggs et al., 2012a, 2012b; and Daniluk et al., 2013). The vertical temperature gradient can be interpreted to quantify upward or downward fluxes corresponding to streamflow gains or losses, respectively (Gordon et al., 2012). Thus, a combined approach of seepage runs, surface geophysical surveys, and streambed temperature logging could be used to locate predominant zones of streambed leakage and to quantify the spatial and temporal variations in the flux through the streambed. Such information can then be used by watershed managers and hydraulic engineers to develop stream restoration strategies.

STUDY AREA

The Schuylkill River originates in uplands of Schuylkill and Carbon Counties in eastern Pennsylvania and flows more than 200 km southeastward to the Delaware River at Philadelphia (Figure 1). Along its course, the Schuylkill River is an important resource used for recreational fishing and boating, cooling water at thermoelectric generation facilities, and drinking water to more than 1.5 million people (Schuylkill Action Network, 2008). Nevertheless, the headwaters area of the Schuylkill River, referred to as the upper Schuylkill River, is underlain by the extensively mined Southern Anthracite Coalfield (Biesecker et al., 1968; Growitz et al., 1985). Environmental degradation associated with the legacy mining affects local and downstream aquatic resources.

Structurally, the Southern Anthracite Coalfield is a downwarped synclinorium (canoe-shaped fold), the axes of which generally parallel the northeast-southwest–trending ridges and valleys in the region (Wood et al., 1968). The coal-bearing Pennsylvanian-age rocks are commonly exposed on the valley sides and underlie the valleys. More than a dozen commercial coalbeds in the study area range in thickness from 2 to 3 m (Pennsylvania Geological Survey, 1889; Wood et al., 1968). Most of the anthracite mines in the area were developed during the mid-1800s to mid-1900s by the underground "room-and-pillar" method, which employed a complex network of shafts and tunnels within coal and across intervening strata to connect multiple coalbeds. Groundwater was typically pumped to the surface or to drainage tunnels during active mining, and, in various locations, streams crossing over the mines were rerouted to reduce infiltration and associated pumping costs (Ash et al., 1953). Unmined walls of coal, or "barrier pillars," usually were left intact at the mine boundaries that later acted as underground dams, restricting the flow of groundwater between adjacent mine complexes (Ash et al., 1949; Ash and Kynor, 1953) (Figure 1).

The abandoned underground mines in the upper Schuylkill River basin now are extensively flooded by groundwater. The flooded mine workings, referred to as mine pools, are drained by gravity through tunnels, boreholes, and fractures to numerous AMD outfalls on the Schuylkill River and its tributaries (Biesecker et al., 1968; Growitz et al., 1985). Elevated concentrations of sulfate, iron, and other metals in the AMD continue to degrade the quality of receiving streams (Cravotta et al., 2014). Consequently, 200 km of stream segments in the upper Schuylkill River basin are designated "impaired by AMD" and listed under the Clean Water Act section 303(d) (Pennsylvania Department of Environmental Protection, 2014).

Spatial and temporal hydrological variability can be extreme in AML areas. For example, surface water and groundwater within the upper Schuylkill River basin are intimately connected through karst-like features that facilitate dynamic changes in groundwater recharge, storage, and discharge and that permit the inter-basin transfer of groundwater. Perennial streams crossing the abandoned underground mines beneath the West West Branch Schuylkill River and West Branch Schuylkill River (Figure 1) lose water and may stop flowing because of streambed leakage to the mines, while streamflow in downstream segments of the West Branch Schuylkill River is sustained by contaminated AMD outfalls from the Pine Knot Tunnel (PKN) and the Oak Hill Boreholes (OAK) (Cravotta et al., 2014). Because of the inter-basin transfer of groundwater through the underground mines, the streamflow

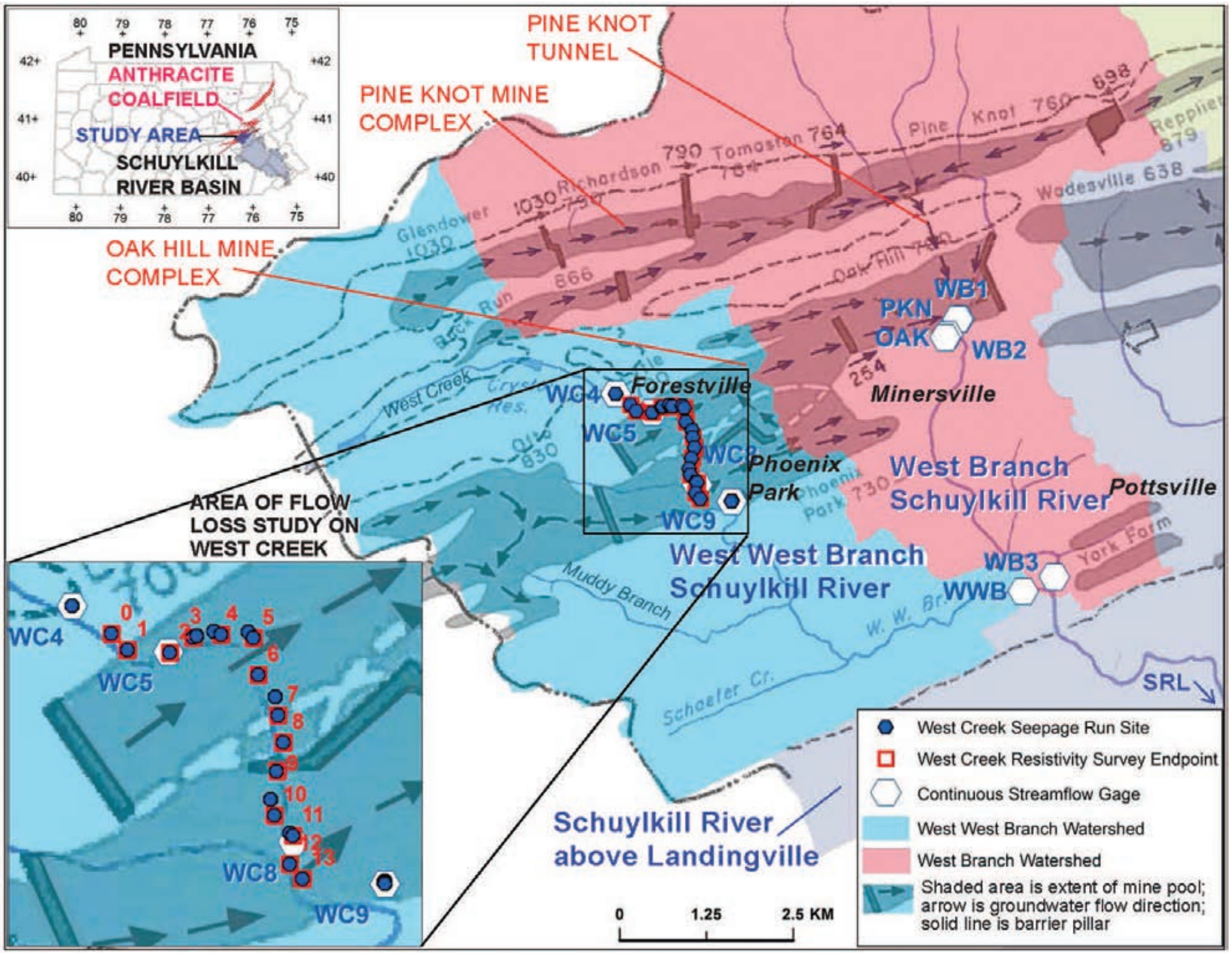

Figure 1. Topographic drainage basins (colored polygons), flooded extent of underground mines (dark gray shade), and hydrological monitoring sites in the upper Schuylkill River basin, Southern Anthracite Coalfield, Pennsylvania. Approximate areal extent of flooded underground mines, including barrier pillar locations and flow directions, was reported by Biesecker et al. (1968). Descriptions of monitoring sites are given in Table A1.

yield (discharge divided by topographic drainage area) for the West Branch Schuylkill River is larger than expected, and that of the West West Branch Schuylkill River is smaller than expected compared to nearby, unmined areas (Cravotta et al., 2014), as explained below.

West Creek is a perennial tributary, upstream from Muddy Branch, in the headwaters of the West West Branch Schuylkill River that drains mostly forested land (82 percent of the 22.4 km^2 watershed) and is unaffected by AMD (Figure 1). However, during low-flow conditions, segments of West Creek that cross underground mines downstream from the perennial headwaters (Figure 1) can lose all flow through the stream channel, resulting in intermittently dry segments (Figure 2).

Streamflow of West Creek in the segment extending southeastward (downstream) from Forestville (WC4) to Phoenix Park (WC9) has been hypothesized to leak from the stream channel to the underlying Oak Hill Mine complex (composed of the Lytle and Oak Hill Collieries, plus part of the Phoenix Park Colliery) and then flow as groundwater westward beneath the topographic watershed divide until it exits as AMD from the Oak Hill Boreholes outfall to the adjacent West Branch Schuylkill River (Figures 1 and 3) (Cravotta et al., 2014).

MATERIALS AND METHODS

This study employed multiple, complementary methods of investigation: (1) to identify the primary locations, quantities, and effects of streambed leakage on the streamflow and aquatic habitat of West Creek, and (2) to document potential quantitative and qualitative relations among the streamflow losses on West Creek, the discharge of AMD from OAK, and the effects on

Figure 2. Photographs of West Creek at WC4 above mined area (A, B) and at WC8 below mined area (C, D). Streamflow at WC4 is perennial; (A) high-flow conditions, (B) low-flow conditions. Streamflow at WC8 is intermittent; (C) high-flow conditions, (D) low-flow conditions.

downstream waters within the West Branch Schuylkill River and West West Branch Schuylkill River subbasins (Figure 1).

Discharge

Instantaneous and continuous streamflow measurements were taken at numerous locations throughout the study area. To investigate the magnitude and approximate locations of streamflow lost or gained along West Creek, standard area-velocity techniques were used to measure instantaneous discharge on a given date at multiple locations along the 3.1 km segment from WC4 to WC9 (Figure 1 and Table A1). These synoptic seepage runs were conducted for a range of flow conditions on nine dates during April 2012 to July 2015. On a given date, all the measurements were conducted using a top set wading rod equipped with either a Price pygmy current meter, SonTek FlowTracker2 (FT2) handheld acoustic Doppler velocimeter (ADV), or Marsh McBirney Model 2000-11 Flo-Mate portable velocity meter. Replicate measurements at a single cross section using different meters indicated consistent results for a given flow condition.

Streamflow-gauging stations for continuous monitoring of stream stage and discharge were established

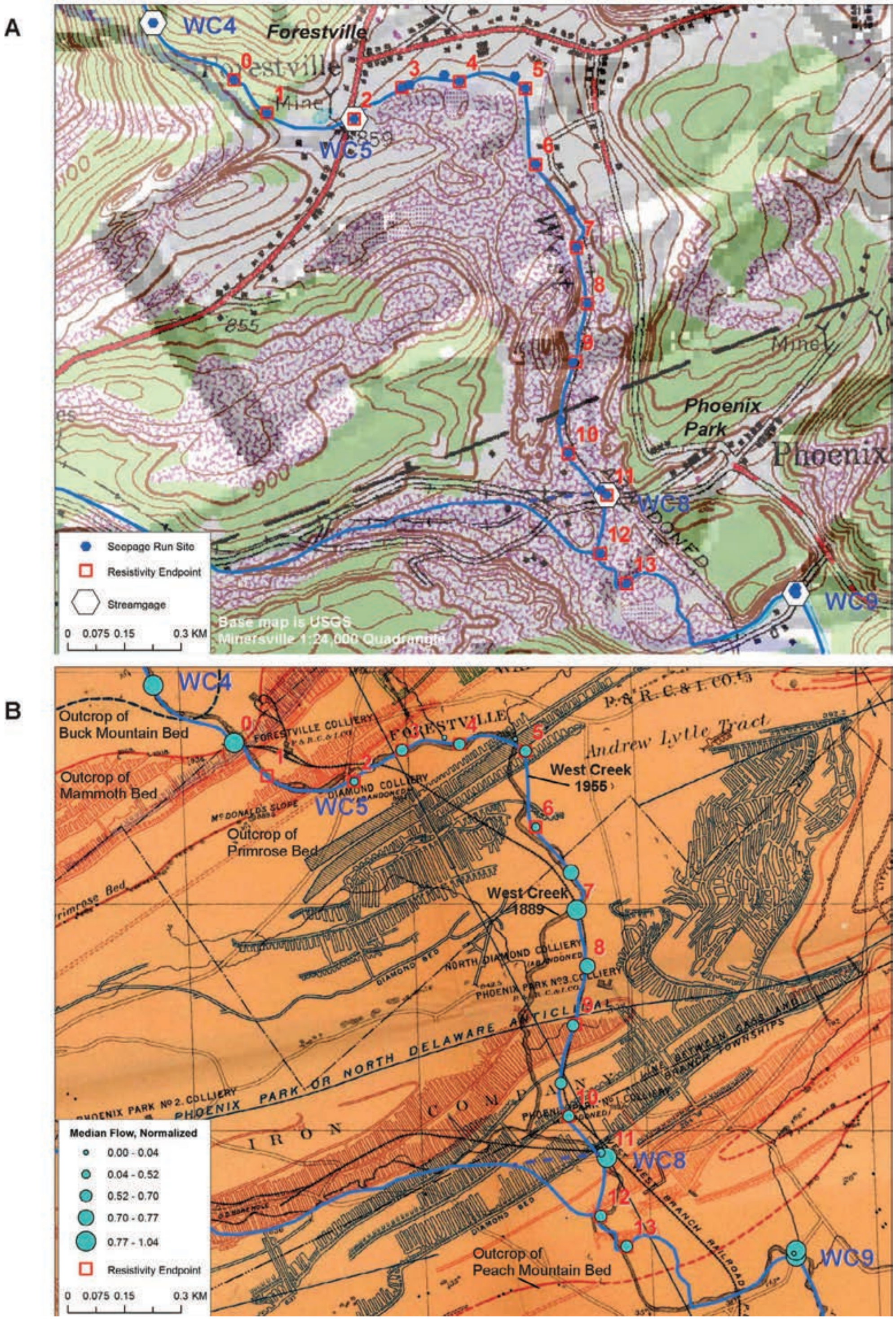

Figure 3. Detailed map views of West Creek flow-loss study area showing hydrological and geophysical survey site locations on: (A) 1:24,000 Minersville, PA, topographic map overlying flooded underground mine pools (Biesecker et al., 1968); and (B) historical underground mine map (Pennsylvania Geological Survey, 1889). Polygonal symbols on mine map represent underground mine workings. Current stream route (as mapped in 1955) is shown as blue trace on A and B. Point symbols indicate locations of streamflow gauges, seepage run sites, and the start and end of electrical resistivity survey segments (numbered 0–13). Graduated symbols for flow data indicate median normalized value compared to WC4 for seepage runs during May 2014 through July 2015.

by the U.S. Geological Survey (USGS) in 2014 at four locations on West Creek, near the top (WC4), bottom (WC9), and intermediate locations (WC5 and WC8) along the 3.1 km segment that crossed the Oak Hill Mine complex (Table A1). Other gauging stations were previously established in 2005–2006 at the nearby AMD outfall from PKN and at sites upstream (WB1) and downstream (WB3) from PKN on the West Branch Schuylkill River and the West West Branch (WWB) Schuylkill River and in 2014 at OAK (Figure 1 and Table A1). The four West Creek stations are topographically upstream from the streamflow gauge at WWB and are inferred to be hydrologically linked to the PKN and OAK outfalls and the associated downstream gauges on the West Branch Schuylkill River (WB2, WB3) by the underground mine pools that extend beneath the topographic divide between the two watersheds (Figure 1). At each streamflow gauging station, a vertical staff gauge and a submersible, vented pressure transducer were installed to measure stream stage (water depth). The transducers recorded the stage to a precision of 0.006 m or better at 15 minute intervals. The transducer data were downloaded, and streamflow was measured periodically from January 2012 through September 2015 for the current study. Discharge data are available in the USGS National Water Information System (NWIS; http://dx.doi.org/10.5066/F7P55KJN).

During the period of operation, instantaneous discharge at each gauging station was measured over a range of low-to-moderate flow conditions to develop stage-discharge ratings for each site (Rantz et al., 1982). Extrapolation of stage-discharge ratings for high-flow conditions was based on established ratings for the nearby long-term streamflow gauging station on the Schuylkill River at Landingville (SRL), which is 15 km downstream from WWB and WB3 (Table A1). The daily average streamflow values at each station were used with the PART computer program (Rutledge, 1998; Risser et al., 2005) to estimate the annual hydrologic budget for the contributing area above the station, including the percentages of total streamflow that were base flow and runoff. For the purposes of comparison with the limited flow record of the newer gauges on West Creek, the hydrograph analysis was completed for the 1 year period of July 2014 to June 2015 and also for the period October 2005 through September 2015, if available. By dividing the flow rate by the topographic drainage area or contributing area, the normalized flow rates (yields) could be compared to precipitation data for the period of interest and to those for other stations. Precipitation data for 2005–2015 were available from nearby USGS streamflow gauging stations (01469500, 01470500, 01468500) and a USGS weather station (403628076134201) within the upper Schuylkill River basin (USGS NWIS, http://dx.doi.org/10.5066/F7P55KJN); the average of daily totals at those stations were used for analysis.

Water Quality

Water-quality monitoring was conducted repeatedly at streamflow gauges and other selected sites to document the spatial and temporal variations in stream characteristics. Data on water-quality constituents at each synoptic streamflow site or streamflow gauging station were collected when discharge was measured or stage data were downloaded from pressure transducers. A YSI 556 multiparameter sonde was used to measure temperature, pH, specific conductance (SC), dissolved oxygen (DO), and oxidation-reduction potential (ORP) where flow was concentrated (typically near the staff gauge). The pH/ORP electrode was calibrated in pH 4.0, 7.0, and 10.0 buffer solutions and in ZoBell's solution. Values of ORP were corrected to 25°C relative to the standard hydrogen electrode (Eh) and used to compute the activities of Fe (II) and Fe (III) species from dissolved iron in accordance with the Nernst equation (Nordstrom, 1977).

Water-quality grab samples for chemical analysis were collected at least quarterly at the streamflow gauges on West Creek during 2014–2015 and the associated gauges on the West West Branch and West Branch Schuylkill River during 2012–2015 (Table A1; data available in USGS NWIS, http://dx.doi.org/10.5066/F7P55KJN). The alkalinity of the unfiltered water samples was titrated in the field using 0.16 N H_2SO_4 to a fixed end point pH of 4.5 (American Public Health Association, 1998). Concentrations of major anions (SO_4, Cl) in 0.45-μm-filtered, unpreserved subsamples were analyzed by ion chromatography (IC), and concentrations of major cations (Ca, Mg, Na, K) and selected trace metals (Fe, Mn, Al, Ni, Zn) in unfiltered, acidified subsamples and in corresponding 0.45-μm-filtered, acidified subsamples were analyzed by inductively coupled plasma–atomic emission spectroscopy (ICP-AES) or inductively coupled plasma–mass spectrometry (ICP-MS) using standard laboratory methods (Fishman and Friedman, 1989). Anion and cation analyses were conducted at the USGS National Water Quality Laboratory in Denver, CO, or the Actlabs Laboratory in Toronto, Ontario. USGS Standard Reference Water Samples (SRWS) submitted to each of the laboratories indicated comparable results for the major and trace constituents. The net-acidity concentration was calculated using selected data (pH, Fe, Mn, Al, and alkalinity) following methods of Kirby and Cravotta (2005). The pH and concentrations of selected trace metals (Zn and Ni) were compared to criteria for freshwater aquatic life, after adjusting for sample hardness (U.S. Environmental Protection Agency, 2013).

Electrical Resistivity

Surface geophysical surveys were conducted repeatedly along a 3.1 km segment of West Creek spanning the Oak Hill Mine complex. Electrical resistivity surveys along the stream channel were performed using an MPT DAS-1 Electrical Impedance Tomography System with 32 electrodes spaced at 5 m intervals (http://mpt3d.com/das1.html). Initial surveys were conducted along the "upper reach" from 230 to 530 m downstream from WC4 to WC5, in the area of Forestville (Figure 1, between points labeled 0 to 2), where complete flow loss had been observed. These surveys were conducted over a range of low- to moderate-flow conditions at approximately the same locations on April 27, September 13, and September 27, 2012. Additional resistivity surveys were conducted during moderately high-flow conditions May 12–15, 2014, along the 2.1 km segment that begins in the upper segment at approximately 400 m downstream from the streamflow gauge at WC4 and ends in the lower segment approximately 2540 m downstream from WC4 and 270 m downstream from WC8 (Figure 1). Eleven surveys of 155 m length and a twelfth of 110 m length were numbered 1 to 12 in downstream sequence (Figure 1). The surveys were generally conducted along straight segments and skipped segments where sharp bends were present. Thus, the ending and starting locations of sequential surveys did not always coincide (e.g., survey 1 was located between resistivity points 1 and 2; survey 12 was located between resistivity points 12 and 13). The electrical resistivity data are available at http://faculty.kutztown.edu/sherrod/PublicationMaterials.

A dipole-dipole array, which is useful for resolving spatially confined objects in the near subsurface (Oldenburg and Li, 1999; Schrott and Sass, 2008), was chosen for collection and processing of the resistivity data. A base electrode '*a*' spacing of 5 m was used with a maximum n value of 6. The *a* spacing was expanded to values of 10 m, 15 m, and 20 m as possible with the 32 electrodes to achieve greater depth of penetration. The resistivity data were inverted with ERTLab (Geostudi Astier srl and Multi-Phase Technologies LLC, 2006). The data for each survey were filtered to remove readings from electrodes with poor contact (the pebble- to boulder-sized sediment of the streambed sometimes inhibited the passage of current into the subsurface, especially when the stream channel was dry) or with a voltage of less than 0.1 mV, projected onto a mesh having one quarter of the electrode spacing, and inverted with the numerical core set to 10 maximum outer inversion iterations, 15 maximum internal iterations, and a tolerance of 0.001 for the internal iterations. The initial roughness factor was set to 10, and the data percent error for noise was set to 3 percent, with a constant error term of 0.001 mV. These parameters constrain the inversion process and are described in detail in the ERTLab documentation (Geostudi Astier srl and Multi-Phase Technologies LLC, 2006). All surveys were allowed to converge to an inversion solution with a data residual of less than the chi-square value, indicating a good fit of the inversion model to the raw data and forward model (LaBrecque et al., 1996).

Electromagnetic Conductivity

Surface electromagnetic (EM) survey data were collected by using an EM-31 apparent conductivity device manufactured by Geonics along most of the same 2.1 km segment of West Creek that had been surveyed in 2014 using resistivity (Figure 1; stations 0 to 11). The EM survey was completed by wading the stream during moderate-flow conditions on December 7 and 8, 2015, and recording conductivity readings at 10 m spacing along the approximate midpoint in the stream channel. Both horizontal dipole (HD) and vertical dipole (VD) measurements were obtained by holding the instrument in a horizontal position 1 m above the streambed and then rotating the instrument 90 degrees (along the horizontal axis) to take the second reading. The orientation of the pole-like instrument, when taking readings, was parallel to the stream channel (with the transmitter pointing downstream and the receiver pointing upstream). The effective depths of exploration for the horizontal and vertical dipoles are approximately 6 m and 3 m, respectively, beneath the stream channel. Ackman and Jones (1991) and Grgich et al. (2004) previously demonstrated that such measurements could indicate zones of relatively high conductivity associated with flow loss through vertical water-filled fractures and water-filled subsidence-related voids within the first 6 m beneath the stream channel. The EM survey data are available at http://faculty.kutztown.edu/sherrod/PublicationMaterials.

Streambed Temperature Profiles

To document potential temporal variations in streambed leakage, temperature probes were installed into the streambed along the intermediate segment of West Creek within the boundaries of resistivity surveys 6, 7, 9, 10, and 11 (Figure 1). Each probe was constructed of metal conduit (pipe) with cutouts at fixed distances to accommodate data-logging temperature sensors (Thermocron iButtons model #DS1922L, Embedded Data Systems, www.embeddeddatasystems.com). The uppermost sensor was installed at the top of streambed, such that the other three sensors were at depths of approximately 0.03 m, 0.06 m, and 0.10 m within the streambed. The temperature sensors were programmed to record data at 20 minute intervals using a resolution of $\pm 0.0625°C$ at an accuracy of $\pm 0.5°C$. Two sets of probes were installed, each for a 2 month period: the first set during September 12–November 6, 2014, and the second during November 11, 2014–January 5, 2015. During the first period, stream-water levels were low. Although water was pooled in some areas, the stream was not flowing at the time of installation nor at the time of extraction. The second set of temperature probes was installed in approximately the same location as the first set. The stream was not flowing at the time of installation, but it was flowing at a moderate stage at the time of extraction of the second set of probes. The Matlab program VFLUX (Gordon et al., 2012) was used to calculate the vertical flux through the streambed at high temporal resolution. The flux was calculated for the intervals between the sensors, with the deepest (0.085 m) corresponding to the depth interval 0.06 to 0.10 m. Soil parameters in the program were set to the default values (porosity, $N =$ 0.28; thermal dispersivity, Beta = 0.001 m; baseline thermal conductivity, kCal = 0.0045 cal/[s·cm·°C]; volumetric heat capacity of sediment, C_SCal = 0.5 cal/[cm^3·°C]; volumetric heat capacity of water, C_WCal = 1.0 cal/[cm^3·°C]), which are within the range of expected values for site conditions with large rocks and boulders overlying sandy sediment with minor silts and clays (Lapham, 1989). The temperature data are available at http://faculty.kutztown.edu/sherrod/PublicationMaterials.

RESULTS AND DISCUSSION

The results from longitudinal streamflow and water-quality surveys, surface geophysical surveys, streambed temperature profiles, continuous streamflow gauging, and quarterly water-quality monitoring at selected stations within West Creek and the surrounding watersheds were obtained independently. Thus, the results can generally be presented and discussed independently, but herein they are integrated to provide context for discussion and interpretation of the information provided by the different methods.

Streamflow and Water Quality Vary Spatially and Temporally

Synoptic measurements of streamflow and water quality along the 3.1 km study segment of West Creek (between WC4 and WC9) documented multiple locations and variations in the quantities of losses and gains in streamflow. Repeated measurements on different dates at the seepage survey stations, which generally coincided with the end points of the resistivity survey segments (Figure 3A), indicated substantial spatial and temporal variability. Thus, to reveal typical downstream changes, the streamflow values at downstream points were normalized to (divided by) the streamflow value at the most upstream station on that date, and the median normalized streamflow and the median water quality at each station along the main channel were emphasized (Figures 3B and 4).

Measurable streamflow was observed along the entire length of West Creek during typical base-flow (median) to high-flow conditions (Figures 3B and 4) and was recorded continuously at the upstream station, WC4, and downstream station, WC9 (Figure 5). However, during low-flow conditions, complete losses of streamflow in the 300 to 600 m "upper reach" between stations WC4 and WC5, between resistivity stations 0 and 2, and dry conditions at WC5 and various intermediate points to WC8 were observed, specifically during low-flow seepage runs in April and September 2012 and August and November 2014 (Figures 4 and 5A).

Streamflow was added to West Creek by intermittent contributions from three small, unnamed tributaries and diffuse groundwater inflows within the intermediate segment from 700 to 2,350 m downstream from WC4. For example, despite intermittent streamflow (intermittent dry channel) upstream and downstream, continuous groundwater inflows resulted in perennial streamflow in a short segment 1,400 to 1,500 m downstream from WC4, between resistivity stations 6 and 7. Nevertheless, streamflow 1,650 to 2,050 m downstream from WC4, between stations 7 and 10, was intermittent and completely lost from the channel during low-flow conditions.

The locations where streamflow frequently disappeared, between resistivity stations 0 and 2 (upstream from WC5) or stations 7 and 10 (upstream from WC8), extended further upstream within these segments as the amount of streamflow transmitted from the headwaters decreased. Likewise, at moderate- to high-flow conditions, only partial flow losses or minor gains were recorded in these "losing" segments (Figures 3B, 4, and 5B). The net change in streamflow volume could be positive or negative, depending on whether losses within a measurement segment exceeded the combined volumes of the inflows and any water transmitted from upstream. Other investigations of streams underlain by longwall mines in the northern Appalachian Coalfield (e.g., Cifelli and Rauch, 1986; Dixon and Rauch, 1990; and Carver and Rauch, 1994) showed some segments of stream reaches that dried up during

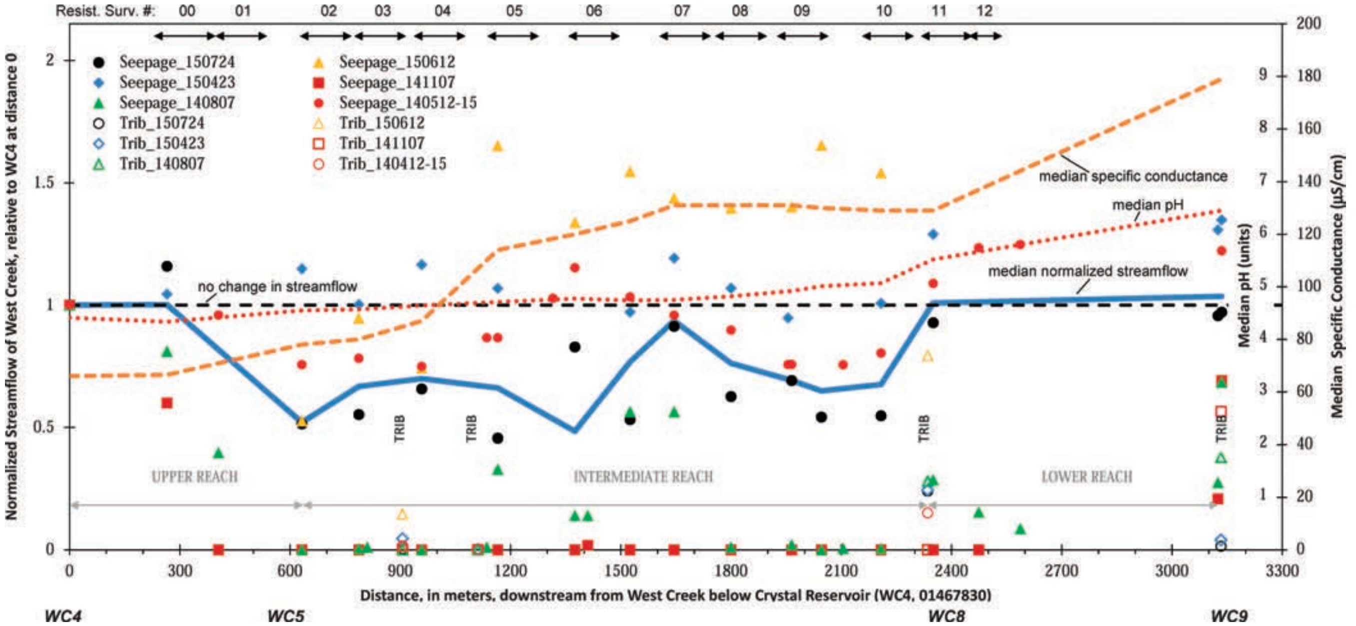

Figure 4. Summary results of seepage surveys along the 3.1 km study length of West Creek from WC4 (0 m) to WC9 (3130 m) during May 2014 to July 2015. Streamflow was normalized by dividing the measurement at each point by the streamflow value at WC4 on the date of the survey. Point symbols indicate individual streamflow measurements, solid symbols indicate values within the channel, and open symbols indicate measurements at tributaries. Electrical resistivity survey locations, illustrated at the top, provide spatial context; detailed results of the resistivity surveys are given in Figures 7, 8, and 10.

low-flow conditions could show gains during high-flow conditions while still losing some water to the underground mine(s). Because both gains and losses could have taken place between flow measurement stations on West Creek on a given date, the water-quality variations along the flow path augmented the streamflow measurements.

The pH and SC of West Creek increased progressively downstream from WC5 to WC9 (Figure 4), primarily because of volumetrically small inflows of high-ionic-strength, net-alkaline groundwater seepage that were of increasing importance during low-flow conditions. The high SC and pH of the groundwater and other inflows in the intermediate segment contrasted with the low SC and pH of water transmitted downstream from the headwaters. Thus, the chemical data revealed gains in streamflow downstream or within the same segments that experienced flow losses. Because of such gains combined with downstream losses along the streamflow path, the total streamflow lost from West Creek along its flow path was greater than the simple difference between streamflow measured at the most upstream point at WC4 and the downstream points at WC8 or WC9 (Figure 4 and Table A2). (The total flow entering West Creek upstream from WC8 or WC9 is the sum of that at WC4 plus any gains from tributaries and groundwater inflows documented during seepage surveys.)

Despite a high-quality physical aquatic habitat at the most upstream site on West Creek, WC4 (Figure 2; see Supplemental Material), the water chemistry was net acidic (median 3.9 mg/L as $CaCO_3$) with relatively low pH (4.5), low SC (70 µS/cm), low concentrations of sulfate (13.5 mg/L), iron (0.045 mg/L), and hardness (9.9 mg/L as $CaCO_3$), and elevated concentrations of dissolved aluminum (0.40 mg/L) and zinc (0.034 mg/L) compared to the water sampled in the intermediate to lower segments of West Creek (WC8, WC9; Table A3). Because of its acidity and moderately elevated concentrations of aluminum and zinc, the water at WC4 did not meet criterion continuous concentration (CCC) thresholds for protection of freshwater aquatic life (Table A3) and did not support fish (as reported in the Supplemental Material). Water quality similar to that at WC4 was observed at WC5, when streamflow was transmitted downstream through the upper segment to WC5. However, during low base-flow conditions, streamflow disappeared along the stream channel before reaching station WC5. Nevertheless, further downstream at points along the flow path to WC8 and WC9, streamflow with progressively higher pH and SC appeared within the channel as evidence of streamflow gains (Figure 4).

Although streamflow was intermittent at WC5 and WC8, perennial streamflow was maintained within a segment between resistivity end-points 6 and 7 in the

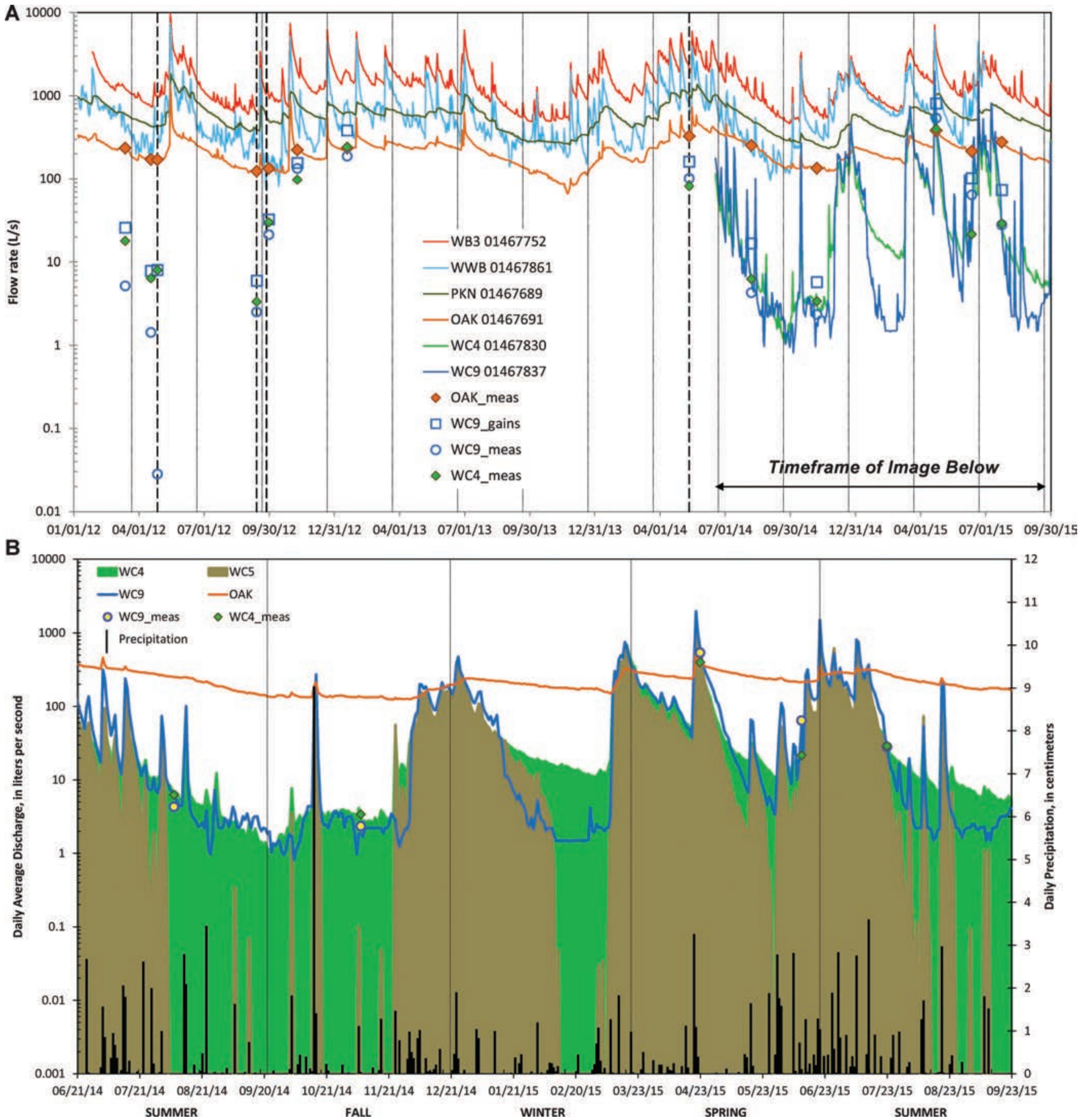

Figure 5. Daily discharge hydrographs for West Branch (WB3), West West Branch (WWB), Pine Knot Tunnel (PKN), Oak Hill Boreholes (OAK), and three streamflow gauges on West Creek (WC4, WC5, and WC9, in downstream order) during 2012–2015 study period: (A) daily discharge, with symbols indicating the measured flows at WC4 and WC9 plus the estimated cumulative inflow (WC9_gains) from WC4 to WC9 (flow at WC4 plus total of inflows to WC9) during synoptic seepage surveys, with vertical dashed lines for resistivity survey dates, and (B) comparison of daily discharge at OAK, WC4, WC5, and WC9, plus daily precipitation data for June 2014–September 2015.

intermediate segment between WC5 and WC8 (Figures 3 and 4) and in a longer segment in the downstream segment below end-point 12 to WC9. As explained in more detail later, these perennial stream segments coincided with the original, natural channel route, whereas the adjoining intermittent segments coincided with zones of historical coal outcrops or shallow underground mining (Figure 3B). Water-quality samples at WC9 were net alkaline (median net acidity <0) with near-neutral pH (6.6), elevated SC (315 µS/cm), elevated concentrations of sulfate (99 mg/L) and hardness (108 mg/L as $CaCO_3$), moderate concentration of iron (0.075 mg/L), and low concentration of aluminum (<0.1 mg/L) compared to the median values for upstream samples (Table A3). However, during high-flow conditions, a larger proportion of streamflow was transmitted from the headwaters to downstream points on West Creek. Under such conditions, the downstream water quality retained much of its upstream character (low pH, low SC, low hardness) because proportionally smaller inflows of groundwater had less influence on the overall downstream water quality. During high flows, the streamflow and water-quality measurements indicated net gains from WC4 to WC9, despite streamflow leakage through the streambed to the mine(s). Because of the streambed leakage, the rate of streamflow gain (e.g., L/s/km^2 of drainage area), or yield, was less than expected if no mining had occurred (Tables 1 and A2, see "Annual Water Budget for Study Period" section).

The stream water near the mouth of the West West Branch (WWB), downstream from the confluence of West Creek and Muddy Branch, was consistently net alkaline with near-neutral pH (median 7.5) and relatively low concentrations of dissolved metals compared to upstream sites and CCC thresholds (Table A3). Excess acidity, if present, from West Creek was offset by alkalinity contributions downstream from WC9, including additional groundwater seepage and a large net-alkaline inflow from the Muddy Branch (Figure 1). Likewise, the downstream water on the West Branch (WB3) near the confluence with WWB was consistently net alkaline with near-neutral pH; however, WB3 exhibited elevated concentrations of dissolved metals and other contaminants from AMD discharged by OAK and PKN (Table A3).

During the 13 seepage runs, an average of 13.7 L/s of "clean" stream water was lost from West Creek over the 300 m segment between stations WC4 and WC5, and an average total of 53.4 L/s was lost over the entire 2.1 km segment that crosses the Oak Hill Mine complex between stations WC4 and WC9 (Table A3). These losses equate to 6.9 percent and 19.3 percent, respectively, of the daily average discharge of 221 L/s from the Oak Hill Boreholes during the dates of the seepage runs (Table A2). Assuming the 300-m-long losing segment between WC4 and WC5 is 1.5 m wide, an average downward flux of 3.05×10^{-5} m/s through the streambed is computed (by dividing the lost streamflow of 13.7 L/s, or 0.0137 m^3/s, by the 450 m^2 area of the channel). Likewise, assuming the entire 2.1 km segment between WC4 and WC9 is 1.5 m wide, the cumulative loss from West Creek equates to an average

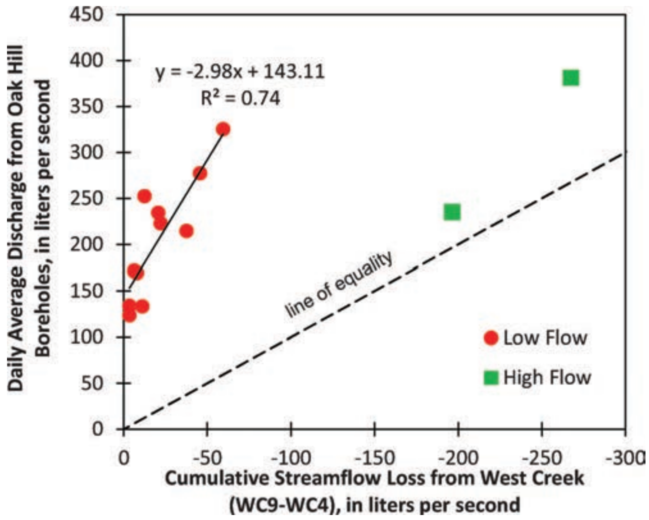

Figure 6. Comparison of daily discharge from Oak Hill Boreholes (OAK) with cumulative streamflow lost from West Creek between WC4 above mined area and WC9 below mined area, during March 2012–September 2015. Note that during low-flow conditions, the discharge of OAK is sustained at approximately 140–150 L/s (intercept), and it increases with the streamflow lost from West Creek.

downward flux of 1.70×10^{-5} m/s across the total 3,150 m^2 stream-channel area.

During low- to moderate-flow conditions, the estimated quantities of streamflow lost from West Creek during seepage runs were closely correlated with the corresponding daily discharge from OAK (Figure 6); however, for the two seepage runs conducted during high-flow conditions (January 18, 2013, and April 23, 2014), the cumulative losses from West Creek deviated from this correlation and approached the magnitude of the discharge from OAK on those dates (Figure 6). The daily discharge from OAK was generally correlated with streamflow at nearby stream gauges (Figure 5A); however, the peaks and troughs in the hydrograph for OAK were subdued with extended recessions compared to those for West Creek (Figure 5B). This difference in the hydrographs implies that recharge by streambed leakage from West Creek may be stored in the Oak Hill Mine pool and released gradually as discharge from OAK. Similar surface-water/groundwater interactions had been previously reported for the West Branch and Pine Knot Mine pool (Cravotta et al., 2014).

Annual Water Budget for Study Period

Wide variations in the annual streamflow yields and in the proportions of streamflow that may be attributed to base flow or runoff were exhibited at gauging stations on West Creek and nearby locations within the upper Schuylkill River basin during July 1, 2014, through

Table 1. *Hydrograph-separation analysis and components of the annual hydrologic budget for continuous streamflow gauging stations in the West Creek and associated watersheds of upper Schuylkill River basin, Schuylkill and Berks Counties, PA, July 1, 2014–June 30, 2015 (site descriptions are in Figure 1).*[a]

Map ID	Gauge Location	Station Number	Drainage Area (km^2)	Mean Streamflow[b] (L/s)	Mean Streamflow[b] (cm/yr)	Stream-flow Index[c] (%)	Mean Baseflow[d] (L/s)	Mean Baseflow[d] (cm/yr)	Base-flow Index (%)	Mean Runoff[e] (L/s)	Mean Runoff[e] (cm/yr)	Runoff Index (%)
West West Branch Schuylkill River												
WC4	West Cr above Forestville	01467830	13.3	69	16.4	16.1	48	11.4	69.5	21	5.0	30.5
WC5	West Cr at Forestville	01467832	13.7	63	14.5	14.2	34	7.8	53.8	29	6.7	46.2
WC8	West Cr at Main St Phoenix Pk	01467835	18.9	82	13.7	13.4	46	7.7	56.2	36	6.0	43.8
WC9	West Cr at Ramtown Rd Phoenix Pk	01467837	22.3	84	11.9	11.7	50	7.1	59.7	34	4.8	40.3
WWB	West Cr West Branch Schuylkill R	01467861	48.5	752	48.9	47.9	639	41.6	85.1	113	7.3	14.9
West Branch Schuylkill River												
WB1	WB Schuylkill River above Pine Knot	01467688	49.8	365	23.1	22.6	281	17.8	77.1	84	5.3	22.9
PKN	Pine Knot Disch 500 m below Tunnel	01467689	*49.1*	484	31.1	30.5	472	30.3	97.4	12	0.8	2.6
PKNWB	PKN + WB1		49.8	849	53.8	52.7	768	48.7	90.5	81	5.1	9.5
OAK	Oak Hill Disch 200 m below	01467691	*21.9*	216	31.1	30.5	212	30.5	98.1	4	0.6	1.9
WB3	WB Schuylkill River above WWB	01467752	61.7	1368	70.0	68.6	1218	62.3	89.0	150	7.7	11.0
Schuylkill River												
SRL	Schuylkill River at Landingville	01468500	340.5	6103	56.6	55.4	4933	45.7	80.7	1170	10.9	19.3

[a]Hydrograph separation was conducted using the "PART" computer program (Rutledge, 1998) to divide annual streamflow into base-flow and runoff contributions on the basis of daily average flow values during July 1, 2014, through June 30, 2015.
[b]Streamflow (yield) expressed as centimeters per year by dividing streamflow in liters per second by the drainage area in square kilometers and then multiplying by the factor 3.156.
[c]Streamflow index was computed as the ratio, expressed as percent, of total annual streamflow yield to average total annual rainfall of 102.1 cm/yr based on daily rainfall at local USGS streamflow gauging stations (01469500, 01470500, 01468500) and weather station 403628076134201.
[d]Base flow is expressed as liters per second, centimeters per year, and percent of total annual streamflow (base-flow index).
[e]Runoff, computed by subtracting the base flow from total streamflow, is expressed as liters per second, centimeters per year, and percent of total annual streamflow (runoff index).

June 30, 2015 (Table 1). Instead of relatively constant yields for nested or neighboring stations based on mean streamflow, which may be expected for the same rainfall under unaltered conditions, large differences were computed, ranging from 11.9 cm/yr for West Creek (WC9) to 70.0 cm/yr for West Branch (WB3) (Table 1). The low discharge yields of the West Creek sub-basin (WC9) and the West West Branch Schuylkill River basin (WWB) are inferred to result from streamflow losses to the Oak Hill Mine complex plus losses to the Pine Knot Mine complex, which extends beneath the headwaters area (Figure 1), plus additional diversions. In contrast, the high discharge yield of the West Branch Schuylkill River at WB3 is hypothesized to result from the AMD outfalls at PKN and OAK that discharge water from the respective mines to the West Branch Schuylkill River.

Although the drainage area of West Creek at WC9 (22.3 km^2) was approximately half of that downstream on the West West Branch Schuylkill River at WWB (48.5 km^2), the mean daily streamflow at WC9 was only 11 percent of that at WWB. The corresponding annual streamflow yields were 48.9, 11.9, and 16.4 cm/yr for WWB, WC9, and WC4, respectively. Although a low yield at WC9 was anticipated, considering the previously documented streamflow losses, the low yield at

WC4 was not. Approximately 1.5 km upstream from WC4, water is diverted from the Crystal Reservoir on West Creek for public supply (Figure 1). Furthermore, the drainage area upstream from the Crystal Reservoir is underlain by the Pine Knot Mine complex, which also intercepts runoff and recharge in this area (Figure 1).

The annual streamflow yield of 23.1 cm/yr at West Branch above the Pine Knot Tunnel (WB1) was less than half of the 56.6 cm/yr reference value for the downstream gauge on the Schuylkill River at Landingville (SRL), which drains the 340.5 km^2 area including the West West Branch and West Branch Schuylkill River basins (Table 1). The missing streamflow from the 49.8 km^2 watershed contributing to WB1 was discharged from PKN, which enters the West Branch about 70 m downstream from WB1. The combined flows of PKN and WB1 above the Pine Knot Tunnel (PKN + WB1), expressed as a yield of 53.8 cm/yr, were comparable to that for the SRL reference gauge outside the mined area, indicating surface water lost to the Pine Knot Mine complex was restored as AMD from PKN. However, downstream from OAK, the West Branch (WB3) had a much larger yield (70.0 cm/yr) than the SRL reference value or the adjacent West West Branch Schuylkill River (WWB, 48.9 cm/yr) at their confluence (Table 1). The excessive yield at WB3 can be attributed to the gain in flow from OAK. If the Oak Hill Mine complex did not capture the flow loss from the upper portions of the West Creek basin, this water would have discharged at WWB.

At SRL, outside the mined area, the annual streamflow yield, base-flow yield, and base-flow index (baseflow/streamflow) were 56.6 cm/yr, 45.7 cm/yr, and 80.7 percent, respectively, from July 1, 2014, to June 30, 2015 (Table 1). The streamflow yield of 56.6 cm/yr at SRL equates to 55.4 percent of the 102.1 cm/yr total annual precipitation during the budget period. Assuming this reference yield of 56.6 cm/yr would apply to the upstream sub-basins, the corresponding streamflows based on the topographic drainage areas at WB3 and WWB are estimated to be 1107 L/s and 870 L/s, respectively. The difference between the measured and estimated flows for WB3 is 261 L/s (=1368 − 1107), which is comparable to 216 L/s discharge from the Oak Hill Boreholes (Table 1). Somewhat greater flow gained at WB3 than discharged by OAK is consistent with additional transfer from West Creek to the Pine Knot Mine complex (Figure 1). Likewise, the difference between the measured flow for WWB and the estimated flow using the SRL yield is −118 L/s (=752 − 870). This value indicates greater streamflow lost from West Creek than that measured during the seepage runs (−53.4 L/s; Table A2) and is consistent with additional losses upstream from WC4 to the Pine Knot Mine complex plus diversions to the Crystal Reservoir water supply.

Surface Geophysical Surveys Indicate Variably Conductive Zones beneath Streambed

The resistivity surveys demonstrated spatial and temporal variability in streambed conductivity in the upper segment of West Creek, above WC5, during 2012, and spatial variability within the upper, intermediate, and lower segments above WC9 during 2014. The resistivity data collected in 2012 were acquired on different dates for the same general locations between end-points 0 and 2 within the upper segment of West Creek (Figures 3A and 3B). The results for the 2012 surveys are arranged in downstream (left to right) and chronological (top to bottom) sequence, with data for the date of the lowest measured streamflow at the top (April 27, 2012) and data for the date of the highest measured streamflow at the bottom (September 27, 2012) (Figure 7A). The latter survey was extended upstream to capture the full extent of the low-resistivity anomaly (potential flow loss zone) indicated during the two preceding surveys. Each profile indicates resistivity values from the streambed surface to a depth of approximately 30 m. All document a high-resistivity upper layer of greater than 1,000 ohm-meters (Ω·m) from the streambed surface to a depth of 5 to 10 m in the upper segment of West Creek. This zone transitions to an intermediate-resistivity zone of between 300 Ω·m and 1,000 Ω·m, with anomalous low-resistivity (high-conductivity) values of less than 300 Ω·m in local zones at depths from about 5 m to greater than 30 m.

The resistivity data collected in 2014 for surveys 1 to 12 (from resistivity end-points 1 to 13) span a 2.1 km segment where West Creek crosses the underground Oak Hill Mine complex (Figure 1). The starting survey segment 1 (resistivity end-points 1 to 2) of the 2014 surveys (Figure 7B) coincided with the downstream segment of the 2012 surveys (Figure 7A). The profiles for 2014 are displayed with a different color scale than that used for 2012. As indicated by previous surveys in the upper reach, the 2014 profiles generally indicate a longitudinally extensive 5- to 10-m-thick high-resistivity layer near the surface and decreasing resistivity with depth beneath the streambed. The high-resistivity layer at the surface was disrupted locally, primarily within surveys 6, 8, 9, and 10, where low-resistivity anomalies also extended to depths of 10 to 30 m. These low-resistivity anomalies are interpreted to indicate relatively conductive water-saturated zones that could be locations of streamflow loss, as previously described for the "leaky streambed" between resistivity end-points 7 to 11, or could be locations of groundwater discharge,

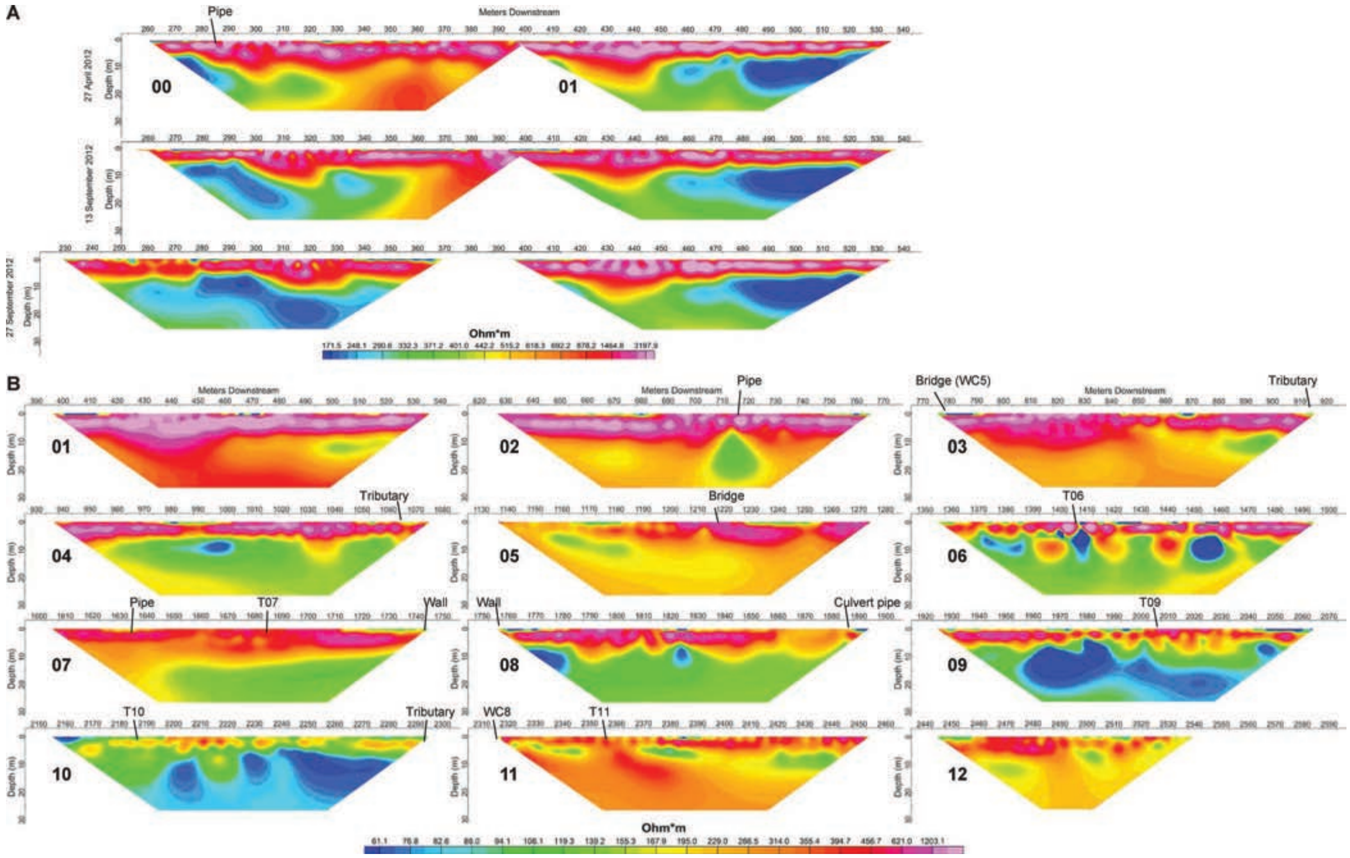

Figure 7. Electrical resistivity survey profiles for: (A) 0.3 km length of West Creek upstream from Forestville, April 27, September 27, and November 9, 2012; and (B) 2.1 km length of West Creek downstream from Forestville to Phoenix Park, May 12–15, 2014. Locations of stream gauges (WC5 and WC8), hyporheic temperature probes (T06, T07, T09, T10, and T11), and various structures are noted. Locations of resistivity stations and stream gauges are shown in Figures 1 and 3.

as described for survey 6 (between resistivity end-points 6 and 7) (Figures 3 and 4).

The location and orientation of the low-resistivity anomaly in the uppermost survey segment, between 260 and 350 m downstream from WC4 (Figure 7A), are coincident with the mapped outcrop of the Mammoth Bed, which was indicated to dip 25 to 30 degrees southeastward approximately perpendicular to the survey segment (Figure 3B). Underground mine workings on the Mammoth Bed (Bottom Split) underlie this segment. Likewise, the location of the low-resistivity anomaly in the following survey segment, between 480 and 530 m downstream from WC4, is coincident with the mapped outcrop of the Primrose Bed (Figure 3B). However, this survey segment was aligned at an oblique angle across the coalbed (Figure 3B), and the shape of the low-resistivity anomaly is broad compared to the thickness of the coalbed.

EM-31 survey data were collected in December 2015 during moderate-flow conditions along most of the same segment of West Creek as the 2014 resistivity surveys (between resistivity end-points 0 to 11) (Figure 8). The EM-31 conductivity readings for the HD and VD orientations at a given location were generally correlated; however, greater conductivity was indicated for 6-m-depth (HD) readings than 3-m-depth (VD) readings at most points along the stream channel. These results are consistent with the resistivity survey profiles that indicated a persistent high-resistivity layer near the streambed surface overlying more conductive material at depth (Figure 7). Furthermore, the locations of anomalously high or low EM-31 conductivity generally correlated with electrical resistivity anomalies. Specifically, high-EM conductivity and low-resistivity readings were consistently observed toward the upstream end of survey 0 (250–320 m), the downstream end of survey 1 (500 to 600 m), the upper end of survey 5 (1,100–1,250 m), most of survey 6 (1,390–1,500 m), and most of surveys 8, 9, and 10 (1,780–2,350 m). Note that in the upper 250–320 m zone, the HD conductivity peaks (at 6 m) were offset downstream from the VD peaks (at 3 m). This offset is consistent with the low-resistivity anomaly that angles approximately 30 degrees downward from the surface (Figure 7A)

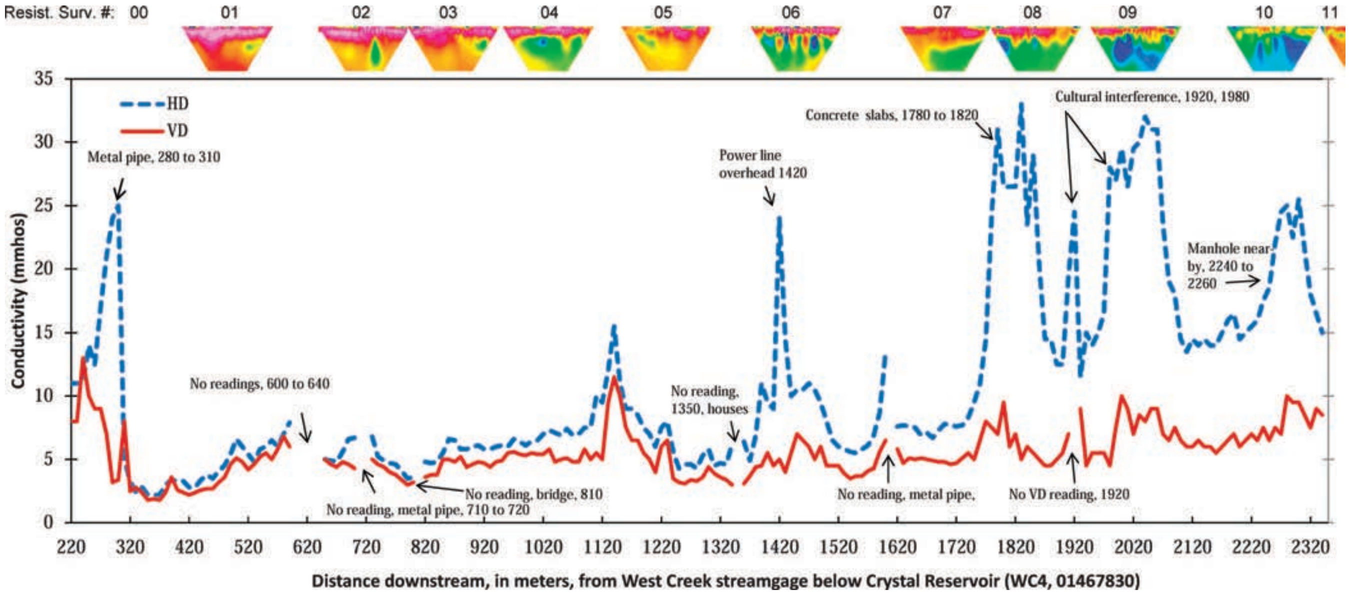

Figure 8. Results of electromagnetic conductivity (EM31) survey along 2.1 km length of West Creek from Forestville (230 m downstream from WC4) to Phoenix Park (2,360 m downstream to WC8), December 7–8, 2015. Approximate locations of resistivity surveys shown in Figure 7 are shown in compressed form along top of graph.

following the same orientation as the mapped coalbed in this location (Figure 3B).

Streambed Temperature Profiles Indicate Temporal Variations in Vertical Flux

A trial investigation of streambed flux using temperature probes was conducted within segment 1 (not reported herein), which was followed by more extensive investigations within the less accessible stream segment along resistivity survey segments 6 and 11 (locations of T06, T07, T09, T10, and T11 indicated in Figure 7B). For the latter effort, temperature probes logged the vertical temperature gradients from the top of the streambed to a maximum depth of 0.085 m over two 2 month intervals. Temperature-derived flux graphs show results at the greatest depth for each location (Figure 9). No-flow to low-flow conditions dominated during the first period, from September 12 to November 6, 2014 (Figure 9A), whereas moderate- to high-flow conditions dominated during the second period, from November 11, 2014, to January 5, 2015 (Figure 9B). The data for the first period at T09 were lost due to equipment failure.

The magnitude and direction of temperature-derived flux through the stream channel varied depending on the flow conditions and the location of each probe. Generally, during both the first (September to November) and second (November to January) periods, the flux estimates for probes at different locations were temporally correlated to one another and were also, to varying degrees, responsive to changes in the flow recorded at WC5 (Figures 9A and 9B). Because the thermal properties, heat transport, and flow through variably saturated media violate the assumptions within VFLUX (Gordon et al., 2012), the results when flow was indicated at WC5 are emphasized. When the stream channel experienced intermittent flow due to precipitation, such as that on October 15–16, 2015, downward flux (positive value) as high as 2.1×10^{-5} m/s was indicated (Figure 9A); however, these conditions were short lived; upstream flow ceased October 18 (Figure 9A). During the second period, rain events and sustained streamflow toward the end of November and into December resulted in persistent, downward flux of 0.5 to 1.2×10^{-5} m/s at T06, T07, T10, and T11, and smaller, less persistent downward flux at T09 (Figure 9B).

During the first period, the temperature probe at the most upstream location (T06) indicated a consistent downward flux and the least variation in magnitude compared to the other probes; T06 was downstream from the perennial upstream segment between resistivity end-points 5 and 6 (Figure 3). Likewise, during the second period, the flux estimates for T06 were consistently downward and, thus, could indicate that streamflow was consistently lost through the streambed in that general location. Also, during the second period, the two most upstream probes (T06 and T07) and the most downstream probe (T11) exhibited less variability and more sustained downward flux compared to the two intermediate sites (T09 and T10), possibly

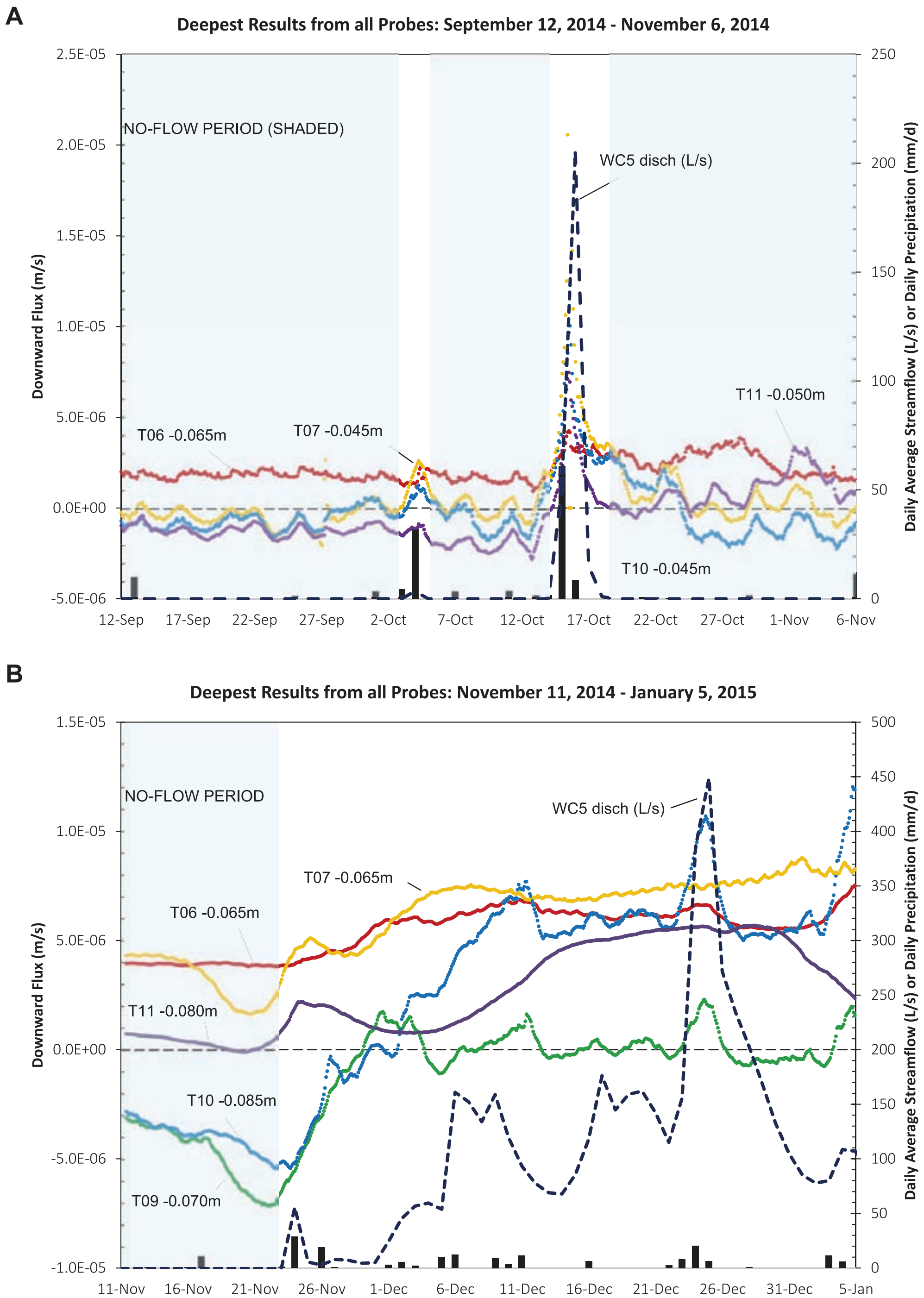

Figure 9. Temporal variations in streambed flux calculated from vertical temperature gradients at locations (T06, T07, T09, T10, and T11) within intermediate segment of West Creek, downstream from WC5 and upstream from WC8: (A) September 12, 2014–November 6, 2014; (B) November 11, 2014–January 5, 2015. Positive values are downward flux; negative values are upward flux. Locations of temperature probes in relation to seepage run and resistivity survey sites are shown in Figure 7B. Corresponding daily streamflow at WC5 and daily precipitation for the study area (excerpted from Figure 5) are shown for reference. Shading indicates periods of no-flow conditions, when the streambed may be variably saturated and VFLUX computations may be invalid.

reflecting a continuous streamflow past the former locations (note that a tributary adds flow to West Creek upstream from T11, just upstream from WC8) during this period, but not past the locations of T09 and T10 until later in the period. Changes from upward (negative values) to downward fluxes during late November and greater variations indicated for T09 and T10 could indicate these segments gradually changed to flowing and, hence, losing conditions. Last, by comparing the two time periods, the maximum downward fluxes were indicated for the first large runoff event in October 14–16, 2015, which followed an extended dry period without upstream flow (at WC5) (Figure 9A). Generally smaller downward fluxes, but of comparable magnitude, were indicated during the second period, when greater, sustained upstream flow was occurring (Figure 9B). The initial extreme downward flux during the first period may have exceeded those estimated during the second period, despite larger flows, because of possible decreases in the unsaturated storage capacity and decreases in the vertical hydraulic gradient after streamflow had returned to the segment.

Despite potential uncertainties and local variations in the temperature-derived flux data, the range of values was in good agreement with estimates calculated on the basis of streamflow loss during seepage runs (Table A2). For the seepage runs, an average downward flux estimate of 1.70×10^{-5} m/s was indicated for the entire 2.1 km segment between WC4 and WC9 (computed by dividing 53.4 L/s or 0.0534 m^3/s lost by a total 3,150 m^2 stream-channel area), and a corresponding estimate of 3.05×10^{-5} m/s was indicated for the leaky streambed in the upper 300 m segment between WC4 and WC5 (computed by dividing 13.7 L/s or 0.0137 m^3/s lost by the 450 m^2 area of the channel).

Historical Mining Map Provides Context for Current Hydrological Observations

The general location of streamflow losses within the upper reach, approximately 300 to 600 m downstream from WC4, between resistivity survey end-points 0 to 2 (Figures 3B and 4), coincided with the historically mapped outcrop locations of the Mammoth and Primrose coalbeds (Pennsylvania Geological Survey, 1889). The historic mine map indicated these coalbeds were approximately perpendicular to the channel and dipped 25 to 30 degrees southeastward (downstream). Although the streambanks along the channel in this segment exhibited signs of excavation, the channel appeared to be intact and stable, with gravel- to boulder-sized bed material along the entire stream course.

Approximately 1,000 m downstream from WC5, between resistivity end-points 6 and 7, the channel consistently gained groundwater seepage with higher pH and SC than upstream (Figures 3 and 4). This short perennial segment of the stream appeared to align with the original stream channel location compared to the 1889 mine map (Figure 3B), which shows the identical stream path as the USGS 1892 Pine Grove 15 minute topographic map. However, downstream from this reach, between resistivity end-points 7 and 11, all streamflow was lost during low-flow conditions. This 600-m-long "leaky" channel segment (1,700 to 2,300 m downstream from WC4) apparently had been relocated eastward from its original path shown on the 1889 mine map (Figure 3B). Along this reach, the stream crosses over the axis of the Phoenix Park or North Delaware Anticline, where the underground mine workings on the Diamond and Primrose Beds were at relatively shallow depth (Pennsylvania Geological Survey, 1889; Wood et al., 1968, cross sections C-C′ and D-D′). A gangway on the Diamond Bed has a mapped elevation of 682 ft (206 m) where it crosses beneath the stream channel, between resistivity survey end-points 9 and 10, and where the surface elevation is approximately 780 ft (236 m) (Figures 3A and 3B). Again, except for a distance of about 150 m downstream from WC8, between resistivity end-points 12 and 13, and another 300-m-long segment immediately upstream from WC9, much of the present stream path appears to deviate from its original route to WC9.

Persistent, sometimes visible, groundwater inflows restored perennial streamflow and aquatic habitat (see Appendix) to West Creek upstream from WC9, below resistivity end-point 12 (Figures 3 and 4). In particular, immediately upstream from the streamflow gauge at WC9, a perennial spring (identified as USGS station 014678369; USGS NWIS, http://dx.doi.org/10.5066/F7P55KJN) discharged groundwater with near-neutral pH (6.4 to 7.0) and elevated SC (790 to 850 μS/cm) during 2012–2015. This spring was the predominant source of streamflow at WC9 during low-flow conditions. The spring emanates about 5 m east of the streambank from the southern base of an overgrown pile of mined rock that is 15–20 m higher than the streambed; the historic 1889 mine map and the 1892 topographic map show an unnamed tributary (now buried) crossing this area from the northeast and entering the stream at the same point as the current spring (Figure 3B).

SUMMARY AND CONCLUSIONS

The Oak Hill Mine complex extends beneath the West West Branch and West Branch Schuylkill River sub-basins and facilitates the eastward transfer of water from the West West Branch to the West Branch. Streamflow lost from West Creek to the underlying Oak Hill Mine complex, in the headwaters of the West West Branch Schuylkill River, eventually discharges from the Oak Hill Boreholes. Additionally, recharge in the northeastern part of West Creek is inferred to enter the Pine Knot Mine complex and discharge to PKN. The contributions of AMD to the West Branch result in greater streamflow than would be expected based on its topographic drainage area and account for a large fraction of the AMD contaminant load that degrades the Schuylkill River. Likewise, because of the streamflow losses from the West Creek sub-basin, the annual streamflow of the West West Branch Schuylkill River is less than would be expected based on its topographic drainage area. The streamflow losses from West Creek account for approximately one fifth of the annual discharge from the Oak Hill Boreholes. Thus, if the streamflow losses from West Creek can be prevented, the discharge volume and contaminant loading from the Oak Hill Boreholes can be reduced, while at the same time the aquatic habitat of West Creek can be restored.

Repeated longitudinal streamflow measurements along the West Creek channel combined with continuous streamflow gauging and continuous temperature logging within the streambed at selected points indicated spatial and temporal variations in the magnitude and duration of the loss of streamflow from the stream channel to the subsurface. During low flow, complete loss of streamflow was observed between stations WC4 and WC5, whereas during high flow, streamflow was gained (net increase) along this segment, even though some streamflow was still lost to the underlying mines.

Surface geophysical surveys indicated variably conductive zones beneath the streambed of West Creek along the 2.1 km segment over the Oak Hill Mine complex. The electrical resistivity and electromagnetic conductivity surveys identified a relatively extensive low-conductivity (high resistivity) zone beneath the streambed to 5 to 10 m depth, which was underlain by moderately conductive material to a depth of 30 m. Both layers were interrupted locally by anomalously high conductivity (low resistivity) zones, which are interpreted to indicate water saturation and potential locations of streamflow loss or groundwater inflow to the stream. The low-resistivity anomalies in the upper part of West Creek were consistently located by repeated surveys over a range of flow conditions, but they increased in size as the streamflow increased. These changes in the apparent volume of the conductive zones imply an increase in water saturation and potential for greater recharge during high-flow conditions. The locations of apparent streamflow loss and low-resistivity anomalies in the 300-m-long "leaky" upper segment of West Creek near Forestville coincide with the historically mapped locations of coalbed outcroppings and associated underground mine workings. The locations of streamflow loss along the 600-m-long leaky intermediate segment coincide with shallow (30-m-deep) underground workings where the stream crosses the axis of an anticline. This channel segment apparently has been relocated eastward from its original path as shown on historical maps.

Continuously logged temperature profiles through the streambed corroborate the interpretation of temporal variations in streambed leakage. Temperature probes at 0.085 m depth within the hyporheic zone of the intermediate segment downstream from Forestville indicated variable fluxes ranging to a maximum of 2.1×10^{-5} m/s (downward) during flowing conditions. The downward flux estimates are comparable to the loss estimates during seepage runs, normalized by the streamflow area. Cumulative streamflow lost from West Creek during seepage runs averaged 53.4 L/s, including 13.7 L/s lost in the upper segment above Forestville. Assuming the 2.1 km segment that crosses the Oak Hill Mine complex is 1.5 m wide, the cumulative streamflow loss during seepage surveys equates to an average downward flux of 1.70×10^{-5} m/s across the total 3,150 m^2 stream-channel area, which is within the range of flux values indicated by the temperature profiles. Likewise, assuming the 300-m-long losing segment in the upper segment is 1.5 m wide, the loss of 13.7 L/s equates to an average downward flux of 3.05×10^{-5} m/s across the 450 m^2 area of the channel.

Downstream from Forestville, both gains and losses were apparent over the range of hydrologic conditions. Generally, the water from upstream was slightly net acidic (3.9 mg/L as $CaCO_3$) with low pH (4.5), low SC (70 μS/cm), and elevated concentrations of dissolved aluminum (0.40 mg/L) and zinc (0.034 mg/L). In contrast, inflows from tributaries or groundwater seepage downstream from Forestville were net alkaline with higher pH and SC. Consequently, the SC and pH of West Creek increased downstream from Forestville, even where downward leakage through the streambed resulted in net losses in streamflow. Streamflow gains from groundwater seepage to the stream and perennial streamflow were observed within a relatively short intermediate segment at 1,400 to 1,700 m downstream from WC4 (between resistivity survey end-points 6 and 7), where the channel appears to follow its historical route. This brief perennial segment is bracketed by losing, intermittent segments upstream and downstream, where the straightened stream channel appears to have been relocated from its natural route.

The combination of surface geophysical surveys plus instantaneous streamflow and water-quality surveys along the entire segment of West Creek on multiple dates effectively indicated the locations and the magnitude of streamflow loss and, thus, can be useful for watershed and resource managers to identify stream segments for restoration priority (Figure 10). The identified segments 1, 2, and 3 (Figure 10), in order of decreasing priority, correspond to those reaches with consistent downward flux through the streambed and anomalous subsurface conductivity. The geophysical surveys, alone, were insufficient to establish if stream-

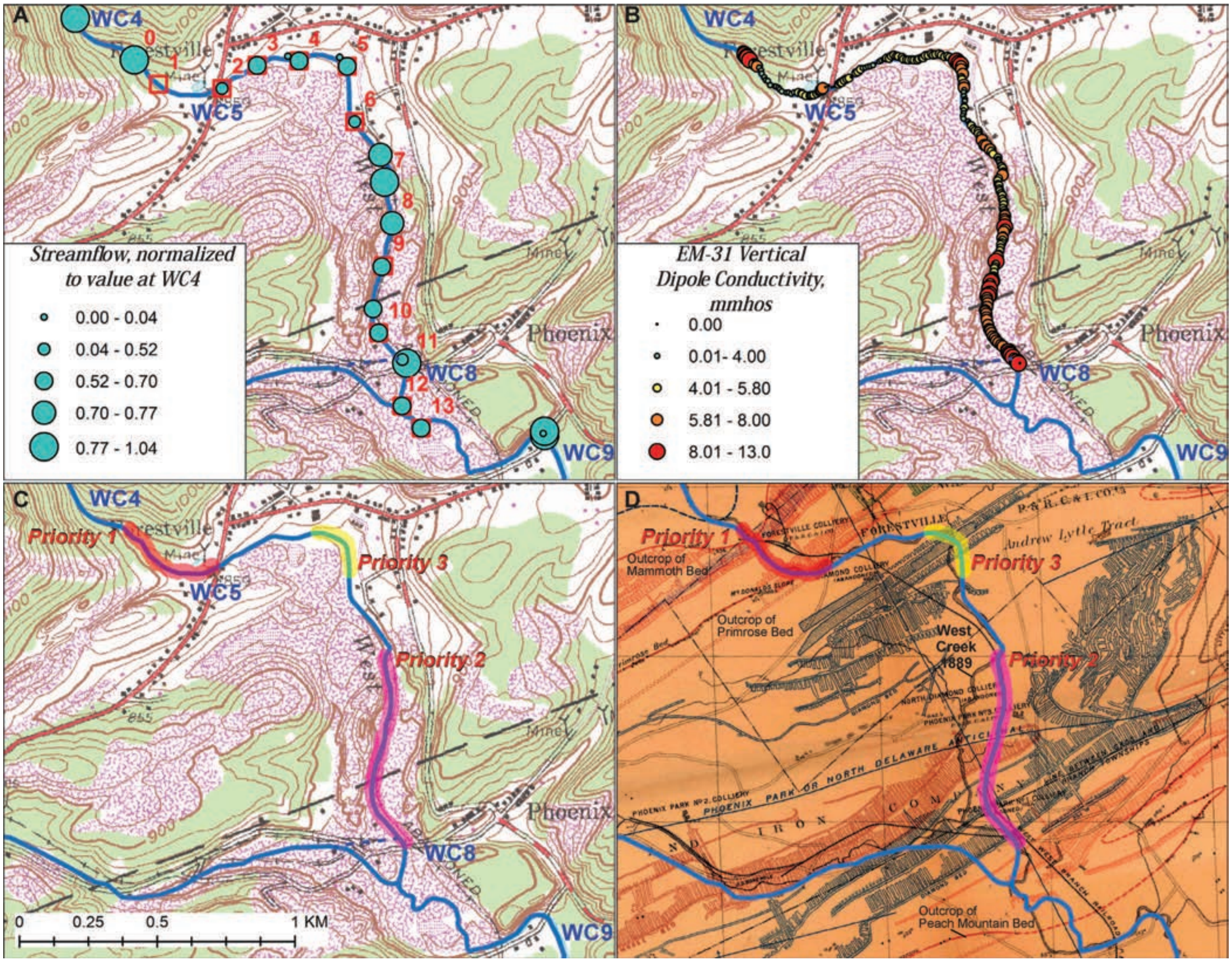

Figure 10. Summary of data and stream restoration priorities for West Creek: (A) median normalized streamflow value compared to WC4 for seepage runs during May 2014 through July 2015; (B) EM-31 vertical dipole conductivity values measured at approximately 3 m depth during December 7–8, 2015; and (C, D) stream restoration priorities 1, 2, and 3 on (C) Minersville topographic quadrangle base (USGS, 1955) and (D) historical underground mine map (Pennsylvania Geological Survey, 1889). Symbols in A indicate locations of seepage run flow and water-quality sites and the start and end of electrical resistivity survey segments (numbered 0–13).

flow was losing or gaining in a zone indicated to be anomalous (high conductivity) or if some other feature such as a metal object caused a geophysical anomaly. For that matter, streamflow data alone were insufficient to isolate segments of flow loss because, in some segments, both gains and losses occurred. Corresponding water-quality data were helpful to indicate where such gains took place (based on higher pH and SC of inflowing groundwater compared to the stream water already in the channel). Additionally, the water budget evaluation plus evaluation of maps showing historical mining and hydrography were helpful to provide geographic context, to validate the interpretations of surface-water losses to underground mines, and to indicate potential strategies and limitations of future restoration.

The methods used in this investigation would be generally applicable for the assessment of hydrological inter-connections and interactions in other extensively mined settings. The specific information collected for the study will be useful to watershed and resource managers to develop stream restoration strategies for West Creek, which could also reduce the discharge of associated AMD from the Oak Hill Boreholes. For example, rather than replacing the stream with an artificial rip-rap or concrete-lined channel, other more environmentally appealing approaches could be applied to create aquatic habitat in the extensively mined setting. Where the streambed appears to be intact and the vertical losses take place in a relatively discrete zone, grout injection directly into the streambed may be appropriate to decrease the conductivity beneath the streambed (e.g., Ackman and Jones, 1991). Grout injection would typically be conducted when water is present in the channel to transmit the grout into the high-conductivity zones. Alternatively, stream lining or stream channel relocation may be appropriate, especially where the existing channel is artificially straight, lacks integrity, and/or is devoid of desirable habitat characteristics. If a lining is used, instead of sealing the length of channel to keep water within, overlapping segments of the lining, such as shingles on a roof, may be helpful to permit diffuse groundwater seepage to enter the channel and join the water from upstream points. Concurrent streamflow and geophysical measurements could be conducted during grout injection or stream channel reconstruction to determine if the grout or channel lining is effective and guide the reconstruction work. Streamflow measurements and additional aquatic biological surveys would generally be appropriate to determine the effectiveness of any such restoration and associated recovery of aquatic life after water returns to the channel.

SUPPLEMENTAL MATERIAL

Supplemental Material associated with this article can be found online at http://faculty.kutztown.edu/sherrod/PublicationMaterials.

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REFERENCES

Ackman, T. E. and Jones, J. R., 1991, Methods to identify and reduce potential surface streamwater losses into abandoned underground mines: *Environmental Geology and Water Science*, Vol. 17, pp. 227–232.

American Public Health Association, 1998, Alkalinity (2320)/titration method. In Clesceri, L. S., Greenberg, A. E., and Eaton, A. D. (Editors), Standard Methods for the Examination of Water and Wastewater (20th): American Public Health Association, Washington, DC, pp. 2.26–2.29.

Archie, G. E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: *Transactions of the American Institute of Mining, Metallurgical, and Petroleum Engineers*, Vol. 146, pp. 54–62.

Ash, S. H. and Kynor, H. D., 1953, *Barrier Pillars in the Southern Field, Anthracite Region of Pennsylvania*: U.S. Bureau of Mines Bulletin 534, 30 p.

Ash, S. H.; Eaton, W. L.; Hughes, K.; Romischer, W. M.; and Westfield, J., 1949, *Water Pools in Pennsylvania Anthracite Mines*: U.S. Bureau of Mines Technical Paper 727, 78 p.

Ash, S. H.; Hower, C. S.; Kennedy, D. O.; and Lesser, W. H., 1953, *Mine Pumping Plants, Anthracite Region of Pennsylvania*: U.S. Bureau of Mines Bulletin 531, 151 p.

Bernhardt, E. S.; Lutz, B. D.; King, R. S.; Fay, J. P.; Carter, C. E.; Helton, A. M.; Campagna, D.; and Amos, J., 2012, How many mountains can we mine? Assessing the regional degradation of Central Appalachian rivers by surface coal mining: *Environmental Science & Technology*, Vol. 46, pp. 8115–8122.

Bianchin, M.; Smith, L.; and Beckie, R., 2011, Defining the hyporheic zone in a large tidally influenced river: *Journal of Hydrology*, Vol. 406, 1–2, pp. 16–29.

Biesecker, J. E.; Lescinsky, J. B.; and Wood, C. R., 1968, *Water Resources of the Schuylkill River Basin*: Pennsylvania Department of Forests and Waters Water Resources Bulletin 3, 198 p.

Binley, A.; Cassiani, G.; Middleton, R.; and Winship, P., 2002a, Vadose zone flow model parameterisation using cross-borehole radar and resistivity imaging: *Journal of Hydrology*, Vol. 267, pp. 147–159.

Binley, A.; Winship, P.; West, L. J.; Pokar, M.; and Middleton, R., 2002b, Seasonal variation of moisture content in unsaturated sandstone inferred from borehole radar and resistivity profiles: *Journal of Hydrology*, Vol. 267, pp. 160–172.

Briggs, M. A.; Lautz, L. K.; and McKenzie, J. M., 2012a, A comparison of fibre-optic distributed temperature sensing to traditional methods of evaluating groundwater inflow to streams: *Hydrological Processes*, Vol. 26, pp. 1277–1290.

Briggs, M. A.; Lautz, L. K.; McKenzie, J. M.; Gordon, R. P.; and Hare, D. K., 2012b, Using high-resolution distributed temperature sensing to quantify spatial and temporal variability in vertical hyporheic flux: *Water Resources Research*, Vol. 48, W02527, 16 p.

Burkholder, B. K.; Grant, G. E.; Haggerty, R.; Khangaonkar, T.; and Wampler, P. J., 2008, Influence of hyporheic flow and geomorphology on temperature of a large, gravel-bed river, Clackamas River, Oregon, USA: *Hydrological Processes*, Vol. 22, pp. 941–953.

Burrows, J. E.; Peters, S. C.; and Cravotta, C. A., III, 2015, Temporal geochemical variations in above- and below-drainage coal mine discharge: *Applied Geochemistry*, Vol. 62, pp. 84–95. (http://dx.doi.org/10.1016/j.apgeochem.2015.02.010).

Cardenas, M., 2009, Stream-aquifer interactions and hyporheic exchange in gaining and losing sinuous streams: *Water Resources Research*, Vol. 45, W06429, 13 p.

Carver, L. and Rauch, H. W., 1994, Hydrogeologic effects of subsidence at a longwall mine in the Pittsburgh Coal seam. In Peng, S. S. (Editor), *Proceedings of the 13th Conference on Ground Control in Mining*: West Virginia University, Morgantown, W.V., pp. 298–307.

Cifelli, R. C. and Rauch, H. W., 1986, Dewatering effects from selected underground coal mines in north-central West Virginia. In Peng, S. S. (Editor), *Proceedings of the 2nd Workshop on Surface Subsidence due to Underground Mining*: West Virginia University, Morgantown, W.V., pp. 249–263.

Clifford, J. and Binley, A., 2010, Geophysical characterization of riverbed hydrostratigraphy using electrical resistance tomography: *Near Surface Geophysics*, Vol. 8, pp. 493–501.

Constantz, J.; Stonestrom, D.; Steward, A. E.; Niswonger, R. N.; and Smith, T. R., 2001, Analysis of streambed temperatures in ephemeral channels to determine streamflow frequency and duration: *Water Resources Research*, Vol. 37, No. 2, pp. 317–328.

Cravotta, C. A., III, 2008, Dissolved metals and associated constituents in abandoned coal-mine discharges, Pennsylvania, USA: 1. Constituent concentrations and correlations: *Applied Geochemistry*, Vol. 23, pp. 166–202. (http://dx.doi.org/10.1016/j.apgeochem.2007.10.011).

Cravotta, C. A., III; Goode, D. J.; Bartles, M. D.; Risser, D. W.; and Galeone, D. G., 2014, Surface-water and groundwater interactions in an extensively mined watershed, upper Schuylkill River, Pennsylvania, USA: *Hydrological Processes*, Vol. 28, pp. 3574–3601. (http://dx.doi.org/10.1002/hyp.9885).

Daniluk, T. L.; Lautz, L. K.; Gordon, R. P.; and Endreny, T. A., 2013, Surface water-groundwater interaction at restored streams and associated reference segments: *Hydrological Processes*, Vol. 27, pp. 3730–3746. (http://dx.doi.org/10.1002/hyp.9501).

Dixon, D. Y. and Rauch, H. W., 1990, The impact of three longwall coal mines on streamflow in the Appalachian Coalfield. In Peng, S. S. (Editor), *Proceedings of the 9th International Conference on Ground Control in Mining*: West Virginia University, Morgantown, W.V., pp. 169–182.

Feng, Q.; Li, T.; Qian, B.; Zhou, L.; Gao, B.; and Yuan, T., 2014, Chemical characteristics and utilization of coal mine drainage in China: *Mine Water and the Environment*, Vol. 33, pp. 276–286. (http://dx.doi.org/10.1007/s10230-014-0271-y).

Fishman, M. J. and Friedman, L. C. (Editors), 1989, *Methods for Determination of Inorganic Substances in Water and Fluvial Sediments*: U.S. Geological Survey Techniques of Water-Resources Investigations Book 5, Chapter A1, 545 p.

Geostudi Astier srl and Multi-Phase Technologies LLC, 2006, *ERTLab 3D Electrical Resistivity Tomography Inversion Software User Manual*: Geostudi Astier srl and Multi-Phase Technologies LLC, Livorno, Italy, 89 p.

Goode, D. J.; Cravotta, C. A., III; Hornberger, R. J.; Hewitt, M. A.; Hughes, R. E.; Koury, D. J.; and Eicholtz, L. W., 2011, *Water Budgets and Groundwater Volumes for Abandoned Underground Mines in the Western Middle Anthracite Coalfield, Schuylkill, Columbia, and Northumberland Counties, Pennsylvania—Preliminary Estimates with Identification of Data Needs*: U.S. Geological Survey Scientific Investigations Report 2010–5261, 54 p. (http://pubs.usgs.gov/sir/2010/5261/).

Gordon, R. P.; Lautz, L. K.; Briggs, M. A.; and McKenzie, J. M., 2012, Automated calculation of vertical pore-water flux from field temperature time series using the VFLUX method and computer program: *Journal of Hydrogeology*, Vol. 420–421, pp. 142–158.

Grgich, P.; Hammack, R.; Harbert, W.; Sams, J.; Veloski, G.; and Ackman, T., 2004, Delineating groundwater flow paths with surface geophysics: *Journal of Environmental Hydrology*, Vol. 12, paper 12, 10 p.

Growitz, D. J.; Reed, L. A.; and Beard, M. M., 1985, *Reconnaissance of Mine Drainage in the Coal Fields of Eastern Pennsylvania*: U.S. Geological Survey Water-Resources Investigations Report 83–4274, 54 p.

Hagrey, S. and Michaelsen, J., 1999, Resistivity and percolation study of preferential flow in vadose zone at Bokhorst, Germany: *Geophysics*, Vol. 64, No. 3, pp. 746–753.

Hyun, Y.; Kim, H.; Lee, S.; and Lee, K., 2011, Characterizing streambed water fluxes using temperature and head data on multiple spatial scales in Musan stream, South Korea: *Journal of Hydrology*, Vol. 402, pp. 377–387.

Johnson, T.; Versteeg, R.; Huang, H.; and Routh, P., 2009, Data-domain correlation approach for joint hydrogeologic inversion of time-lapse hydrogeologic and geophysical data: *Geophysics*, Vol. 74, pp. F127–F140.

Kimball, B. A.; Walton-Day, K. H.; and Runkel, R. L., 2007, Quantification of metal loading by tracer injection and synoptic sampling, 1996–2000. In Church, S. E.; von Guerard, Paul; and Finger, S. E. (Editors), *Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado*: U.S. Geological Survey Professional Paper 1651, pp. 417–495.

Kirby, C. S. and Cravotta, C. A., III, 2005, Net alkalinity and net acidity 2: Practical considerations: *Applied Geochemistry*, Vol. 20, pp. 1941–1964.

LaBrecque, D.; Miletto, M.; Daily, W.; Ramirez, A.; and Owen, E., 1996, The effects of noise on Occam's inversion of resistivity tomography data: *Geophysics*, Vol. 61, pp. 538–548.

Lambert, D. C.; McDonough, K. M.; and Dzombak, D. A., 2004, Long-term changes in quality of discharge water from abandoned underground coal mines in Uniontown Syncline, Fayette County, PA, USA: *Water Research*, Vol. 38, pp. 277–288.

Lapham, W., 1989, *Use of Temperature Profiles Beneath Streams to Determine Rates of Vertical Ground-Water Flow and Vertical Hydraulic Conductivity*: U.S. Geological Survey Water-Supply Paper 2337, 35 p.

Linde, N.; Binley, A.; Tryggvason, A.; Pedersen, L. B.; and Revil, A., 2006, Improved hydrogeophysical characterization using joint inversion of cross-hole electrical resistance and ground-penetrating radar traveltime data: *Water Resources Research*, Vol. 42, W12404, 16 p.

Mack, B.; McDonald, L. M.; and Skousen, J., 2010, Acidity decay of above-drainage underground mines in West Virginia: *Journal of Environmental Quality*, Vol. 39, pp. 1–8.

Nordstrom, D. K., 1977, Thermochemical redox equilibria of Zobell's solution: *Geochimica et Cosmochimica Acta*, Vol. 41, pp. 1835–1841.

Nordstrom, D. K., 2011, Hydrogeochemical processes governing the origin, transport and fate of major and trace elements from mine wastes and mineralized rock to surface waters: *Applied Geochemistry*, Vol. 26, pp. 1777–1791.

Nyquist, J.; Freyer, P.; and Toran, L., 2008, Stream bottom resistivity tomography to map ground water discharge: *Ground Water*, Vol. 46, No. 4, pp. 1–9.

Oldenburg, D. W. and Li, Y., 1999, Estimating depth of investigation in DC resistivity and IP surveys: *Geophysics*, Vol. 64, No. 2, pp. 403–416.

Pennsylvania Department of Environmental Protection, 2014, *2014 Pennsylvania Integrated Water Quality Monitoring and Assessment Report—Clean Water Act Segment 305(b) Report and 303(d) List*: Pennsylvania Department of Environmental Protection, Harrisburg, PA, 786 p.

Pennsylvania Geological Survey, 1889, Heckscherville Valley, Peaked Mountain, Buck Run, Phoenix Park and Muddy Branch Basins: Pennsylvania Geological Survey, 2nd Series, Southern Coal Field Mine Sheet, No. XII, January 1889, scale 1:1,200.

Rantz, S. E. and others, 1982, *Measurement and Computation of Streamflow:* U.S. Geological Survey, Water-Supply Paper 2175, 2 Volumes.

Reed, P.; DuMontelle, P.; Sargent, M.; and Killey, M., 1983, Nuclear logging and electrical earth resistivity techniques in the vadose zone in glaciated earth materials. In *NWWA/U.S. EPA Conference on Characterization and Monitoring of the Vadose (Unsaturated) Zone*, Las Vegas, Nevada, National Water Well Association, Dublin, Ohio, pp. 580–601.

Risser, D. W., 2006, *Simulated Water Budgets and Ground-Water/Surface-Water Interactions in Bushkill and Parts of Monocacy Creek Watersheds, Northampton County, Pennsylvania—A Preliminary Study with Identification of Data Needs*: U.S. Geological Survey Open-File Report 2006-1143, 31 p.

Risser, D. W.; Conger, R. W.; Ulrich, J. E.; and Asmussen, M. P., 2005, *Estimates of Groundwater Recharge Based on Streamflow-Hydrograph Methods, Pennsylvania*: U.S. Geological Survey Open-File Report 2005-1333, 30 p.

Runkel, R. L.; Kimball, B. A.; Walton-Day, K.; Verplanck, P. L.; and Broshears, R. E., 2012, Evaluating remedial alternatives for an acid mine drainage stream: A model post audit: *Environmental Science & Technology*, Vol. 46, pp. 340–347.

Rutledge, A. T., 1998, *Computer Programs for Describing the Recession of Groundwater Discharge and for Estimating Mean Groundwater Recharge and Discharge from Streamflow Data—Update*: U.S. Geological Survey Water-Resources Investigations Report 98-4148, 43 p.

Schemel, L. E.; Cox, M. H.; Runkel, R. L.; and Kimball, B.A. 2006, Multiple injected and natural conservative tracers quantify mixing in a stream confluence affected by acid mine drainage near Silverton, Colorado: *Hydrological Processes*, Vol. 20, pp. 2727–2743.

Schrott, L. and Sass, O., 2008, Application of field geophysics in geomorphology: Advances and limitations exemplified by case studies: *Geomorphology*, Vol. 93, No. 1–2, pp. 55–73.

Schuylkill Action Network, 2008, *Schuylkill River Facts—Schuylkill Action Network, from Assessment to Protection*: Electronic document, available at http://www.schuylkillactionnetwork.org/

Sherrod, L.; Sauck, W.; and Werkema, D., 2012, A low-cost, *in situ* resistivity and temperature monitoring system: *Ground Water Monitoring & Remediation*, Vol. 32, No. 2, pp. 31–39.

Toran, L.; Hughes, B.; Nyquist, J.; and Ryan, R., 2012, Using hydrogeophysics to monitor change in hyporheic flow around stream restoration structures: *Environmental & Engineering Geoscience*, Vol. 18, No. 1, pp. 83–97.

Toran, L.; Nyquist, J. E.; Fang, A. C.; Ryan, R. J.; and Rosenberry, D. O., 2013, Observing lingering hyporheic storage using electrical resistivity; variations around stream restoration structures, Crabby Creek, PA: *Hydrological Processes*, Vol. 27, No. 10, pp. 1411–1425. (http://dx.doi.org/10.1002/hyp.9269).

Toran, L.; Nyquist, J.; Rosenberry, D.; Gagliano, M.; Mitchell, N.; and Mikochik, J., 2015, Geophysical and hydrologic studies of lake seepage variability: *Ground Water*, Vol. 5, No. 6, pp. 841–850. (http://dx.doi.org/10.1111/gwat.12309).

U.S. Environmental Protection Agency, 2013, *National Recommended Water Quality Criteria—Aquatic Life Criteria Table*: U.S. Environmental Protection Agency, last updated August 22, 2013 (https://www.epa.gov/wqe/national-recommended-water-quality-criteria-aquatic-life-criteria-table).

Vanderborght, J.; Kemna, A.; Hardelauf, H.; and Vereecken, H., 2005, Potential of electrical resistivity tomography to infer aquifer transport characteristics from tracer studies: A synthetic case study: *Water Resources Research*, Vol. 41, W06013, 23 p. (http://dx.doi.org/10.1029/2004WR003774).

Ward, A.; Fitzgerald, M.; Gooseff, M.; Voltz, T.; Binley, A.; and Singha, K., 2012, Hydrologic and geomorphic controls on hyporheic exchange during base flow recession in a headwater mountain stream: *Water Resources Research*, Vol. 48, No. 4, W04513, 20 p. (http://dx.doi.org/10.1029/2011WR011461).

Wood, G. H., Jr.; Trexler, J. P.; and Kehn, T. M., 1968, *Geologic Maps of Anthracite-Bearing Rocks in the West-Central Part of the Southern Anthracite Field Pennsylvania, Eastern Area*: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-528, 6 plates.

World Water Assessment Programme (WWAP), 2012, *The United Nations World Water Development Report 4—Managing Water under Uncertainty and Risk (Vol. 1), Knowledge Base (Vol. 2), and Facing the Challenges (Vol. 3)*: Paris, UNESCO, 904 p.

Yang, X.; LaBrecque, D.; and Paprocki, L.2000, Estimation of 3-D moisture content using ERT data at the Socorro-Tech Vadose Zone Facility. In *Proceedings of 13th EEGS Symposium on the Application of Geophysics to Engineering and Environmental Problems*, pp. 915–925.

Younger, P. L., 1997, The longevity of minewater pollution: A basis for decision making: *Science of the Total Environment*, Vol. 194–195, pp. 457–466.

Younger, P. L. and Wolkersdorfer, C., 2004, Mining impacts on the fresh water environment: Technical and managerial guidelines for catchment scale management: *Mine Water and the Environment*, Vol. 23, pp. s2–s80.

APPENDIX

Continuous Discharge Record, Aquatic Biological Surveys, and Limestone Neutralization Test Results in Support of Stream Restoration Strategies in an Abandoned Mine Lands Setting, Schuylkill River Watershed, Pennsylvania, USA, 2012–2015

Continuous Discharge at Gauges

Streamflow at points along the West Creek flow path was highly variable (Figure 4), but it was correlated temporally with that recorded at downstream gauging stations on the West West Branch (WWB) and West Branch (WB3) and at AMD outfalls from the Pine Knot Tunnel (PKN) and the Oak Hill Boreholes (OAK) during 2012–2015 (Figure 5A and Table A1). The daily discharge values at WWB and WB3 generally exhibited coincident peaks and troughs; however, discharge at WB3 was typically about twice that at WWB and also was less variable. Apparently, the streamflow at WB3 was moderated by the upstream contributions of AMD from PKN and OAK. The AMD discharge volumes were relatively constant with subdued peak flows and prolonged recessions compared to the surface waters (Figure 5). During the 12 month period from July 1, 2014, through June 30, 2015 (considered

Table A1. *Streamflow gauging and water-quality monitoring sites, West West Branch, West Branch, and upper Schuylkill River, Schuylkill County, PA (site locations [except SRL] are shown in Figure 1).*

USGS Station Number	Map ID	Site Name	Year Established	Latitude[a]	Longitude[a]
West West Branch Schuylkill River					
01467830	WC4	West Creek above Forestville	2014	40.66877	−76.23796
01467832	WC5	West Creek at Forestville	2014	40.69361	−76.30820
01467835	WC8	West Creek at Main St Phoenix Pk	2014	40.69131	−76.30200
01467837	WC9	West Creek at Ramtown Rd Phoenix Pk	2014	40.68197	−76.29408
01467861	WWB	West West Branch above West Branch	2006	40.67986	−76.28815
West Branch Schuylkill River					
01467688	WB1	West Branch Schuylkill River above Pine Knot Tunnel	2005	40.70413	−76.24969
01467689	PKN	Pine Knot Mine discharge 500 m below tunnel	2005	40.70409	−76.24989
01467691	OAK	Oak Hill Mine discharge 200 m below boreholes	2012	40.70203	−76.25158
01467692	WB2	West Branch below Oak Hill Boreholes outfall	2006	40.70169	−76.25199
01467752	WB3	West Branch Schuylkill River above West West Branch	2006	40.67067	−76.23267
Schuylkill River					
01468500	SRL	Schuylkill River at Landingville	1947	40.62917	−76.12500

[a]Coordinates referenced to the North American Datum of 1983 (NAD 83). Values are decimal degrees.

for water budget estimates; Table 1), the range of daily discharge values varied by a factor of 5 at PKN and OAK compared to factors of 15 at WB3 and 63 at WWB. In contrast, for the same period, the range of daily discharge values varied by more than three orders of magnitude at the gauges on West Creek (WC4, WC5, and WC9). The greatest variability was exhibited by the intermediate gauge (WC5), where the streamflow was intermittent.

Perennial streamflow was transmitted from the mostly forested area upstream from Forestville (WC4) to the segment overlying the Oak Hill Mine complex (Figures 3, 4, and 5). The streamflow at WC4 was frequently greater than that downstream at WC5 or WC9 during 2012–2015 (Figures 5B, A1A, and A1B). During periods of negligible recharge or runoff, persistent decreases in flow downstream from WC4 (losing conditions) were evident, such as low rainfall conditions in September 2014 or May 2015, or subfreezing conditions in February 2015, whereas increases in flow downstream were evident during periods of higher than normal rainfall, such as June 2015 (Figures 5B and A1). Sustained streamflow losses approaching 10 L/s from the 300 to 600 m upper reach, downstream from WC4 and immediately upstream from WC5, were recorded during low-flow periods (Figure A1A); however, greater losses, exceeding 50 L/s, were indicated during wet conditions, such as those experienced during spring of 2015 (Figure A1A). During the same time, the downstream segment of West Creek between WC4 and WC9 exhibited net gains in streamflow (Figure A1B).

Considering the difference between the daily average discharge at WC4 and WC5 during July 1, 2014–June 30, 2015 (Table 1), an average loss of only 6.3 L/s was computed, which is about half of the average loss indicated during the seepage runs (Table A3). Gains were measured in this upper segment during the seepage run April 23, 2015, and also for brief periods during "wet" hydrologic conditions (Table A2 and Figures 3, 5B, and 6A). During the wet conditions in April 2015, a net increase in streamflow was indicated by the difference between the recorded streamflow at upstream and downstream gauges (WC5 − WC4); however, at the same time, water was likely to have been lost through the streambed to the underlying mines. Likewise, the difference between the continuously measured discharge at WC4 and WC9 during July 1, 2014–June 30, 2015 (Table 1) indicated an average net gain of 14.5 L/s over the year; however, this indicated net difference between WC4 and WC9 does not accurately account for the total gains and cumulative losses along the segment as measured at intermediate locations during seepage runs (Figures 3 and 5B). Because of gains and losses within some stream segments, the cumulative losses (indicated by point symbols for seepage run measurements in Figures 5A and A1B) would generally be larger than those indicated by the difference in recorded streamflow at fixed location gauging stations.

Aquatic Biological Surveys

Streamflow restoration combined with water-quality and habitat improvement could lead to the recovery of fish and associated aquatic organisms in the West West Branch and West Branch Schuylkill River watersheds. Aquatic biological surveys in 2014 demonstrated the presence of fish, including brook trout and pollution-sensitive macroinvertebrate taxa, in the downstream

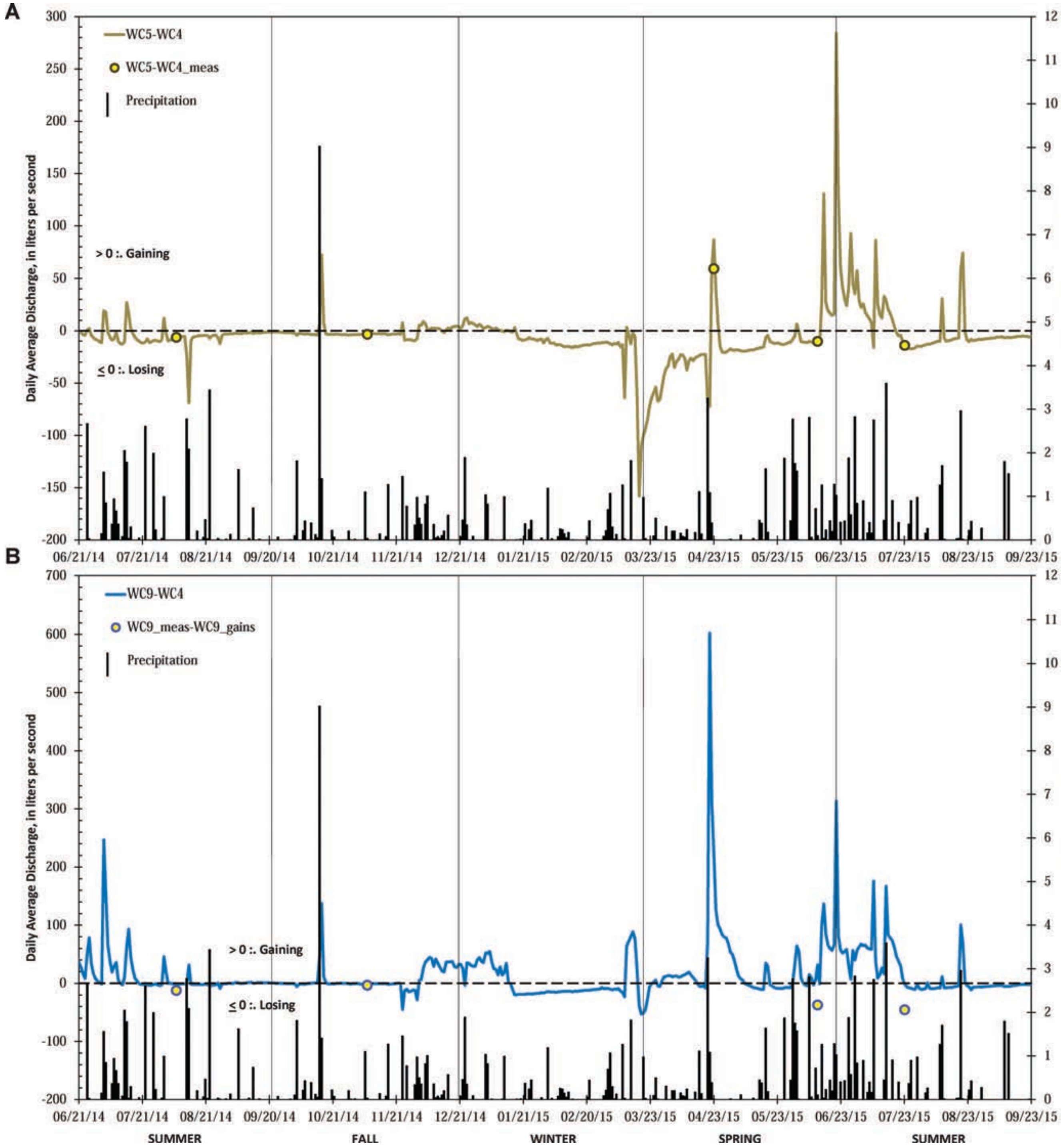

Figure A1. Daily precipitation and downstream changes in daily streamflow of West Creek at station WC4 upstream from mined area and two downstream stations, WC5 and WC9, during June 2014–September 2015: (A) Difference between WC4 and WC5; and (B) difference between WC4 and WC9. Values greater than 0 indicate net gains in streamflow from WC4 to downstream sites. Because of gains and losses within the stream segment(s), cumulative losses (indicated by point symbols for seepage run measurements) are larger than those indicated by the difference in recorded streamflow at fixed location gauging stations.

Table A2. *Measured streamflow at selected stations on West Creek during seepage runs in 2012–2015, including the estimated total gains and total losses between stations WC4 and WC5 or WC9 and the comparison of losses from West Creek with discharge from Oak Hill Boreholes (site locations are shown in Figures 1 and 3).*

Date of Seepage Run (YYYYMMDD)	WC4, Measured (L/s)	WC5, Measured (L/s)	WC5 − WC4, Change in Streamflow (L/s)	WC9, Measured (L/s)	WC9 − WC4, Cumulative Total Gains[a] (L/s)	WC9 − WC4, Cumulative Total Losses[b] (L/s)	WC9 − WC4, Cumulative Total Losses as Percentage of Total Gains (%)	OAK, Daily Average Flow[c] (L/s)	WC5 − WC4, Upstream Losses as Percentage of OAK (%)	WC9 − WC4, Cumulative Total Losses as Percentage of OAK (%)
20120313	17.93	3.71	−14.22	5.19	25.90	−20.71	80.0	234.29	6.1	8.8
20120418	6.40	0.00	−6.40	1.43	7.83	−6.40	81.7	171.56	3.7	3.7
20120427	8.04	0.00	−8.04	0.03	8.04	−8.01	99.6	169.72	4.7	4.7
20120913	3.35	0.00	−3.35	2.52	6.00	−3.48	58.0	123.73	2.7	2.8
20120930	29.96	23.82	−6.15	21.33	32.46	−11.13	34.3	133.39	4.6	8.3
20121109	97.73	96.40	−1.33	133.47	155.64	−22.17	14.2	222.79	0.6	10.0
20130118	241.97	97.68	−144.29	187.26	383.43	−196.17	51.2	235.28	61.3	83.4
20140512	81.59	61.74	−19.85	101.31	160.72	−59.40	37.0	325.37	6.1	18.3
20140807	6.29	0.00	−6.29	4.30	16.71	−12.40	74.2	252.36	2.5	4.9
20141107	3.40	0.00	−3.40	2.35	5.75	−3.40	59.1	134.21	2.5	2.5
20150423	398.46	457.66	59.20	537.40	804.68	−267.29	33.2	381.19	−15.5	70.1
20150612	21.58	11.36	−10.22	64.14	101.64	−37.50	36.9	214.55	4.8	17.5
20150724	28.86	14.84	−14.02	28.04	73.66	−45.62	61.9	277.17	5.1	16.5
Average	72.73	59.02	−13.72	83.75	137.11	−53.36	55.5	221.20	6.9	19.3
Median	21.58	11.36	−6.40	21.33	32.46	−20.71	58.0	222.79	4.6	8.8
Maximum	398.46	457.66	59.20	537.40	804.68	−3.40	99.6	381.19	61.3	83.4
Minimum	3.35	0.00	−144.29	0.03	5.75	−267.29	14.2	123.73	−15.5	2.5

[a]Cumulative gains is the sum of flow at WC4 plus all inflows indicated by increased streamflow between measurement points from WC4 to WC9.

[b]Cumulative losses is the sum of all outflows indicated by decreased streamflow between measurement points from WC4 to WC9.

[c]The average discharge from OAK during seepage runs was comparable to the average daily discharge of 224 L/s during January 1, 2012–September 30, 2015 (Figure 5) and 216 L/s during the 12 month period of July 1, 2014–June 30, 2015 (Table 1).

Table A3. *Water-quality data for West West Branch and West Branch Schuylkill River, Schuylkill County, PA, 2012–2015.*[a]

	West West Branch Schuylkill River				
Parameter	WC4[b]	WC5[c]	WC8	WC9	WWB
Flow (L/s)	33.8 (3.57/683)	45.3	34.6 (0/606)	39.6 (1.76/651)	470 (166/1940)
Temp. (°C)	13.2 (1.5/17.6)	12.7	15.2 (1.8/17.7)	14.3 (1.9/17.8)	11.4 (0.1/18.6)
DO	9.85 (8.0/15.2)	10	9.4 (5.7/13.8)	9.0 (6.9/14.5)	9.9 (8.3/12.5)
Eh (mV)	425 (320/610)	510	313 (230/470)	315 (230/410)	300 (210/500)
SC (mS/cm)	70 (60/270)	77	150 (120/240)	315 (160/790)	340 (210/550)
pH (units)	*4.5 (4.3/5.5)*	*4.4*	*5.8* (*4.6*/6.2)	6.6 (*5.6*/7.0)	7.5 (6.5/7.9)
Alkalinity	0.5 (0.3/1.1)	0.7	2.8 (1.6/6.6)	16.7 (2.0/78)	42 (20/99)
Net acidity	3.9 (1.3/5.1)	4.1	−1.4 (−5.7/1.1)	−15.6 (−76.4/0.1)	−38.4 (−93.2/−19.0)
Hardness	9.9 (9.2/17.0)	9.6	28.6 (18.3/50.6)	108 (23.8/401)	142 (64.4/241)
SO_4, diss.	13.5 (12/18)	12	30 (15/48)	99 (21/339)	109 (45/147)
Cl, diss.	8.4 (4.6/73.7)	10.9	17.7 (11.9/62.7)	13.0 (7.9/58.9)	8.4 (5.1/45.2)
Ca, diss.	1.7 (1.6/3.7)	1.7	6.7 (3.7/12.2)	30.0 (5.4/117)	28.9 (13.3/44.7)
Mg, diss.	1.3 (1.2/1.9)	1.3	2.9 (2.2/4.9)	7.9 (2.5/26.4)	17.2 (7.6/26.8)
K, diss.	0.8 (0.7/1.3)	0.9	1.3 (0.7/2.0)	2.0 (0.9/3.0)	1.7 (1.2/2.0)
Na, diss.	5.2 (3.2/40.6)	6.4	9.3 (7.4/34)	9.9 (8.0/32.5)	10.6 (7.0/32.4)
Al, diss.	*0.40 (0.20/0.50)*	*0.40*	*0.10* (<0.10/*0.40*)	<0.10 (<0.10/*0.30*)	<0.10 (<0.10/*0.12*)
Fe, diss.	0.045 (0.03/0.07)	0.04	0.02 (<0.01/0.04)	0.075 (0.02/0.27)	0.04 (0.017/0.25)
Mn, diss.	0.265 (0.26/0.33)	0.26	0.19 (0.11/0.23)	0.22 (0.20/0.42)	0.22 (0.047/0.66)
Ni, diss.	0.007 (<0.005/0.009)	0.008	0.008 (0.006/0.010)	0.006 (<0.005/0.010)	0.010 (<0.005/0.018)
Zn, diss.	*0.034* (0.025/*0.049*)	*0.052*	*0.033* (0.025/*0.039*)	0.029 (0.006/*0.043*)	0.021 (0.005/0.076)

	West Branch Schuylkill River				
	WB1	PKN	OAK	WB2	WB3
Flow (L/s)	177 (0/937)	561 (267/1170)	222 (119/411)	1080 (413/2310)	1250 (530/2970)
Temp. (°C)	13.3 (0.1/20.2)	11 (10.4/11.6)	14.8 (14.3/15.1)	12.1 (7.2/13.8)	11.8 (7.1/15)
DO	9.9 (5.6/13.1)	10.3 (6.7/10.6)	1.9 (0.4/3.3)	9 (7.7/10.8)	9.65 (8.7/11.2)
Eh (mV)	400 (330/600)	270 (210/370)	210 (150/250)	250 (210/320)	240 (170/290)
SC (mS/cm)	170 (100/1950)	560 (500/620)	970 (830/1010)	560 (400/730)	550 (420/680)
pH (units)	*5.0 (4.0/5.5)*	6.5 (6.0/7.0)	6.3 (*5.9*/6.8)	6.4 (*5.7*/6.8)	7.0 (6.3/7.2)
Alkalinity	1.3 (0/3.6)	40 (30/47)	150 (120/170)	50 (28/82)	50.5 (34/69)
Net acidity	5.72 (0.57/182)	−26.6 (−31.8/−21.5)	−115 (−133/−84.3)	−35.4 (−61.2/−19.1)	−42.9 (−61.6/−28.2)
Hardness	52.6 (15.1/1140)	247 (219/282)	441 (398/516)	240 (133/323)	233 (133/309)
SO_4, diss.	52 (15/1330)	219 (186/267)	372 (351/495)	210 (114/315)	189 (105/279)
Cl, diss.	15.7 (6.16/42.8)	26 (18.4/40.4)	9.29 (8.17/13.6)	21.9 (15.9/36.3)	25.6 (17.3/68)
Ca, diss.	9.7 (3.1/199)	36.8 (32.3/44.6)	93.6 (86.1/114)	39.9 (23/58.7)	41 (25/57.7)
Mg, diss.	6.81 (1.8/161)	36.9 (33.7/45.1)	52.6 (44.6/58.2)	34.3 (17.7/43)	30.4 (17.3/40.2)
K, diss.	0.8 (0.58/3.6)	1.45 (1.18/1.7)	2.08 (1.6/2.4)	1.3 (0.85/1.8)	1.75 (1.28/2.8)
Na, diss.	11.8 (7.0/23.7)	14.4 (11.6/19.6)	32 (30.4/34.5)	17.4 (13.2/77.7)	21 (15.4/37.5)
Al, diss.	***0.96*** (*0.42*/***26.8***)	<0.10 (<0.10/*0.20*)	*0.10* (<0.10/*0.26*)	<0.10 (<0.10/*0.13*)	<0.10 (<0.10/*0.10*)
Fe, diss.	0.097 (0.045/*1.05*)	*4.7 (2.77/5.74)*	*17.0 (8.72/19.8)*	*5.43 (3.18/8.60)*	*2.11 (1.39/2.78)*
Mn, diss.	0.469 (0.190/14.1)	2.10 (1.69/2.59)	3.49 (2.80/4.07)	1.95 (1.25/2.98)	1.78 (1.09/2.58)
Ni, diss.	0.020 (0.005/***0.538***)	0.045 (0.036/0.057)	0.036 (0.031/0.041)	0.036 (0.023/0.049)	0.032 (0.018/0.044)
Zn, diss.	*0.054* (0.023/***0.987***)	0.098 (0.070/***0.388***)	0.034 (0.019/0.058)	0.073 (0.052/0.099)	0.052 (0.044/0.075)

Values are median (minimum/maximum); 20 quarterly samples per site, except one sample for WC5 and eight samples for WC4, WC8, and WC9 only during 2014–2015; tot. = total; diss. = dissolved (<0.45 mm); values in italics do not meet criterion continuous concentration (CCC), and values in bold italics exceed criterion maximum concentration (CMC), for freshwater aquatic life (U.S. Environmental Protection Agency, 2013).

[a]Site descriptions are given in Table A1; site locations are shown in Figure 1.

[b]The median values indicate typical base-flow characteristics, whereas the minimum and maximum values represent low-flow to high-flow characteristics.

[c]Samples for laboratory chemical analysis were collected once at WC5. Those data plus repeated field measurements of pH and SC demonstrated the water quality at WC5 was indistinguishable from that at WC4.

sites on West Creek (WC9) and West West Branch (WWB) plus West Branch (WB3); however, fish were absent from the two upstream sites surveyed on West Creek (WC4) and West Branch (WB1). The two "fish-less" upstream sites had low pH (≤5.5) and marginally elevated concentrations of dissolved aluminum (≥0.2 mg/L) and zinc compared to hardness-adjusted CCC thresholds (Table A3).

Table A4. *Summary of fish taxa collected September 11, 2014, at sample sites on West Creek (WC4 and WC9), West West Branch (WWB), and West Branch (WB1 and WB3) of upper Schuylkill River basin, Schuylkill County, PA.*[a]

Fish Identified		West West Branch			West Branch	
Common Name	Scientific Name	WC4	WC9	WWB	WB1	WB3
Blacknose dace	*Rhinichthys atratulus*	0	25	25	0	0
Creek chub	*Semotilus atromaculatus*	0	21	7	0	0
Fallfish	*Semotilus corporalis*	0	0	0	0	2
White sucker	*Catostomus commersoni*	0	1	4	0	10
Northern hog sucker	*Hypentelium nigricans*	0	0	7	0	0
Green sunfish	*Lepomis cyanellus*	0	2	5	0	0
Pumpkinseed	*Lepomis gibbosus*	0	5	1	0	0
Bluegill	*Lepomis macrochirus*	0	10	14	0	0
Bluegill × Green sunfish	*Lepomis* sp.	0	1	1	0	0
Largemouth bass	*Micropterus salmoides*	0	0	1	0	0
Brown trout	*Salmo trutta*	0	0	5	0	2
Brook trout	*Salvelinus fontinalis*	0	23	22	0	6
Total fish		0	88	92	0	20
Total species		0	8	11	0	4

[a]Fish were collected by electrofishing over a 150 m segment consisting of mixed riffle, run, and pool habitats. Captured fish were held for identification and measurement by Heather Eggleston and Robin Brightbill of USGS, checked for anomalies, and then released in accordance with methods described by U.S. Environmental Protection Agency (1993).

Despite their absence from upstream segments, fish of several species were collected in the perennial downstream segments of West Creek, West West Branch, and West Branch (Table A4), where the pH was near neutral and dissolved aluminum and zinc concentrations were less than aquatic CCC thresholds (Table A3). Specifically, in the perennial segment of West Creek at Phoenix Park (WC9), eight fish species including 88 total individuals were recovered, including 23 brook trout (*Salvelinus fontinalis*). Creek chub (*Semotilus atromaculatus*) and Blacknose dace (*Rhinichthys atratulus*), which are tolerant of low pH (Butler et al., 1973), were also abundant. Further downstream on the West West Branch above West Branch (WWB), 11 species were identified from 92 total fish recovered, including 22 brook trout and five brown trout (*Salmo trutta*). On the adjacent West Branch (WB3), a total of four species were identified from 20 individual fish recovered, including six brook trout and two brown trout. White sucker (*Catostomus commersoni*), which is a pollution-tolerant species (Barbour et al., 1999), also was found at each of the three sites where fish were captured.

Benthic macroinvertebrate samples were collected on October 1, 2014, at the sites of fish surveys using a D-frame kick net (500 μm mesh) to capture debris and organisms dislodged from the streambed in accordance with methods of Barbour et al. (1999). Two shallow riffle areas of approximately 0.5 m^2 (1 m^2 total) were "kicked" upstream from the net for a total of 30 seconds each. Macroinvertebrate metrics were computed following guidelines of the Pennsylvania Department of Environmental Protection (2013), including the total number of individuals (organisms), percentage of pollution-sensitive taxa (e.g., Ephemeroptera or mayflies), percentage of pollution-tolerant taxa (e.g., Chironomidae or midges), and various diversity indices that consider pollution tolerances including the Hilsenhoff Biotic Index (HBI; Hilsenoff, 1988) and Shannon Diversity Index (SDI; Pielou, 1966). The basic metrics were combined to compute "multimetric" composite scores for the Index of Biotic Integrity (IBI; Pennsylvania Department of Environmental Protection, 2013), the Macroinvertebrate Aggregated Index for Streams (MAIS; Smith and Voshell, 1997), and the Macroinvertebrate Biotic Integrity Index (MBII; Klemm et al., 2003).

On the basis of macroinvertebrate data (Table A5), the benthic macroinvertebrate communities in West Creek (WC4 and WC9), West West Branch (WWB), and West Branch (WB3) Schuylkill River reflect water-quality conditions ranging from unimpaired (very good to excellent) to impaired (fair to very poor). Although no aquatic macroinvertebrates were recovered at WB1, which was previously described as exhibiting poor habitat and water quality, a diverse variety of aquatic organisms was collected at the other four sites sampled (WC4, WC9, WWB, WB3).

The macroinvertebrate IBI scores for the West Creek and West West Branch sites indicated water quality "attaining" biological usage criteria and potentially qualifying for exceptional value (EV) anti-degradation protection, whereas the IBI scores for the West Branch site with macroinvertebrates (WB3) indicated impaired

Table A5. *Summary of metrics for macroinvertebrate taxa collected October 1, 2014, at sites on West Creek (WC4 and WC9), West West Branch (WWB), and West Branch (WB1 and WB3) of the upper Schuylkill River basin, Schuylkill County, PA.*[a]

	West West Branch			West Branch	
Metrics[b]	WC4	WC9	WWB	WB1	WB3
Total taxa richness (count of taxa)	14	20	22	0	7
Total number (sum of individuals)	214	204	297	0	200
Total number/m^2	214	204	297	0	200
Percent dominant taxa (single)	49.1	38.2	34.3	100.0	95.5
Percent dominant taxa (5 dominant)	93.5	82.4	76.4	100.0	99.0
Total EPT (sum of all blue rows)	149	63	205	0	2
Percent EPT	69.6	30.9	69.0	0.0	1.0
Total EPT (PTV 0–4)	139	60	42	0	2
Percent EPT (PTV 0–4)	65.0	29.4	14.1	0.0	1.0
Percent Ephemeroptera	0	0.5	24.6	0	0
Number Ephemeroptera taxa	0	1	73	0	0
Number Plecoptera taxa	121	46	3	0	2
Number Trichoptera taxa	28	16	129	0	0
Beck's Index version 3	296	148	63	0	4
Intolerant taxa PTV ≤5	141	110	158	0	6
Percent sensitive individuals (PTV 0–3)	65.4	49.0	14.5	0.0	1.5
Number Chironomidae taxa	55	78	55	0	191
Percent Chironomidae	25.7	38.2	18.5	0	95.5
Percent non-insect taxa	2.3	2.5	6.7	0	1.5
Number collector-filterers (CF)	26	10	124	0	0
% scrapers (SC)	0.5	0.5	12.1	0	1
% haptobenthos (CL + SP, SC + PR)	0.5	0	0	0	0
Shannon Diversity Index (for IBI)	1.46	2.03	2.19	0.00	0.26
Simpson Diversity Index (for MAIS)	0.68	0.79	0.82	1.00	0.09
Hilsenhoff Biotic Index (HBI)	2.64	3.87	5.17	10	5.97
HBI water quality designation	Excellent	Very Good	Fair	Very Poor	Fairly Poor
PADEP IBI score	92.3	93	84	0	20.6
PADEP IBI designation	Attaining EV	Attaining EV	Attaining EV	Impaired	Impaired
MAIS score	11	12	16	2	3
MAIS classification	Fair	Fair	Good	Poor	Poor
MBII score	48.7	46.7	42.7	0	9.2
MBII classification	Fair	Fair	Fair	Poor	Poor

EPT = Ephemeroptera (mayflies), Plecoptera (stoneflies), or Trichoptera (caddisflies); PTV = pollution tolerance value; CL = clingers; SP = sprawlers; PR = predators; IBI = Index of Biotic Integrity; MAIS = Macroinvertebrate Aggregated Index for Streams; MBII = Macroinvertebrate Biotic Integrity Index.

[a]Macroinvertebrate samples collected and identified by Heather Eggleston of USGS using D-frame kick net (500 μm mesh) over 1 m^2 riffle kick area in accordance with Barbour et al. (1999).

[b]Metric computations by Charles Cravotta follow guidelines of Pennsylvania Department of Environmental Protection (PADEP) (2013).

quality. Two other aquatic quality multimetric indices, the MAIS and MBII, were correlated with the IBI scores; these metrics indicated "fair" to "good" aquatic quality at WC4, WC9, and WWB and "poor" aquatic quality at WB3. Chironomids, which are tolerant of pollution, were the dominant taxa at WB3, comprising more than 95 percent of the 200 organisms counted; only 1 percent of the organisms were identified as pollution-intolerant "EPT" taxa, i.e., Ephemeroptera (mayflies), Plecoptera (stoneflies), or Trichoptera (caddisflies). At the three sites within the West West Branch sub-basin (WC4, WC9, and WWB), EPT taxa ranged from 30.9 to 69.6 percent of the total organisms counted, compared to chironomids, which ranged from 18.5 to 38.2 percent of the total taxa. The percentage of pollution-sensitive individuals increased from 1.5 percent at WB3 to 14.5, 49.0, and 65.4 percent at WWB, WC9, and WC4, respectively. It is notable that stoneflies and caddisflies were the dominant EPT taxa at WC4 and WC9, whereas caddisflies and mayflies were dominant at WWB.

In the perennial headwaters site on West Creek (WC4), a high-quality macroinvertebrate assemblage, including pollution-sensitive stoneflies (Plecoptera) and caddisflies (Trichoptera), was collected, despite the absence of fish (Table A5). The habitat at WC4 appeared relatively pristine, with sustained streamflow across a clean gravel substrate in pools formed by sandstone boulders (Figures 2A and 2B). Nevertheless, the water quality at WC4 had moderately low pH (4.3

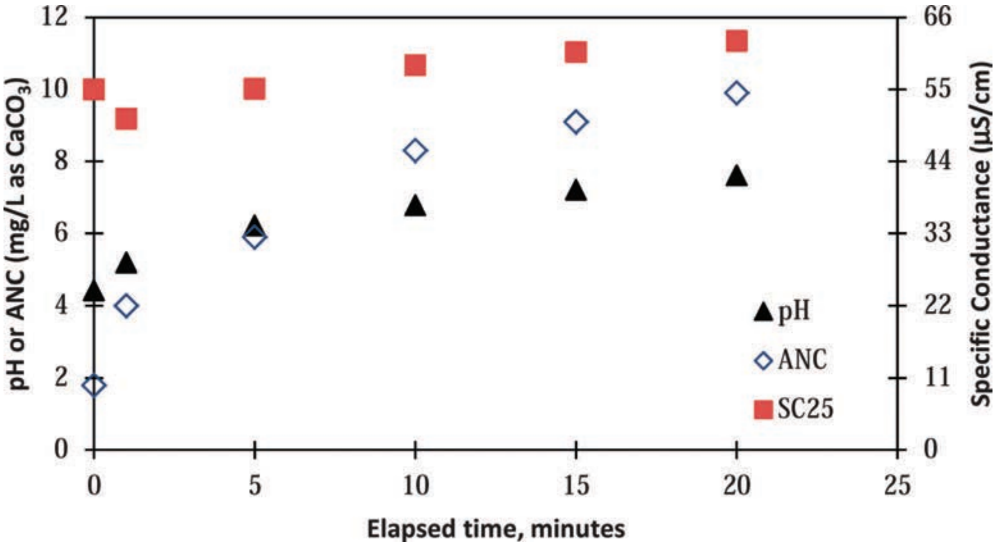

Figure A2. Summary changes in the pH, acid-neutralizing capacity (ANC), and specific conductance (SC) during limestone sand kinetic experiment for neutralization of water from West Creek at WC4, September 18, 2015. A total of 0.80 kg of <4 mm washed limestone "sand" was added at once to 16 L of water from West Creek at WC4.

to 5.5) and moderately elevated concentrations of dissolved aluminum (0.20 to 0.50 mg/L) and zinc (0.025 to 0.049 mg/L), none of which meets CCC thresholds (Table A3).

Limestone Sand Could Neutralize Acidity

A simple kinetic experiment was performed on September 18, 2015, to evaluate the potential to neutralize the net-acidic water from the headwaters of West Creek through limestone sand dosing (e.g., Cravotta, 2010; Cravotta et al., 2010). A total of 0.80 kg of <4-mm-diameter washed limestone "sand" was added at once to 16 L of water collected from West Creek at WC4. The water was gently stirred, and at 1 minute elapsed time, the pH increased from 4.4 to 5.2, while the alkalinity (acid-neutralizing capacity) increased from <2 to 4 mg/L as $CaCO_3$. After 5 minutes, the pH increased to 6.2, and the alkalinity to increased 5.9 mg/L as $CaCO_3$ (Figure A2). Thus, relatively short contact time with limestone sand would be needed for the stream water to be neutralized. Given an average daily flow of 69 L/s and an average net acidity of 3.9 mg/L as $CaCO_3$, the total annual acidity load is 8.54 tonnes/yr at WC4. An equivalent amount of limestone would be needed to neutralize this acidity. Assuming a $CaCO_3$ purity of 95 percent for the limestone, approximately 200 tonnes would provide a 20 year supply. Thus, end-dumping a large amount of limestone sand into West Creek at an upstream location(s) could increase the pH and alkalinity (marginally) and, presumably, facilitate removal of the dissolved Al and Zn, which are near aquatic toxicity thresholds.

APPENDIX REFERENCES

Barbour, M. T.; Gerritsen, J.; Snyder, B. D.; and Stribling, J. B., 1999, *Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers—Periphyton, Benthic Macroinvertebrates, and Fish*: U.S. Environmental Protection Agency Report EPA 841-B-99-002, 11 Chapters, 4 Appendixes.

Butler, R. L.; Cooper, E. L.; Crawford, J. K.; Hales, D. C.; Kimmel, W. G.; and Wagner, C. C., 1973, *Fish and Food Organisms in Acid Mine Waters of Pennsylvania*: U.S. Environmental Protection Agency Report EPA-R3-73-032, 158 p.

Cravotta, C. A., III, 2010, Abandoned mine drainage in the Swatara Creek Basin, Southern Anthracite Coalfield, Pennsylvania, USA—2. Performance of passive-treatment systems: *Mine Water and the Environment*, Vol. 29, pp. 200–216. (http://dx.doi.org/10.1007/s10230-010-0113-5)

Cravotta, C. A., III; Brightbill, R. A.; and Langland, M. J., 2010, Abandoned mine drainage in the Swatara Creek Basin, Southern Anthracite Coalfield, Pennsylvania, USA—1. Streamwater-quality trends coinciding with the return of fish: *Mine Water and the Environment*, Vol. 29, pp. 176–199. (http://dx.doi.org/10.1007/s10230-010-0112-6).

Hilsenhoff, W. L., 1988, Rapid field assessment of organic pollution with family-level biotic index: *Journal of North American Benthological Society*, Vol. 7, pp. 65–68.

Klemm, D. J.; Blocksom, K. A.; Fulk, F. A.; Herlihy, A. T.; Hughes, R. M.; Kaufmann, P. R., Peck, D. V.; Stoddard, J. L.; Thoeny, W. T.; Griffith, M. B.; and Davis, W. S., 2003, Development and evaluation of a macroinvertebrate biotic integrity index (MBII) for regionally assessing mid-Atlantic highlands streams: *Environmental Management*, Vol. 31, No. 5, pp. 656–669.

Pennsylvania Department of Environmental Protection., 2013, *A Benthic Macroinvertebrate Index of Biotic Integrity for Wadeable Freestone Riffle-Run Streams in Pennsylvania*: Pennsylvania Department of Environmental Protection, Bureau of Point and Non-Point Source Management, Division of Water Quality Standards, Harrisburg, PA, 145 p.

Pielou, E. C., 1966, Shannon's formulae as a measure of specific diversity: Its use and misuse: *American Naturalist*, Vol. 100, pp. 463–465.

Smith, E. P. and Voshell, J. R., Jr., 1997, Studies of Benthic Macroinvertebrates and Fish in Streams within EPA Region 3 for Development of Biological Indicators of Ecological Condition. Part 1. Benthic Macroinvertebrates: U.S. Environmental Protection Agency, Washington, DC, USA, Final Report for Cooperative Agreement CF821462010.

U.S. Environmental Protection Agency, 1993, *Fish Field and Laboratory Methods for Evaluating the Biological Integrity of Surface Waters*: U.S. Environmental Protection Agency Report EPA 600/R-92/111, 348 p.

U.S. Environmental Protection Agency, 2013, *National Recommended Water Quality Criteria—Aquatic Life Criteria Table*: U.S. Environmental Protection Agency, https://www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table. (last updated August 22, 2013).