QUANTITY AND QUALITY OF STREAM WATER DRAINING MINED AREAS OF THE UPPER SCHUYLKILL RIVER BASIN, SCHUYLKILL COUNTY, PENNSYLVANIA, USA, 2005-2007[1]

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Abstract: Hydrologic effects of abandoned anthracite mines were documented by continuous streamflow gaging coupled with synoptic streamflow and water-quality monitoring in headwater reaches and at the mouths of major tributaries in the upper Schuylkill River Basin, Pa., during 2005-2007. Hydrograph separation of the daily average streamflow for 10 streamflow-gaging stations was used to evaluate the annual streamflow characteristics for October 2005 through September 2006. Maps showing stream locations and areas underlain by underground mines were used to explain the differences in total annual runoff, base flow, and streamflow yields (streamflow/drainage area) for the gaged watersheds. For example, one stream that had the lowest yield (59.2 cm/yr) could have lost water to an underground mine that extended beneath the topographic watershed divide, whereas the neighboring stream that had the highest yield (97.3 cm/yr) gained that water as abandoned mine drainage (AMD). Although the stream-water chemistry and fish abundance were poor downstream of this site and others where AMD was a major source of streamflow, the neighboring stream that had diminished streamflow met relevant in-stream water-quality criteria and supported a diverse fish community. If streamflow losses could be reduced, natural streamflow and water quality could be maintained in the watersheds with lower than normal yields. Likewise, stream restoration could lead to decreases in discharges of AMD from underground mines, with potential for decreased metal loading and corresponding improvements in downstream conditions. Additional streamflow measurements and geophysical surveys along the stream segments identified as probable losing reaches could indicate where streambed sealing or stream rerouting may be appropriate restoration strategies. Longer-term streamflow data and investigation of the surface-water/ground-water interactions would be needed to evaluate possible consequences of streamflow restoration on flooding and water quality.

Additional Key Words: Streamflow; hydrograph; hydrologic budget; water quality.

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Introduction

Problem

Although metal-laden drainage from abandoned mines can affect aquatic quality in extensively mined watersheds, losses of surface water to underground mines can eliminate the aquatic habitat. For example, in the humid, temperate climatic setting of the Anthracite Coalfield of eastern Pennsylvania, USA (Fig. 1), second- and third-order stream channels overlying extensive underground mines can be dry or intermittently flowing while the mines remain substantially flooded (Ash et al., 1949; Ash and Whaite, 1953; Hollowell, 1974; Reed et al., 1987; Chaplin et al., 2007). The hydrology of these extensively mined watersheds is analogous to that for karst terrains; however, the quality of ground water in the coalfields typically is not controlled by reactions with limestone (e.g. White, 1988; Saskowski and White, 1993). Water that encounters pyrite-oxidation products in coal waste and mined rock can become contaminated with acidity, sulfate, iron, and other metals (Ladwig et al., 1984; Cravotta, 1994). Eventually, the contaminated ground water may resurface as abandoned mine drainage (AMD) from tunnels, boreholes, or fractures at topographically low points (Growitz et al., 1985; Wood, 1996; Ballaron, 1999). Although the AMD can restore streamflow lost from upstream reaches overlying the mines, the downstream quality and aquatic ecosystem tend to be impaired by metals from the AMD (Cravotta and Bilger, 2001; Cravotta and Kirby, 2004; Cravotta, 2005).

Study Area

The Anthracite Coalfield in Pennsylvania consists of four large coalfields within an area of about 8,850 km^2 in the Appalachian Mountain Section of the Ridge and Valley Physiographic Province in eastern Pennsylvania (Wood et al., 1986; Berg et al., 1980; Eggleston et al., 1999; Way, 1999). Structurally, the Northern, Eastern Middle, Western Middle, and Southern Anthracite Coalfields are parts of parallel, moderately to deeply downwarped synclinoria. Most mines in the region were developed to access multiple coalbeds of the Llewellyn and Pottsville Formations of Pennsylvanian Age. In the Southern Anthracite Coalfield, 38 coalbeds with average thicknesses from 0.3 to 2.5 m have been identified and mined to depths exceeding 1,000 m; sandstone, siltstone, and conglomerate are the dominant lithologies; limestone has not been mapped (Wood et al., 1986; Berg et al., 1980; Brady et al., 1998).

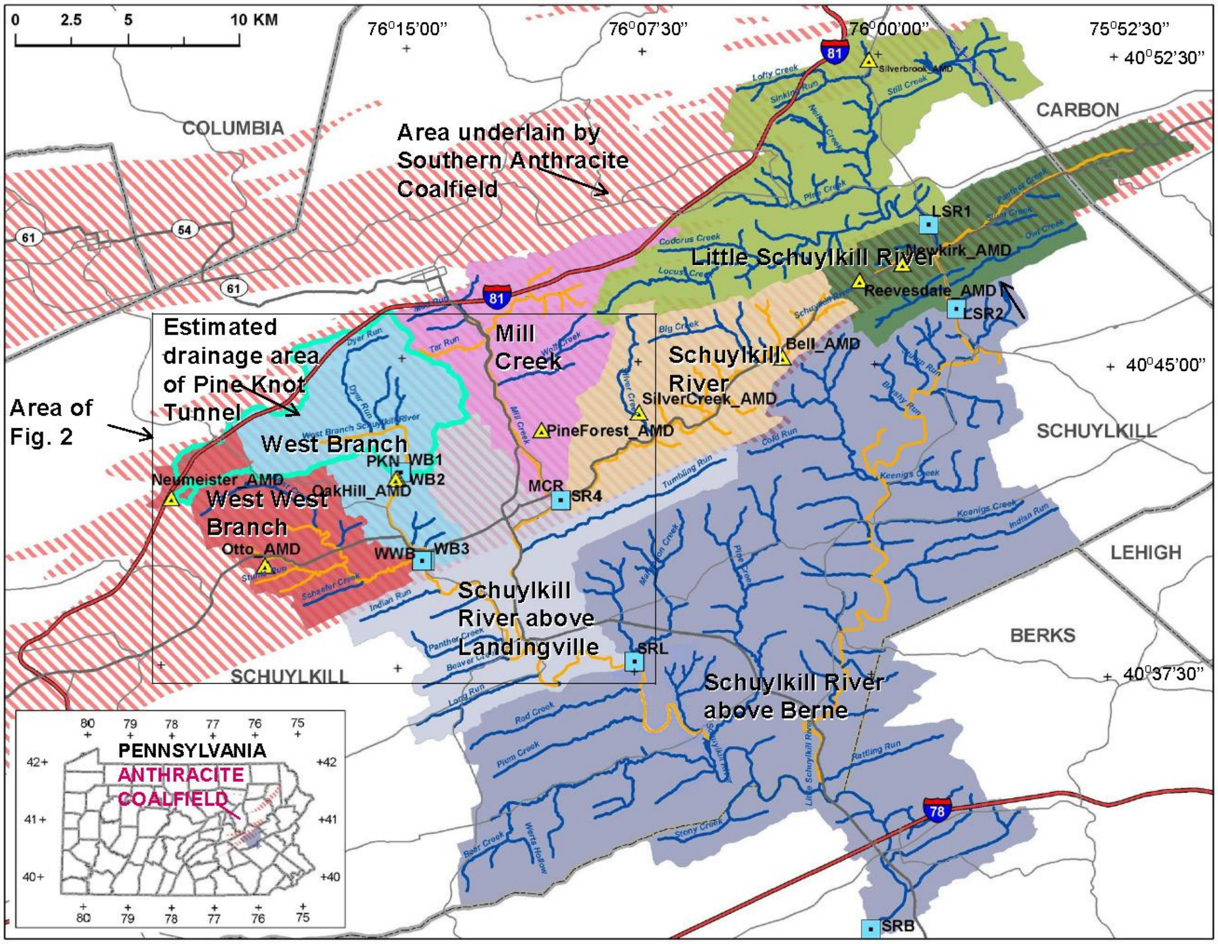

Figure 1. Drainage basins for the upper Schuylkill River and selected monitoring sites upstream of the U.S. Geological Survey (USGS) streamflow-gaging station at Berne, PA. Drainage basins, indicated by differently colored areas, were delineated from USGS 7.5-minute topographic maps; basins for the Schuylkill River above Landingville and above Berne include the upstream basins. Streamflow-gaging stations (blue squares) and other water-quality stations (yellow triangles) identified on the map are described in Table 1. AMD-impaired stream segments are orange, whereas unimpaired streams are blue (Pennsylvania Department of Environmental Protection, 2004, 2006). Areas underlain by coal-bearing Pennsylvanian-age bedrock of the Anthracite Coalfield are indicated by red hatch symbol (Berg et al., 1980).

The Schuylkill River has a total drainage area of 5,120 km^2 with its headwaters in the uplands of Schuylkill and Carbon Counties and its mouth 208 km downstream on the Delaware River at Philadelphia, PA. In the study area, the upper Schuylkill River Basin encompasses 909 km^2 above the U.S. Geological Survey (USGS) streamflow-gaging station at Berne, Berks County, PA (Fig. 1, station SRB). The long-term average annual precipitation ranges from 115 to 135 cm/yr over the basin; the greatest values are for the uplands (National Climatic Data Center, 2007). Nearly one-third of the basin is underlain by the Southern Anthracite Coalfield

(Fig. 1). Hundreds of AMD sources drain to tributaries within the mined area (Growitz et al., 1985; L. Robert Kimball & Associates, 2000, 2001). Consequently, more than 96 km of stream segments in the basin, including the Little Schuylkill River, West Branch Schuylkill River, and the upper main stem Schuylkill River, are designated "impaired" because of AMD (Pennsylvania Department of Environmental Protection, 2003, 2004).

Strategies for remediation of the AMD in the upper Schuylkill River Basin, based on the reported flow and chemistry of the AMD sources and corresponding passive-treatment guidelines (Hedin et al., 1994), were identified in recent watershed assessments (L. Robert Kimball & Associates, Inc., 2000, 2001). Considering these recommended strategies and the availability of land and funding, various passive-treatment systems were constructed or planned at eight of the largest AMD sources in the basin (Table 1). Detailed descriptions of these treatment systems and results of monitoring, if available, are reported elsewhere. Several examples follow: (1) Downflow limestone beds were implemented in 2003 to treat net-acidic, iron-laden AMD at the Bell Mine (Cravotta and Ward, 2008). (2) Aerobic wetlands were implemented in 2005 to treat net-alkaline, iron-laden AMD at the Otto Mine (Cravotta, 2007). (3) An oxic limestone drain was implemented in 2006 to treat net-acidic, relatively dilute AMD at the Reevesdale Mine (Cravotta, in press). Additionally, (4) an anoxic limestone drain was implemented in 2007 to treat net-acidic, iron-laden AMD at the Pine Forest Mine, and (5) vertical flow, flushable limestone beds have been designed for construction in 2008 to treat net-acidic, aluminum-laden AMD at the Neumeister Mine. Locations of these and other selected AMD sources are provided in Table 1 and Figure 1 to provide spatial context for the gaging stations described in this paper.

The Pine Knot Tunnel Discharge near Minersville, PA (Figs. 1 and 2), was identified in recent watershed assessments as the largest source of metals loading in the upper Schuylkill River Basin (L. Robert Kimball & Associates, Inc., 2000; Pennsylvania Department of Environmental Protection, 2003). However, passive treatment of this AMD source was not considered feasible because of its large flow and iron-loading rates, its proximity to the West Branch Schuylkill River, and the small land area available for treatment. During dry weather periods, the West Branch above the Pine Knot Tunnel (WB1) occasionally would stop flowing,

Table 1. Streamflow gaging and water-quality monitoring sites, upper Schuylkill River Basin, Schuylkill and Berks Counties, Pennsylvania
[ab, above; bl, below; AMD, abandoned mine drainage; m, meters; km^2, square kilometers; nd, no data]

Map ID[a]	USGS Station ID	Site Name and Description	Latitude[b]	Longitude	Drainage Area,[c] km^2	Type of Monitoring[d]
WB1	01467688	West Branch ab Pine Knot Tunnel at Duncott (established 2005)	404215.2	761457.5	49.8	Continuous
PKN	01467689	Pine Knot Tunnel Discharge, 500-m bl, at Duncott (established 2005)	404215.2	761458.5	49.8	Continuous
OakHill_AMD	01467691	Oak Hill Boreholes Discharge, 200-m bl, at West Branch at Duncott	404207.6	761504.5	nd	Quarterly
WB2	01467692	West Branch bl Oak Hill Boreholes at Duncott	404206.1	761507.2	50.0	Quarterly
WB3	01467752	West Branch ab West West Branch at Pottsville (established 2005)	404007.6	761409.9	61.7	Continuous
WWB	01467861	West West Branch ab West Branch at Pottsville (established 2005)	404007.9	761415.4	47.6	Continuous
MCR	01467492	Mill Creek ab Schuylkill River at Port Carbon (established 2005)	404138.1	760952.6	65.3	Continuous
SR4	01467471	Schuylkill River ab Mill Creek at Port Carbon (established 2005)	404137.8	760952.0	69.6	Continuous
LSR1	01469500	Little Schuylkill River ab Tamaqua	404825.0	755819.0	110	Continuous
LSR2	01469700	Little Schuylkill River bl Tamaqua (established 2005)	404623.0	755724.0	168	Continuous
SRL	01468500	Schuylkill River at Landingville	403745.0	760729.0	341	Continuous
SRB	01470500	Schuylkill River at Berne (Berks County)	403121.0	755954.0	909	Continuous
Otto_AMD	403958076191401	Otto Air Shaft AMD (aerobic wetlands, 2005)[e]	403958.0	761913.0	nd	Intermittent
Neumeister_AMD	404134076221501	Neumeister Drift AMD (upflow limestone beds, 2008)	404133.9	762214.3	nd	Intermittent
PineForest_AMD	404320076103201	Pine Forest Mine Tunnel AMD (anoxic limestone drain, 2007)	404320.0	761031.0	nd	Intermittent
SilverCreek_AMD	404403076072401	Silver Creek Mine Tunnel AMD (anoxic limestone drain, proposed)	404348.0	760726.0	nd	Intermittent
Bell_AMD	404512076025501	Bell Water Level Tunnel AMD (downflow limestone beds, 2003)	404510.0	760253.0	nd	Intermittent
Reevesdale_AMD	404705076003201	Reevesdale South Dip 2 Tunnel AMD (oxic limestone drain, 2006)	404703.2	760029.0	nd	Intermittent
Newkirk_AMD	404728075590901	Newkirk Tunnel North Dip AMD (oxic limestone drain, 2002)	404728.0	755908.0	nd	Intermittent
Silverbrook_AMD	405224076001701	Silverbrook Mine Opening AMD (upflow limestone beds, proposed)	405224.0	760016.0	nd	Intermittent

a. Site locations shown in Figure 1.

b. Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). Values are degrees, minutes, seconds; 404215.2 represents 40°42'15.2" north latitude and 761457.5 represents 76°14'57.5" west longitude.

c. Drainage area, for basins shown in Figures 1 and 2, delineated on the basis of topographic contours on USGS 1:24,000 topographic maps.

d. Quarterly monitoring of flow and water quality (Quarterly) and continuous monitoring of stage and temperature (Continuous) were conducted by USGS during 2005-2007. Intermittent monitoring of flow and water quality at various AMD sources was conducted by Schuylkill Action Network (SAN) members, but is not reported herein.

e. AMD sites where passive-treatment systems were constructed or planned have been monitored intermittently for other studies, and are not described in detail hereinafter. The locations of these AMD sites are indicated to provide context for the locations and water quality at streamflow-gaging stations discussed in this paper.

whereas the flow of the Pine Knot Tunnel (PKN) changed little (Fig. 3). Hence, the drainage area of the West Branch above the Pine Knot Tunnel was hypothesized to contribute recharge to the Pine Knot Tunnel (Fig. 2), largely as streambed leakage. Furthermore, the assessments suggested the Oak Hill Mine could be hydrologically connected to the Pine Knot Mine because of their proximity to each other (Fig. 2). The assessments concluded that streamflow restoration in the contributing subwatersheds might be necessary to decrease the AMD flow rates and metals loading. However, because data on the range of flow rates and quality of the AMD sources and associated streams were sparse, the assessments suggested that detailed hydrological data were needed to develop plans for remediation.

Purpose and Scope

This paper summarizes hydrologic data collected by the USGS for an investigation of the effects of abandoned anthracite mines on the streamflow and water quality of major tributaries in the upper Schuylkill River Basin during 2005-2007. The investigation was conducted in cooperation with the Schuylkill Conservation District (SCD), the Schuylkill Headwaters Association, Inc. (SHA), the Pennsylvania Department of Environmental Protection (PaDEP), and the U.S. Environmental Protection Agency (USEPA). The purpose of the investigation was (1) to establish streamflow-gaging stations to document current hydrologic and water-quality conditions in the major tributaries exiting the mined part of the upper Schuylkill River Basin, (2) to estimate the annual hydrologic budget for the major tributaries of the upper Schuylkill River Basin, and (3) to identify the locations and magnitude of leakage from headwater streams to the Pine Knot Mine pool. Continuous streamflow gaging at 10 sites within the watershed coupled with quarterly water-quality monitoring and annual fish surveys at a subset of these sites during 2005-2007 were used to document the current hydrologic conditions. Hydrograph-separation methods were used to estimate annual contributions of runoff and base flow at the 10 gaging stations from October 2005 through September 2006. Additionally, synoptic seepage surveys were conducted in April 2004 and July 2006 to measure losses of stream water to the underground mine complex drained by the Pine Knot Tunnel.

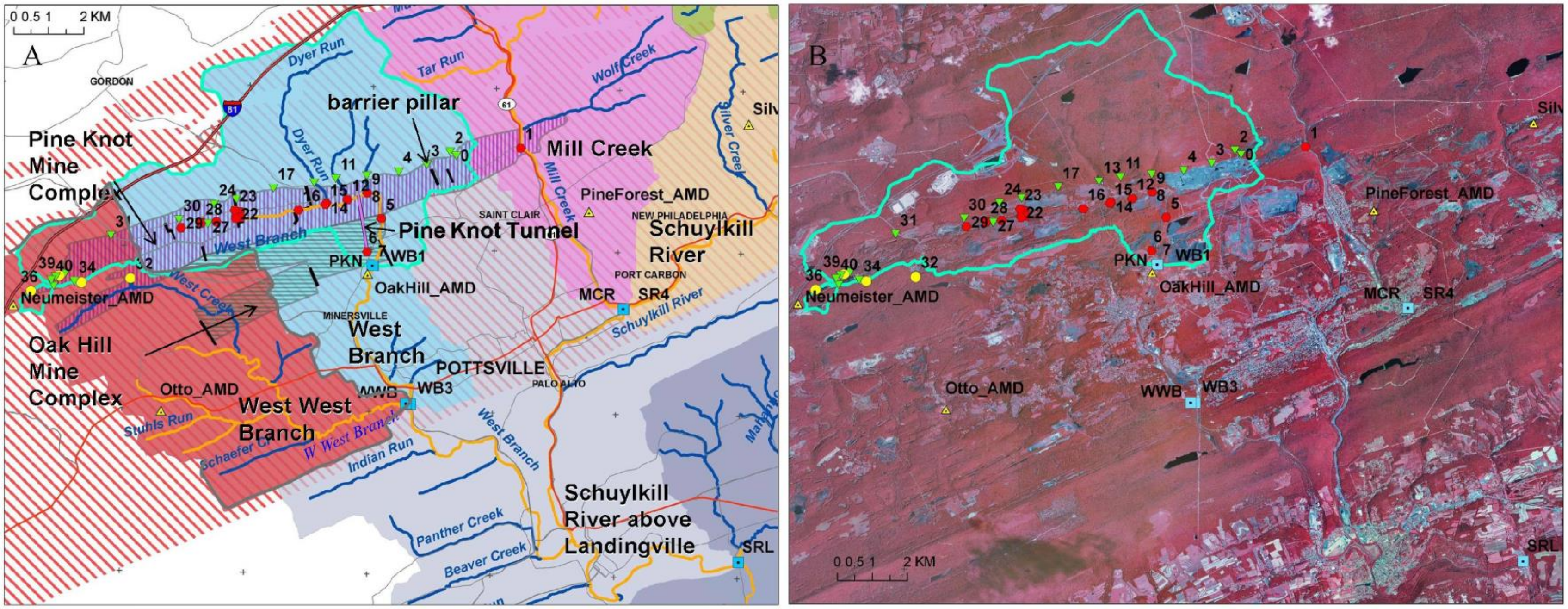

Figure 2. Approximate drainage area shared by the Pine Knot Tunnel Discharge and the West Branch above the Pine Knot Tunnel (blue outline) and locations of water-quality monitoring and seepage measurement sites on base showing: A, perennial streams, roads, and underground mine boundaries (from Michael Hill, Pennsylvania Department of Environmental Protection, written commun., 2005); and B, color infrared aerial imagery. Seepage measurement sites (red dots, green triangles, yellow dots) and results are described in Table 5.

Figure 3. Photos illustrating range of discharge conditions at streamflow-gaging stations on Pine Knot Tunnel (PKN) and West Branch above Pine Knot Tunnel (WB1) during typical dry and wet periods.

Methods

Streamflow-gaging stations for continuous monitoring of discharge were established by the USGS in June 2005, at the Pine Knot Tunnel (PKN) and West Branch above PKN (WB1), and in September 2005 at five additional downstream sites, the West Branch (WB3), West West Branch (WWB), Mill Creek (MCR), Schuylkill River (SR4), and Little Schuylkill River (LSR2), near their outlets from the mined part of the upper Schuylkill River Basin (Fig. 1, Table 1). At each gaging station, a crest-stage gage (CSG), a vertical staff gage, and a submersible, vented pressure transducer with thermister were installed to measure stream stage and temperature. The transducer was equipped with a digital data logger to record stage and temperature at 15-minute intervals.

During 2005-2007, discharge at each gaging station was measured for a range of stages by use of a wading rod and current meter (Rantz et al., 1982). At high stages, a current meter was suspended from the nearest bridge. Corresponding instantaneous measurements of stage and discharge were used to develop stage-discharge ratings for each site (Rantz et al., 1982). For the seven gaging stations established in 2005, the stage-discharge ratings were based on instantaneous measurements of stage and discharge over a range of low-to-moderate flow conditions during 2005-2006. Extrapolation of stage-discharge ratings for high-flow conditions was based on established ratings for nearby gaging stations and the corresponding drainage areas (Table 1). Because the stage-discharge relations changed because of changes in channel geometry during the flood of June 27-29, 2006 (National Weather Service, 2006; U.S. Geological Survey, 2006), two ratings were developed for all but the Schuylkill River gaging station. The daily average streamflow values at each gaging station for the period October 2005 through September 2006 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 gaging station, including the percentages of total streamflow that were base flow and runoff.

To establish water-quality conditions during the study, fish populations were surveyed in October 2005 and October 2006 at the five gaging stations near the outlet of the mined area of the basin. Fish were collected by electrofishing over a 100-yard reach consisting of mixed riffle, run, and pool habitats at each stream site. The fish were measured, identified, checked for anomalies, and then released in accordance with methods of Meador et al. (1993) and Barbour et al. (1999).

Data on pH, alkalinity, acidity, concentrations of total and dissolved (0.45-µm pore-size filter) metals, and other water-quality constituents were collected quarterly during July 2005 to March 2007 at all seven continuous gaging stations installed in 2005 plus the Oak Hill Boreholes Discharge and the West Branch below the Oak Hill Boreholes (Table 1). When samples were collected, temperature, pH, specific conductance (SC), dissolved oxygen (DO), and redox potential (Eh) were measured by use of a calibrated, submersible sonde. Field pH and Eh were determined by use of a combination Pt and Ag/AgCl electrode with a pH sensor. The electrode was calibrated in pH 4.0 and 7.0 buffer solutions and in ZoBell's solution (Wood, 1976). Values for Eh were corrected to 25 °C relative to the standard hydrogen electrode in accordance with methods of Nordstrom (1977).

The alkalinity and "hot peroxide" acidity (hot acidity) of the unfiltered water samples were titrated using sulfuric acid (H_2SO_4) or sodium hydroxide (NaOH) to fixed endpoint pH values of 4.5 and 8.3, respectively (American Public Health Association, 1998a, 1998b). Typically, alkalinity was measured within 24 hours of sampling, whereas acidity was measured several days later at the USGS Pennsylvania Water Science Center laboratory in New Cumberland, PA. Concentrations of major anions (SO_4, Cl) in 0.45-μm filtered, unpreserved subsamples were analyzed by ion chromatography (IC). Concentrations of major cations (Ca, Mg, Na, K) and selected trace metals (Fe, Mn, Al, Ni, Zn) in unfiltered, acidified and in 0.45-μm filtered, acidified subsamples were analyzed by inductively coupled plasma optical emission spectrometry (ICP) at the Actlabs Laboratory in Toronto, Ontario (Crock et al., 1999; Fishman and Friedman, 1989).

Results and Discussion

The annual fish surveys conducted in October 2005 and October 2006 indicated that as many as 11 different fish species inhabited the stream segments near the gaging stations (Table 2). All but one of these fish species were characterized by Barbour et al. (1999) as tolerant to moderately tolerant of pollution and can be found in relatively low-pH waters draining uplands across Pennsylvania (Butler et al., 1973) (Table 2). Blacknose dace (*Rhinichthys atratulus*), white sucker (*Catostomus commersoni*), and brook trout (*Salvelinus fontinalis*) of various sizes were documented at all five sites surveyed (Table 2). The West West Branch (WWB) and Little Schuylkill River (LSR2) had both the greatest diversity and numbers of fish species, reflecting better habitat and water quality than the other sites. The West Branch (WB3) and Mill Creek (MCR) had the lowest species diversity and/or fewest numbers of individual fish, consistent with their degraded water quality (Table 3).

Although the pH was near neutral at most stream sites during the study, water-quality degradation commonly was indicated by elevated concentrations of iron and other dissolved metals in the water column and associated ochreous precipitate on the streambed.

Table 2. Fish species identified and number of individuals counted during annual ecological surveys of upper Schuylkill River tributaries, October 19, 2005, and October 4, 2006[a]

Taxa: ORDER / Family / *Genus species*	Common Name	Minimum pH in PA[b]	Pollution Tolerance[c]	WB3 01467752 05	WB3 01467752 06	WWB 01467861 05	WWB 01467861 06	MCR 01467492 05	MCR 01467492 06	SR4 01467471 05	SR4 01467471 06	LSR2 01469700 05	LSR2 01469700 06
CYPRINIFORMES													
Cyprinidae													
Luxilus cornutus	Common shiner	6.0	M	0	0	0	0	0	0	0	0	0	1
Rhinichthys atratulus	Blacknose dace	5.6	T	1	1	27	29	4	32	32	39	45	72
Rhinichthys cataractae	Longnose dace	5.9	I	0	0	0	0	0	0	0	0	2	2
Semotilus atromaculatus	Creek chub	5.2	T	0	0	4	5	5	1	2	5	43	32
Catostomidae													
Catostomus commersoni	White sucker	4.6	T	0	4	23	7	160	37	10	0	78	70
SILURIFORMES													
Ictaluridae													
Ameiurus nebulosus	Brown bullhead	4.6	T	0	0	1	0	0	0	0	0	0	0
SALMONIFORMES													
Salmonidae													
Oncorhynchus mykiss	Rainbow trout	6.5	M	0	1	0	0	0	0	0	0	0	0
Salmo trutta	Brown trout	5.9	M	0	1	0	0	0	0	0	1	2	1
Salvelinus fontinalis	Brook trout	5.0	M	15	2	32	13	3	0	1	1	3	1
PERCIFORMES													
Centrarchidae													
Lepomis cyanellus	Green sunfish	6.4	T	0	1	1	0	3	0	2	0	0	0
Lepomis gibbosus	Pumpkinseed	4.6	M	0	1	30	5	0	0	0	1	0	2
Lepomis macrochirus	Bluegill	6.5	M	0	0	0	2	0	0	0	0	0	0
Micropterus salmoides	Largemouth bass	4.7	M	0	0	2	0	0	0	0	0	0	1
Percidae													
Etheostoma olmstedi	Tessellated darter	5.9	M	0	0	3	4	0	0	0	0	1	1
Perca flavescens	Yellow perch	5.5	M	0	0	0	0	0	0	0	0	0	1
Total number of individuals collected:				16	10	123	65	175	70	47	47	174	183
Total number of species identified:				2	7	9	7	5	3	5	5	7	11

a. Fish collected and identified by M. D. Bilger and R. A. Brightbill of U.S. Geological Survey and Robert Schott of Pennsylvania Department of Environmental Protection.
b. Minimum pH of occurrence in freshwater in Pennsylvania as reported by Butler and others (1973).
c. Pollution tolerance: I (intolerant), M (moderate), T (tolerant), adapted from Barbour and others (1999).

On the basis of eight quarterly water-quality samples from July 2005 to March 2007 (Table 3), only the West West Branch (WWB) consistently met criteria of the Commonwealth of Pennsylvania (2002) and the Pennsylvania Department of Environmental Protection (2005) for total maximum daily loads (pH 6.0 to 9.0 and concentrations of total Fe < 1.5 mg/L, total Mn < 1.0 mg/L, and total aAl < 0.75 mg/L) and "criteria continuous concentration" (CCC) values of the U.S. Environmental Protection Agency (2002) for protection of freshwater aquatic organisms (dissolved Fe < 1.0 mg/L, dissolved Al < 0.087 mg/L, dissolved Ni < 0.052 mg/L, and

Table 3. Summary of quarterly water-quality data for upper Schuylkill River tributaries, July 2005 - March 2007
[values are median(minimum/maximum) for 8 samples; units are milligrams per liter, except as noted; L/s, liters per second; ^{o}C, degrees Celsius; mV, millivolts; μS/cm, microsiemens per centimeter; diss., dissolved (<0.45 μm); “<” less than]

Constituent	WB1 01467688	PKN 01467689	OakHill_AMD 01467691	WB2 01467692	WB3 01467752	MCR 01467492	WWB 01467861	SR4 01467471	LSR2 01469700
Flow (L/s)	197(2.3/1,054)	558(268/1,334)	206(123/484)	963(391/1,260)	1,314(623/3,483)	408(169/1,759)	790(326/3,597)	909(297/3,427)	2,266(1,107/10,365)
Temp. (^{o}C)	13.2(1.8/20.3)	10.8(10.7/11.2)	15.1(13.9/16.4)	11.8(7.7/14.6)	11.4(6.9/15.2)	11.8(2.7/17.3)	10.4(0.9/15.6)	11(0.9/16.4)	11.7(1.9/19.9)
DO	9.4(7.0/12.6)	10.2(8.4/11.1)	2.6(1.5/3.8)	8.8(7.3/9.5)	9.4(8.7/9.9)	9.6(8.2/13.2)	10.1(8.3/12.3)	9.8(8.3/14.1)	9.35(8.9/13.6)
Eh (mV)	390(300/580)	335(270/470)	280(200/390)	315(250/480)	265(220/370)	330(270/380)	325(160/510)	350(290/400)	305(200/410)
SC (μS/cm)	145(64/790)	560(460/650)	960(860/1050)	580(420/650)	575(400/640)	370(210/420)	285(250/470)	310(230/410)	420(210/540)
pH (units)	5.6(4.3/6.2)	6.3(5.6/6.6)	6.3(5.8/6.4)	6.4(5.8/6.5)	6.9(6.3/7.1)	6.6(5.5/6.9)	7.4(6.9/7.9)	6.8(5.2/6.9)	6.85(6.6/7.3)
Alkalinity	2.4(1.6/3.4)	32(23/42)	155(110/170)	47(30/73)	53(28/69)	9.8(4.9/17)	33(25/94)	17(10/23)	17(9.9/30)
Acidity, hot	3.8(2.1/18)	-19(-22/-11)	-109(-130/-87)	-29(-42/-19)	-35(-61/-21)	2.2(-10/12)	-25(-110/-8.4)	-9.1(-16/-1.0)	-10(-29/-4.0)
SO_4, diss.	49(14/500)	255(240/270)	410(360/450)	245(170/310)	220(160/280)	125(89/160)	98(79/170)	125(93/180)	165(67/220)
Cl, diss.	11(5.1/14)	11(10/13)	6.4(5.2/8.6)	10(9.0/11)	16(11/19)	25(4.7/41)	7.3(4.5/8.6)	7.8(4.1/24)	15(12/17)
Ca, diss.	10(2.8/90)	43(37/48)	99(72/100)	47(34/66)	48(31/58)	26(16/31)	24(20/51)	28(18/42)	39(15/51)
Mg, diss.	6.3(1.7/69)	44(42/48)	55(49/61)	38(30/52)	34(26/48)	17(10/24)	15(12/30)	17(11/24)	21(7.2/31)
K, diss.	0.6(0.4/1.7)	1.3(0.8/1.7)	2.3(1.6/2.9)	1.4(0.9/1.7)	1.9(1.3/2.6)	1.8(0.8/2.4)	1.35(1.0/2.3)	1.3(1.1/2.2)	1.5(1.0/2.3)
Na, diss.	6.1(4.0/9.0)	7.6(6.1/8.3)	33(24/35)	12(10/15)	17(12/18)	15(6.0/28)	7.7(6.3/20)	7.7(4.5/19)	9.7(7.2/20)
Al, total	0.6(0.4/3.4)	0.7(0.6/1.2)	0.3(0.2/0.5)	0.6(0.5/0.8)	0.6(0.3/0.9)	0.85(0.2/1.3)	<0.1(<0.1/0.2)	0.5(0.2/0.9)	0.55(0.4/0.8)
Al, diss.	0.2(<0.1/2.1)	<0.1(<0.1/0.3)	<0.1(<0.1/0.3)	<0.1(<0.1/0.2)	<0.1(<0.1/0.2)	<0.1(<0.1/<0.1)	<0.1(<0.1/<0.1)	<0.1(<0.1/<0.1)	<0.1(<0.1/0.1)
Fe, total	0.13(0.08/0.66)	6.2(4.9/7.3)	18(13/20)	6.9(5.3/12)	4.5(3.6/6.1)	2.0(1.1/3.2)	0.26(0.20/0.74)	2.2(1.4/2.5)	1.9(0.82/2.5)
Fe, diss.	0.085(0.05/0.5)	5.8(4.5/7.0)	18(12/19)	6.8(4.8/10)	2.9(1.8/3.2)	1.5(0.47/2.7)	0.055(0.03/0.19)	1.0(0.51/1.4)	0.97(0.09/1.4)
Mn, total	0.26(0.12/3.2)	2.8(2.2/3.1)	4.0(3.1/4.8)	2.4(1.8/3.2)	2.1(1.5/3.0)	1.5(1.0/2.0)	0.42(0.18/0.63)	1.3(0.83/1.9)	1.6(0.51/2.0)
Mn, diss.	0.26(0.12/3.2)	2.8(2.2/3.0)	4.0(3.1/4.5)	2.4(1.8/3.2)	2.1(1.5/3.0)	1.5(1.0/2.0)	0.42(0.18/0.62)	1.3(0.83/1.9)	1.6(0.51/2.0)
Ni, diss.	0.01(<0.01/0.14)	0.07(0.05/0.08)	0.05(0.04/0.06)	0.05(0.04/0.06)	0.04(<0.01/0.06)	0.03(<0.01/0.04)	0.02(0.01/0.02)	0.04(0.03/0.04)	0.03(0.01/0.04)
Zn, diss.	0.04(0.03/0.38)	0.15(0.12/0.20)	0.05(0.03/0.07)	0.10(0.08/0.16)	0.08(0.07/0.18)	0.08(0.05/0.11)	0.02(<0.01/0.04)	0.07(0.05/0.09)	0.11(0.05/0.15)

dissolved Zn < 0.12 mg/L). Although these criteria were met intermittently at most sites, the intermediate and lower reaches of West Branch (WB2, WB3) and Mill Creek (MCR) consistently were degraded because of dissolved iron and manganese (Table 3). For example, during the study, concentrations of dissolved Fe at West Branch near its confluence with the West West Branch (WB3) ranged from 1.8 to 3.2 mg/L and those at Mill Creek near its confluence with the Schuylkill River (MCR) ranged from 0.47 to 2.7 mg/L. Concentrations of total and dissolved Mn were comparable to dissolved Fe. Because of its limited solubility at near-neutral pH, dissolved Al rarely exceeded the 0.1-mg/L detection limit (Table 3).

The main sources of dissolved metals loading to the streams were AMD sources upstream of the sampled sites (Fig. 1). For example, the intermediate and lower reaches of the West Branch were degraded by AMD from the Pine Knot Tunnel and the Oak Hill Boreholes. During the study, concentrations of dissolved Fe at the Pine Knot Tunnel (PKN) ranged from 4.5 to 7.0 mg/L and those at the Oak Hill Boreholes (OakHill_AMD) ranged from 12 to 19 mg/L, with medians of 5.8 and 18 mg/L, respectively (Table 3). Despite a median concentration of Fe for the Oak Hill Boreholes that was three times greater than that for the Pine Knot Tunnel, the median flow rate for the Pine Knot Tunnel was approximately three times that for the Oak Hill Boreholes. Consequently, the median iron-loading rates (flow multiplied by concentration) were equivalent for these two AMD sources.

The AMD from the Pine Knot Tunnel and Oak Hill Boreholes contributed a large fraction of the streamflow in intermediate and downstream reaches of the West Branch, particularly during periods of dry weather when most of, if not all, the streamflow in the upper reaches of the West Branch infiltrated to the underground mines. When quarterly water-quality samples were collected during 2005-2007, the flow rate of the West Branch above the Pine Knot Tunnel (2.3 to 1,054 L/s) frequently was less than that of the Pine Knot Tunnel (268 to 1,334 L/s) (Table 3). In particular, during July through September 2005 and July through August 2006, the flow at WB1 nearly dried up, whereas the flow of the Pine Knot Tunnel was sustained at a high rate, accounting for most of the streamwater in lower reaches (Figs. 4 and 5).

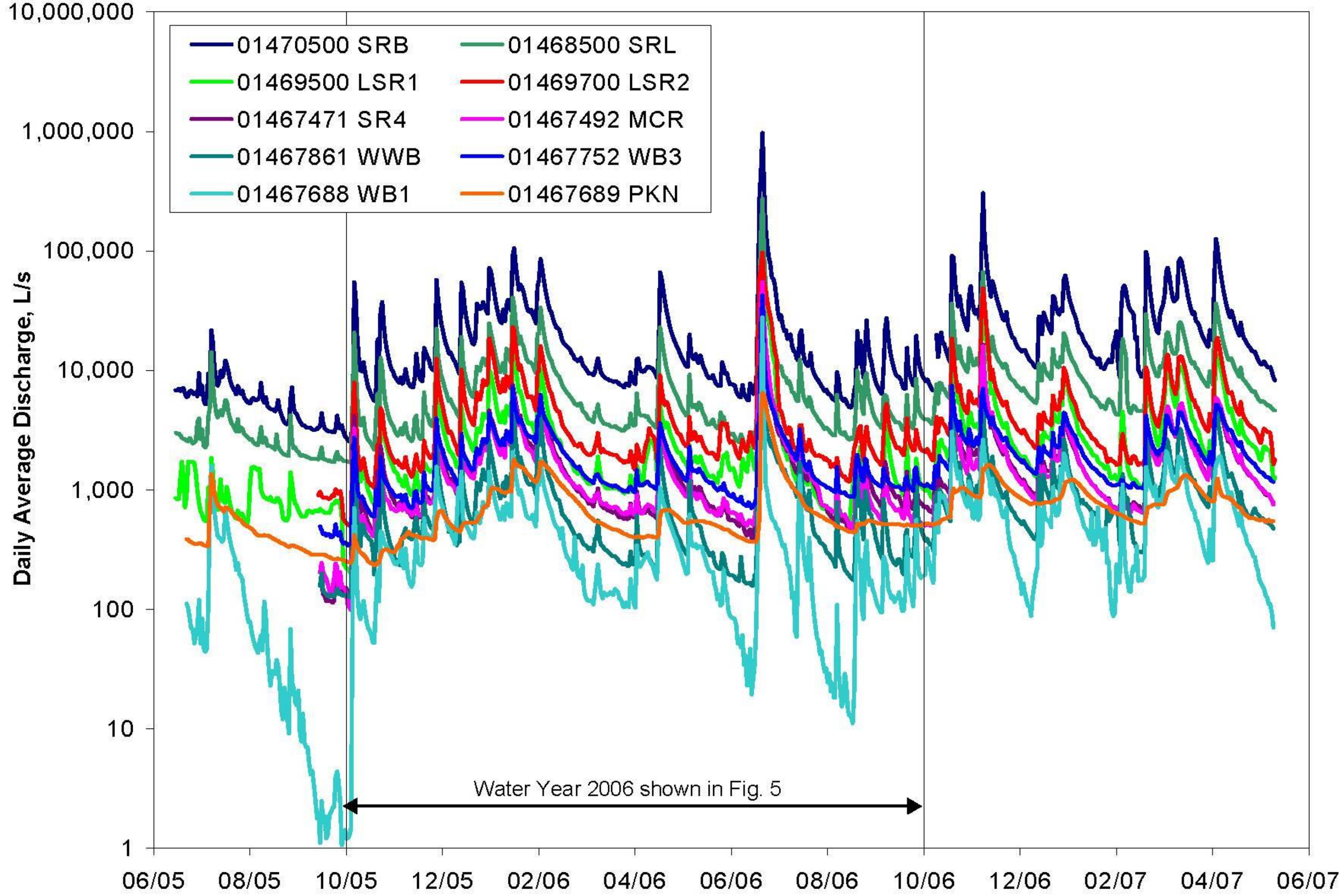

Figure 4. Daily average discharge at 10 continuous streamflow-gaging stations in the upper Schuylkill River Basin, June 2005-May 2007. Site descriptions are in Table 1 and locations are in Fig. 1.

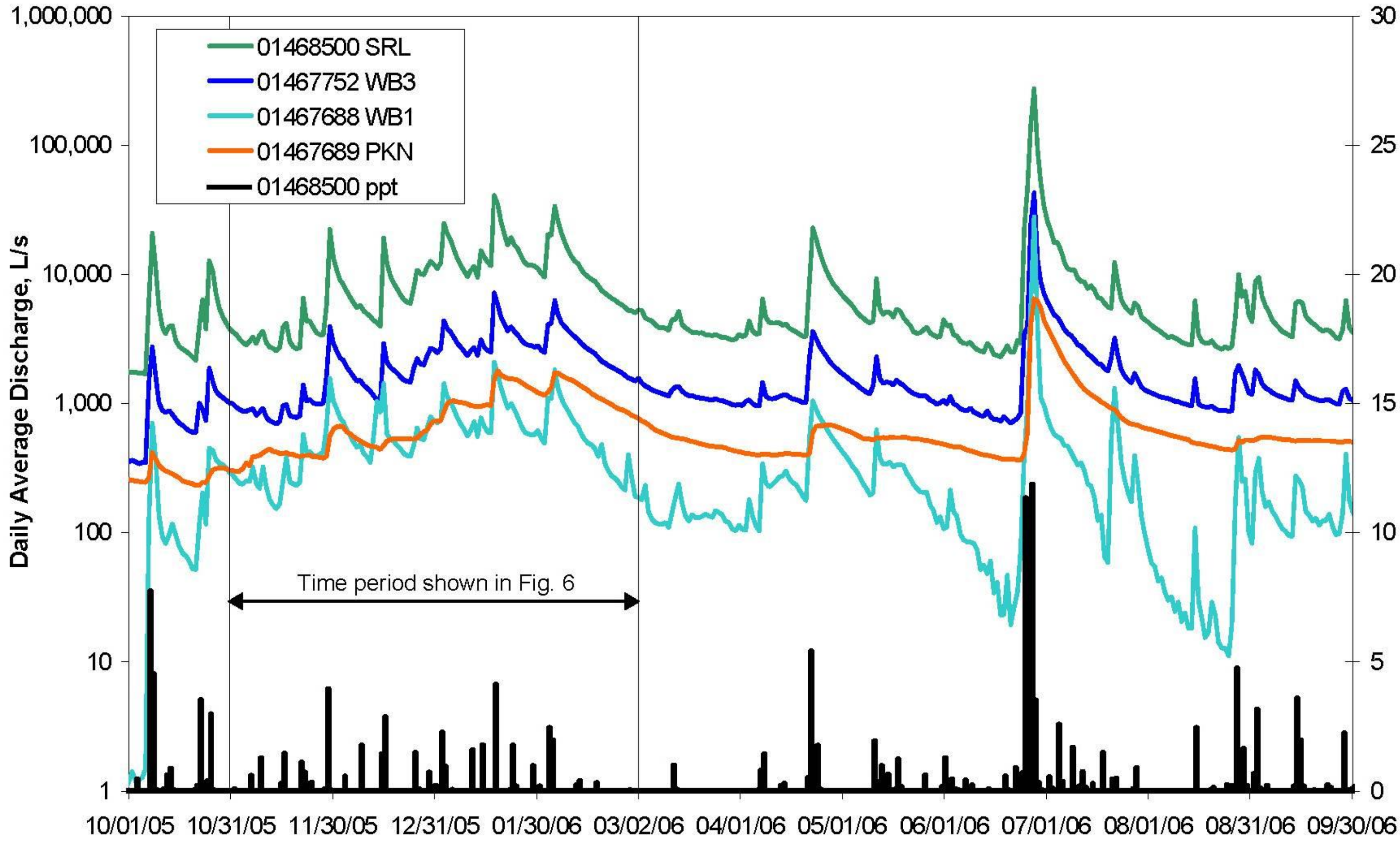

Figure 5. Daily average discharge at the four streamflow-gaging stations associated with the Pine Knot Tunnel Discharge and corresponding daily precipitation (ppt) collected by USGS at Landingville, PA, October 2005-September 2006.

As a complement to synoptic sampling, which emphasized base-flow conditions, continuous streamflow monitoring at 10 gaging stations during 2005-2007 indicated the total range of streamflow as determined from stream stage records (Figs. 4 and 5). The peak discharge occurred at all sites during regional flooding June 27-29, 2006, associated with rainfall totaling 38 to 48 cm in 4 days in the upper Schuylkill River Basin (National Weather Service, 2006; U.S. Geological Survey, 2006). The flood water scoured channels, deposited debris, and damaged instruments at several of the gaging stations installed in 2005. Because of the extreme rainfall that caused the flood, the total annual precipitation during October 2005 through September 2006 was 136 to 160 cm/yr compared to the long-term average of 115 to 135 cm/yr for the basin.

Streamflow hydrographs illustrate the spatial and temporal variability and correlation among gaging stations in the upper Schuylkill River Basin during 2005-2007 (Figs. 4 and 5). Generally, the streamflow volume increased with drainage area above the gaging station (Table 1), and changes in daily discharge were correlated among the sites. Compared to the other sites, however, the discharge and water quality for the Pine Knot Tunnel (PKN) were less variable and those for the West Branch above the Pine Knot Tunnel (WB1) were more variable (Table 3); these sites exhibited disproportionate changes in the magnitude and duration of streamflow during dry and wet periods (Figs. 4 and 5). For example, during sustained dry periods, streamflow at WB1 nearly ceased, whereas the PKN discharge sustained base flow to the West Branch below their confluence. In contrast, during the June 2006 flood and other high-flow events, peak discharge at the Pine Knot Tunnel was smaller but was sustained longer than the West Branch above the Pine Knot Tunnel.

The median flow rates based on quarterly sampling at the AMD and stream sites with gages (Table 3) were always less than the mean flow rates based on continuously recorded stream stage during the study (Table 4). Although the median tends to be less than the mean for typical lognormal (right-skewed) data, the synoptic sampling emphasized base-flow conditions and, hence, excluded the highest flow data. This situation is not unique to this study. Continuous stage records and corresponding computations of continuous discharge generally would be needed to determine the true range, central tendency, and other statistical characteristics of streamflow.

Table 4. Hydrograph-separation analysis and components of the annual hydrologic budget[a] for continuous streamflow-gaging stations in the upper Schuylkill River Basin, October 1, 2005 - September 30, 2006
[km^2, square kilometers; L/s, liters per second; cm/yr, centimeters per year; %, percent]

Map ID[b]	USGS Station ID	Drainage Area, km^2	Mean Streamflow[c]			Mean Base Flow[d]			Mean Runoff[e]	
			L/s	cm/yr	Index, %	L/s	cm/yr	Index, %	L/s	cm/yr
WB1	01467688	49.8	449	28.5	19.2	286	18.1	63.5	163	10.4
PKN	01467689	49.1	739	47.5	32.0	684	44.0	92.6	55	3.5
(PKN+WB1)		49.8	1,189	75.3	50.7	998	63.2	83.9	191	12.1
WB3	01467752	61.7	1,924	98.4	66.3	1,596	81.6	82.9	328	16.8
WWB	01467861	47.6	904	59.9	40.4	584	38.7	64.6	320	21.2
MCR	01467492	65.3	1,746	84.4	56.9	1,221	59.0	69.9	525	25.4
SR4	01467471	69.6	1,835	83.2	56.1	1,246	56.5	67.9	589	26.7
LSR1	01469500	109.8	3,086	88.7	59.8	2,306	66.3	74.7	780	22.4
LSR2	01469700	168.2	4,902	92.0	62.0	3,624	68.0	73.9	1,278	24.0
SRL	01468500	340.5	8,506	78.8	53.1	5,763	53.4	67.8	2,743	25.4
SRB	01470500	908.8	24,299	84.4	56.9	14,609	50.7	60.1	9,690	33.7

a. Hydrologic budget for the annual period relates precipitation (P), streamflow (Q), and evapotranspiration (E) (eqs. 1 and 2). Hydrograph separation was conducted using the "PART" computer program (Rutledge, 1998) to divide annual streamflow into base flow (B) and runoff (R) contributions (eq. 3) on the basis of daily average flow values during Water Year 2006.
b. Site locations described in Figure 1 and Table 1.
c. Streamflow 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 3.16. The streamflow index was computed as the ratio, expressed as percent, of total annual streamflow to average total annual rainfall of 148.4 cm/yr during Water Year 2006, based on total annual rainfall of 159.8 cm/yr at 01469500, 136.1 cm/yr at 01470500, and 149.4 cm/yr at 01468500.
d. Base flow expressed as liters per second, centimeters per year, and percent of total annual streamflow (base-flow index).
e. Runoff expressed as liters per second or centimeters per year was computed by subtracting the base flow from total streamflow.

Differences in streamflow variability at the gaging stations can be attributed to variations in the relative contributions of ground water and runoff to streamflow, which are affected by infiltration and drainage characteristics of the area above the station. Except for the Pine Knot Tunnel (PKN) and the West Branch above the Pine Knot Tunnel (WB1), the cumulative annual discharge for each gaging station was proportional to the drainage area (Table 4). However, the West Branch above the Pine Knot Tunnel typically had smaller flows than expected based on its drainage area. A substantial fraction of the surface water that would flow within the upper reaches of the West Branch is hypothesized to infiltrate to the underground mines and discharge further downstream from the Pine Knot Tunnel and, possibly, the Oak Hill Boreholes (Figs. 1 and 2).

Hydrograph separation and corresponding computations of the annual hydrologic budget for each of the 10 continuous gaging stations were used to evaluate potential effects of the water stored and released from the underground mines on the streamflow characteristics in the upper

Schuylkill River Basin (Table 4). For basins in which the surface-water and ground-water divides coincide, there are no external inflows or outflows of ground water, and the gaging station at the downstream end of the basin measures all outflow, the hydrologic budget equation can be expressed as:

$$P = Q + E + \Delta S_S + \Delta S_G, \quad (1)$$

where P is total precipitation, Q is total streamflow, E is total evapotranspiration, ΔS_S is the change in storage of the surface-water reservoir, and ΔS_G is the change in storage of the ground-water reservoir during the annual period (Freeze and Cherry, 1979, p. 205-206). The values for Q, E, and S can be reported in centimeters over the drainage basin so that their units are consistent with those of P. Assuming no change in surface-water or ground-water storage (ΔS_S and $\Delta S_G = 0$), the total annual evapotranspiration can be estimated as the difference between the measured values for total annual precipitation and the total annual streamflow:

$$E = P - Q. \quad (2)$$

To compute the base flow (B) and runoff (R) components of total annual streamflow, the daily average streamflow data for October 2005 through September 2006 were used with the PART hydrograph-separation program (Rutledge, 1998), assuming that

$$Q = B + R. \quad (3)$$

As explained in more detail by Risser et al. (2005), this estimate for annual base flow that is derived from streamflow recession analysis is comparable to the annual recharge to the watershed.

Although the daily average streamflow of the West Branch above the Pine Knot Tunnel (WB1) occasionally exceeded that of the Pine Knot Tunnel (PKN), particularly during high-flow conditions (Figs. 4, 5, and 6), the total annual streamflow and base-flow yields (expressed as volume/drainage area; cm/yr) at WB1 were substantially less than those for PKN. Because of their shared drainage area, these estimates for WB1 and PKN were substantially less than the values for downstream sites (Table 4). Nevertheless, the combined flows of Pine Knot Tunnel and West Branch above the Pine Knot Tunnel (PKN+WB1), expressed as the yield for this area, were comparable to estimates for the downstream stations. In contrast, the West West Branch (WWB) had the smallest annual streamflow yield (59.2 cm/yr), whereas the West Branch above its confluence with the West West Branch (WB3) had the greatest yield (97.3 cm/yr) (Table 4).

This difference in yields between adjacent watersheds could result from the inter-basin transfer of surface water and ground water via underground mines. The Oak Hill Mine extends beneath the topographic divide for these neighboring watersheds (Fig. 2) and may facilitate this transfer of water from the West West Branch to the West Branch via the Oak Hill Boreholes Discharge.

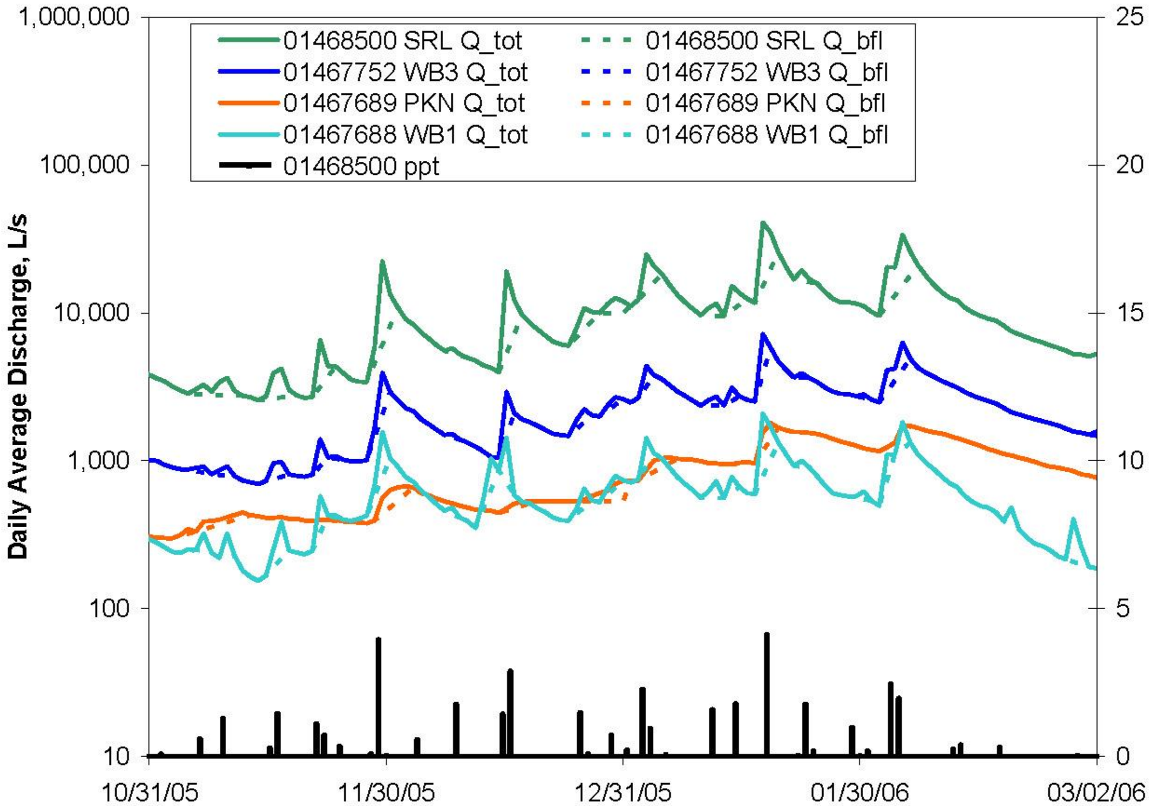

Figure 6. Total streamflow (Q_tot, solid line) and estimated base flow (Q_bfl, dashed line) at the four streamflow-gaging stations associated with the Pine Knot Tunnel Discharge and corresponding daily precipitation (ppt) collected by USGS at Landingville, PA, October, 31, 2005-March 2, 2006. Base flow was computed with the PART hydrograph-analysis computer program (Rutledge, 1998); runoff is the difference between total streamflow and base flow.

Although the annual base flow estimated for the Pine Knot Tunnel (PKN) was smaller than values for most other sites, the ratio of base flow to total streamflow (base-flow index) was largest for PKN (92.6 %) compared to other sites (Table 4, Fig. 6), consistent with its origin as ground water that is gradually released from the flooded underground mine complex. Estimated base flow for PKN and WB1 combined (PKN+WB1) was between values of 38.7 to 81.6 cm/yr for the downstream stations (Table 4). Although these estimates of base flow were computed only for a 1-year period, the results are consistent with estimates reported by Risser et al. (2005)

that are based on the long-term streamflow records for the Little Schuylkill River at Tamaqua (LSR1), Schuylkill River at Landingville (SRL), and Schuylkill River at Berne (SRB).

The synoptic seepage surveys conducted in April 2004 (wet period) and July 2006 (dry period) within the drainage area above the Pine Knot Tunnel (Fig. 2) demonstrated widespread infiltration of relatively "clean" stream water from the unmined valley sides as it flowed into the mined part of the valley overlying the Pine Knot Tunnel (Table 5). For perspective, consider that the 49.82-km^2 drainage area for the West Branch above the Pine Knot Tunnel (WB1) is nearly two times the 25.51-km^2 unmined part of this area. However, instead of a doubling of the streamflow, the measured flow at WB1 was 10 to 20 percent less than the measured flow from the unmined part of the watershed (Table 5). On an annual basis, the discharge from the Pine Knot Tunnel restores the "lost" water to the West Branch at their confluence. However, the stream leakage losses on a given date are not likely to equal the discharge from the Pine Knot tunnel because of the temporary storage and gradual release of ground water stored in the mine pool as "base flow." For example, during the synoptic seepage surveys, the total streamflow of the West Branch below the Pine Knot Tunnel was substantially less than (wet period) or greater than (dry period) two times the flow from the unmined part of the basin (Table 5). The ground-water flow is impeded by unmined coal barriers (Fig. 2) and broken rock that could fill mine voids and follows longer, more tortuous paths than it would as stream water.

Until this study, the Pine Knot Tunnel Discharge was considered the primary source of contaminant loading in the upper Schuylkill River Basin. Despite its proximity to the Pine Knot Tunnel, little data had been collected on the flow and quality of the Oak Hill Boreholes. This study demonstrated that the iron loading from the Oak Hill Boreholes Discharge is equivalent to that from the Pine Knot Tunnel and that the origin of the water discharged from the Oak Hill Boreholes could differ from the Pine Knot Tunnel. Although seepage surveys on tributaries within the contributing area to the Pine Knot Tunnel demonstrated hypothesized surface-water losses to the Pine Knot Mine pool, restoration of the streamflow to the West Branch within the mined area would be difficult because of the widespread distribution of potential leakage; approximately 11 km of streams above the Pine Knot Tunnel could be involved. In contrast, less than 2 km of West Creek in the upper reaches of the West West Branch flow across the Oak Hill Mine (Fig. 2). Because a smaller area is involved, the restoration of streamflow to West Creek

Table 5. Flow at sites within drainage area of Pine Knot Tunnel, April 13, 2004, and July 18, 2006, [UNT, unnamed tributary; km², square kilometers; L/s, liters per second; nd, no data]

Map ID[a]	Site Name and Relation to Pine Knot Tunnel[b]		Latitude[c]	Longitude	Drainage Area,[d] km^2	Instantaneous Flow, L/s	
						4/13/2004	7/18/2006
0	UNT east of Wimsey	u	404357.7	761318.5	0.42	6.80	0.20
2	UNT at Wimsey	u	404401.3	761326.0	1.22	83.26	7.36
3	UNT at Powerline	u	404349.1	761354.1	0.80	11.89	6.51
4	UNT at Repplier	u	404342.2	761428.0	0.12	3.40	0.00
10	Wheeler Cr above Mines	u	404338.3	761506.8	3.43	93.17	6.23
11	Wagner Run above Mines	u	404335.0	761544.6	2.48	56.64	18.41
13	Dyer Run above mines	u	404331.1	761610.9	12.16	486.25	52.68
17	UNT 1	u	404325.3	761700.6	0.31	2.55	0.00
18	UNT 2, above Mines	u	404314.9	761744.9	1.05	7.65	0.00
24	Rock swale, water source	u	404309.8	761811.4	0.44	5.10	10.48
27	UNT 3, above confluence	u	404251.8	761819.1	0.35	15.86	2.83
30	UNT 4, above mines	u	404255.1	761854.4	0.82	35.40	2.12
31	UNT 5, loss to mines	u	404239.6	762016.8	0.53	45.31	2.83
34	UNT6, loss to small pit	u	404156.8	762100.4	0.01	2.27	0.00
37	UNT 7, loss to large pit	u	404203.6	762111.9	0.82	18.12	0.00
39	UNT 7, headwaters	u	404200.4	762123.0	0.06	nd	1.27
35	Neumeister Drift Discharge	u	404152.1	762125.6	0.45	21.52	7.48
40	UNT 9, loss to large pit	u	404157.8	762128.4	0.04	1.13	0.00
Sum total for sites with drainage area above mines (total of upstream sites)					**25.51**	**896.32**	**118.40**
5	West Branch at bridge	d	404258.7	761448.5	46.26	742.83	91.47
9	Wheeler Cr above confluence	d	404322.1	761506.1	3.84	90.62	8.78
12	Wagner Run above confluence	d	404315.6	761530.2	3.02	87.51	12.18
14	Dyer Run above confluence	d	404312.4	761555.8	12.72	417.72	79.86
15	West Branch above Dyer Run	d	404310.9	761556.9	14.00	139.90	76.46
16	West Branch at Thomaston	d	404305.5	761629.6	13.29	115.55	0.00
21	West Branch, below UNT2	d	404258.0	761739.5	7.50	nd	0.00
19	UNT 2, loss to pit	d	404303.0	761740.6	1.22	0.85	0.00
22	West Branch, wetlands2	d	404256.9	761744.9	6.12	0.00	0.00
20	UNT 2, at confluence	d	404259.0	761744.9	1.24	26.05	0.00
23	Rock swale, water loss	d	404304.3	761746.5	0.62	nd	0.00
25	West Branch, constructed channel	d	404253.6	761808.6	5.09	76.75	0.00
26	West Branch, wetlands1	d	404252.9	761827.0	4.58	84.11	0.00
28	West Branch, below pond	d	404251.8	761827.7	4.51	27.75	0.00
29	UNT 4, above confluence	d	404247.5	761851.5	0.98	58.06	0.00
7	**West Branch ab Pine Knot Tunnel (WB1)**	**d**	**404215.2**	**761457.5**	**49.82**	**742.83**	**107.90**
6	**Pine Knot Tunnel ab West Branch (PKN)**	**d**	**404227.7**	**761505.4**	**49.13**	**644.56**	**999.70**
Sum total of WB1 and PKN above Oak Hill[e]		**d**	**404322.1**	**761506.1**	**50.02**	**1,387.39**	**1,107.60**

a. Site locations are shown in Figures 2 and 3.

b. Site designated u or d for drainage upstream (u) or downstream (d) of mined area within Pine Knot Tunnel basin.

c. Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). Values are degrees, minutes, seconds; 404215.2 represents 40°42'15.2" north latitude and 761457.5 represents 76°14'57.5" west longitude.

d. Drainage area delineated on the basis of topographic contours on U.S. Geological Survey 1:24,000 topographic maps.

e. Sum total of WB1 and PKN does not add watershed areas because these overlap; only the two flow rates are summed.

and associated reductions of flow from the Oak Hill Boreholes Discharge could be less difficult than corresponding efforts to reduce flow of the Pine Knot Tunnel. If streamflow losses along West Creek could be reduced, natural streamflow and water quality may be maintained in the West West Branch. With a large reduction in the flow volume of the Oak Hill Boreholes Discharge, passive-treatment strategies may be considered.

Passive treatment may not be feasible for large AMD sources such as the Pine Knot Tunnel and Oak Hill Boreholes because these and other AMD sources commonly are located along streams and because large areas may be needed for construction of passive-treatment systems (e.g. Hedin et al., 1994; Watzlaf et al., 2004). Consequently, efforts to restore the environment of watersheds affected by abandoned mines, such as the upper Schuylkill River Basin, commonly warrant a combination of streamflow restoration and treatment of selected AMD sources. Ideally, streamflow restoration could maintain clean water at the surface by minimizing leakage into underlying mines and, consequently, could eliminate or decrease the flow and loading of metals from AMD sources. If the flow and metals-loading rates could be reduced, passive treatment of large sources of AMD may become feasible. Nevertheless, if a decline in the mine-pool level exposes pyritic rock in the mine to air and renewed oxidation, water quality may become more acidic and metal laden (e.g. Cravotta, 1994). Hydrological and geochemical modeling could be useful to evaluate potential changes in water quality of the underground mines and AMD discharges in response to changes in mine-pool levels.

Accurate data on the locations and quantities of streambed leakage are needed to implement streamflow restoration in mined watersheds. Seepage surveys used in this study require water to be flowing in the channel and only provide general information regarding locations of potential leakage; reaches below these locations could lose water transmitted downstream. Geophysical surveys could be performed along stream segments identified as probable or possible losing reaches to assist in determination of where streambed sealing or stream rerouting may be appropriate restoration strategies (e.g. Ackman and Jones, 1991).

Generally, streamflow in extensively mined areas is expected to respond differently to storm or drought events compared to unmined areas. For example, a hydrologic budget for the upper Shamokin Creek Basin was computed by Becher (1991) using the long-term streamflow record (1932-1992) for Shamokin Creek near Shamokin. Becher concluded that streamflow in the upper Shamokin Creek Basin is sustained by discharges from water stored in the mines and, consequently, is less variable than that for nearby unmined basins with equivalent watershed areas. As indicated for the lower reaches of the West Branch, streamflow from the upper Shamokin Creek Basin had greater base flow during drought and smaller peak flows during storms compared to nearby unmined basins that had greater proportions of runoff contributing to the streamflow.

By diverting runoff water to stream channels instead of mine storage, the restoration of streamflow in mined watersheds could decrease base flow and increase peak flows and potential for flooding in downstream reaches. However, resource managers and engineers contemplating stream restoration and other alternatives for rehabilitation could devise mitigation for these hydrological effects. For example, road crossings and other structures may need to be replaced or relocated. Additionally, water storage features such as basins or wetlands along the flood plain may be warranted to compensate for decreased infiltration and storage within the mine pool. Hydrological modeling may be useful to indicate possible interactions between the ground water and surface water and to indicate the potential effects of stream restoration and water-storage features on streamflow characteristics.

Conclusions

Seepage surveys and hydrograph analysis indicated that abandoned mines affect streamflow characteristics in the upper Schuylkill River Basin. The seepage surveys during wet and dry periods demonstrated extensive streamflow losses in the mined area above the Pine Knot Tunnel, with corresponding streamflow gains downstream where the lost water resurfaced as AMD from the Pine Knot Tunnel and Oak Hill Boreholes. Nevertheless, hydrograph analysis and maps showing stream locations and areas underlain by underground mines indicated that additional areas of streamflow leakage were likely, particularly in the western part of the upper Schuylkill River Basin. For example, compared to the other gaging stations in the basin, the West West Branch had the lowest annual streamflow yield, presumably because it loses water to the underground Oak Hill Mine. In contrast, the neighboring West Branch had the highest yield, presumably because it gains the water lost from the West West Branch as AMD from the Oak Hill Boreholes. Quarterly water-quality monitoring and annual fish surveys on the affected reaches indicated that although the stream-water chemistry and fish abundance were poor in the

West Branch where AMD was a major source of streamflow, the neighboring West West Branch met relevant in-stream water-quality criteria and supported a diverse fish community despite diminished streamflow.

If streamflow losses to the Pine Knot Mine, Oak Hill Mine, and other underground mines could be reduced, natural streamflow and water quality may be maintained. Likewise, stream restoration could lead to decreases in the AMD discharge volumes and metal loading with associated improvements in downstream conditions. However, potential negative environmental effects of stream restoration also warrant consideration. For example, with a reduction in infiltration and a decline in the mine-pool level, pyritic rock that had been submerged in the flooded mines could be exposed to air and renewed oxidation; water quality could become more acidic and metal laden. Furthermore, by diverting runoff to stream channels instead of storage in underground mines, the restoration of streamflow in mined watersheds could decrease base flow and increase potential for flooding in downstream reaches. Resource managers and engineers would need to consider effects of stream restoration on the mine-pool levels, the quality of water in the mines and corresponding AMD discharges, and downstream flows. Hydrological and geochemical modeling may be used to indicate possible hydrological interactions and to indicate the potential variations in water quantity and quality associated with stream restoration and related reclamation strategies. Longer-term continuous and synoptic data for a range of streamflow conditions could be useful to evaluate the validity of model predictions and environmental effects of restoration. Hydrograph-separation methods could be used with the continuous streamflow records to document changes in base flow, runoff, and other components of the hydrologic budget for watersheds in the basin.

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Literature Cited

Ackman, T.E., and Jones, J.R., 1991. Methods to identify and reduce potential surface stream water losses into abandoned underground mines: Environmental Geology and Water Science, v. 17, p. 227-232. http://dx.doi.org/10.1007/BF01701703.

American Public Health Association, 1998a. Acidity (2310)/Titration method, In Clesceri, L.S., Greenberg, A.E., and Eaton, A.D. (eds), *Standard Methods for the Examination of Water and Wastewater* (20th): Washington, D.C., American Public Health Association, p. 2.23-2.25.

American Public Health Association, 1998b. Alkalinity (2320)/Titration method, In Clesceri, L.S., Greenberg, A.E., and Eaton, A.D. (eds), *Standard Methods for the Examination of Water and Wastewater* (20th): Washington, D.C., American Public Health Association, p. 2.26-2.28.

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., and Whaite, T.H., 1953. Surface water seepage into anthracite mines in the Wyoming Valley Basin northern field, anthracite region of Pennsylvania: U.S. Bureau of Mines Bulletin 534, 30 p.

Ballaron, P.B., 1999. Water balance for the Jeddo Tunnel Basin Luzerne County, Pennsylvania: Susquehanna River Basin Publication 208, 32 p.

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 (2nd): U.S. Environmental Protection Agency, EPA 841-B-99-002, 11 chaps., 4 appendixes.

Becher, A.E., 1991. Groundwater resources in and near the anthracite basins of Schuylkill and adjacent counties, Pennsylvania: Pennsylvania Geological Survey, 4th Series, Water Resources Report 64, 59 p.

Berg, T.M., Edmunds, W.E., Geyer, A.R., Glover, A.D., Hoskins, D.M., MacLachlan, D.B., Root, S.I., Sevon, W.D., and Socolow, A.A. (Comps.), 1980. Geologic map of Pennsylvania: Pennsylvania Geological Survey, 4th Series, Map # 1, scale 1:2,500,000, 3 sheets.

Brady, K.B.C., Hornberger, R.J., and Fleeger, G., 1998. Influence of geology on post-mining water quality-Northern Appalachian Basin. In, Brady, K.B.C., Smith, M.W., and Schueck, J.H. (eds.), Coal Mine Drainage Prediction and Pollution Prevention in Pennsylvania: Harrisburg, Pennsylvania Department of Environmental Protection, 5600-BK-DEP2256, p. 8.1-8.92.

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, EPA-R3-73-032, 158 p.

Chaplin, J.J., Cravotta, C.A., III, Weitzel, J.B., and Klemow, K.M., 2007. Effects of historical coal mining and drainage from abandoned mines on streamflow and water quality in Newport and Nanticoke Creeks, Luzerne County, Pennsylvania, 1999-2000: U.S. Geological Survey Scientific Investigations Report 2007-5061, 40 p.

Commonwealth of Pennsylvania, 2002. Chapter 93. Water Quality Standards. Pennsylvania Code, Title 25. Environmental Protection: Harrisburg, PA, Commonwealth of Pennsylvania, p. 93.1-93.226.

Cravotta, C.A., III, 1994. Secondary iron-sulfate minerals as sources of sulfate and acidity: The geochemical evolution of acidic ground water at a reclaimed surface coal mine in Pennsylvania. In, Alpers, C.N., and Blowes, D.W. (eds.), Environmental geochemistry of sulfide oxidation: Washington, D.C., American Chemical Society Symposium Series 550, p. 345-364.

Cravotta, C.A., III, 2005. Effects of abandoned coal-mine drainage on streamflow and water quality in the Mahanoy Creek Basin, Schuylkill, Columbia, and Northumberland Counties, Pennsylvania, 2001: U.S. Geological Survey Scientific Investigations Report 2004-5291, 60 p., 4 appendixes.

Cravotta, C.A., III, 2007. Passive aerobic treatment of net-alkaline, iron-laden drainage from a flooded underground anthracite mine, Pennsylvania, USA: Mine Water and the Environment, v. 26, p. 128-149. http://dx.doi.org/10.1007/s10230-007-0002-8

Cravotta, C.A., III, in press. Laboratory and field evaluation of a flushable oxic limestone drain for treatment of net-acidic, metal-laden drainage from a flooded anthracite mine, Pennsylvania, USA: Applied Geochemistry

Cravotta, C.A., III, and Bilger, M.D., 2001. Water-quality trends for a coal-mined watershed in Eastern Pennsylvania: Geochemistry, Exploration, Environment, Analysis, v. 1, p. 33-50.

Cravotta, C.A., III, and Kirby, C.S., 2004. Effects of abandoned coal-mine drainage on streamflow and water quality in the Shamokin Creek Basin, Northumberland and Columbia Counties, Pennsylvania, 1999-2001: U.S. Geological Survey Water-Resources Investigations Report 03-4311, 58 p.

Cravotta, C.A., III, and Ward, S.J., 2008, Downflow limestone beds for treatment of net-acidic, oxic, iron-laden drainage from a flooded anthracite mine, Pennsylvania, USA--Field evaluation: Mine Water and the Environment, v. 27 (http://dx.doi.org/10.1007/s10230-008-0029-5). http://dx.doi.org/10.1007/s10230-008-0029-5).

Crock, J.G., Arbogast, B.F., and Lamothe, P.J., 1999. Laboratory methods for the analysis of environmental samples. In, Plumlee G.S., Logsdon, M.J. (eds.), The Environmental Geochemistry of Mineral Deposits--Part A. Processes, techniques, and health issues: Society of Economic Geologists, Reviews in Economic Geology, 6A, p. 265-287.

Eggleston, J.R., Kehn, T.M., and Wood, G.H., Jr., 1999. Anthracite. In, Schultz, C.H. (ed.), The geology of Pennsylvania: Pennsylvania Geological Survey, 4th series, Special Publication 1, p. 458-469.

Fishman, M.J., and Friedman, L.C. (eds.), 1989. Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 545 p.

Freeze, R.A., and Cherry, J.A., 1979. Groundwater: Englewood Cliffs, N.J., Prentice-Hall, Inc., 604 p.

Growitz, D.J., Reed, L.A., and Beard, M.M., 1985. Reconnaissance of mine drainage in the coal fields of eastern Pennsylvanian: U.S. Geological Survey Water-Resources Investigations Report 83-4274, 54 p.

Hedin, R.S., Nairn, R.W., and Kleinmann, R.L.P., 1994. Passive treatment of coal mine drainage: U.S. Bureau of Mines Information Circular 9389, 35 p.

Hollowell, J.R., 1974. Hydrology of the abandoned coal mines in the Wyoming valley, Pennsylvania: U.S. Geological Survey Open-File Report 74-237, 47 p.

L. Robert Kimball & Associates, Inc., 2000. Upper Schuylkill River Tributaries Assessment Report: Ebensburg, PA, L. Robert Kimball & Associates, Inc., 30 p., plus maps.

L. Robert Kimball & Associates, Inc., 2001. Little Schuylkill River Assessment Report Ebensburg, PA, L. Robert Kimball & Associates, Inc., 41 p., plus maps.

Ladwig, K.J., Erickson, P.M., Kleinmann, R.L.P., and Poslulszny, E.T., 1984. Stratification in water quality in inundated anthracite mines, eastern Pennsylvania. U.S. Bureau of Mines Report of Investigations 88/37, 35 p.

Meador, M.R., Cuffney, T.F., and Gurtz, M.E., 1993. Methods for sampling fish communities as part of the National Water-Quality Assessment Program: U.S. Geological Survey Open-File Report 93-104, 40 p.

National Climatic Data Center, 2007. Annual climatic summary for selected stations in Schuylkill County, PA (http://www.ncdc.noaa.gov/oa/climate/stationlocator.html)

National Weather Service, 2006. MPE Rainfall Totals (preliminary) June 22, 8 AM - June 30, 8 AM: National Oceanographic and Atmospheric Administration, Middle Atlantic River Forecast Center (http://www.erh.noaa.gov/er/marfc/June2006.pdf)

Nordstrom, D.K., 1977. Thermochemical redox equilibria of Zobell's solution: Geochimica et Cosmochimica Acta, v. 41, p. 1835-1841. http://dx.doi.org/10.1016/0016-7037(77)90215-0.

Pennsylvania Department of Environmental Protection, 2003. Watershed Restoration Action Strategy (WRAS) Subbasin 06A Upper Schuylkill River Watershed Schuylkill, Carbon, and Berks Counties, PA: Harrisburg, PA, Pennsylvania Department of Environmental Protection, 16 p.

(http://www.dep.state.pa.us/dep/deputate/watermgt/wc/Subjects/Nonpointsourcepollution/Initiatives/Wraslist.htm)

Pennsylvania Department of Environmental Protection, 2004. 2004 Integrated list of all waters: Pennsylvania Department of Environmental Protection, 1807 p. (http://www.dep.state.pa.us/dep/deputate/watermgt/wqp/wqstandards/303d-Report.htm).

Pennsylvania Department of Environmental Protection, 2005. Upper Schuylkill River TMDL watershed implementation plan, Schuylkill County: Pennsylvania Department of Environmental Protection, 74 p (http://www.depweb.state.pa.us/watershedmgmt/lib/watershedmgmt/nonpoint_source/implementation/tmdl_upper_schuylkill_river_wrp-final_whole_document.pdf)

Pennsylvania Department of Environmental Protection, 2006. Integrated list nonattaining. (http://www.pasda.psu.edu/data/dep/IntegratedListNonAttaining2006_10.zip)

Rantz, S.E., and others, 1982. Measurement and computation of streamflow: U.S. Geological Survey Water-Supply Paper 2175, 2 vols.

Reed, L.A., Beard, M.M., Growitz, D.J., 1987. Quality of water in mines in the western middle coal field, anthracite region, east-central Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 85-4038, 51 p.

Risser, D.W., Conger, R.W., Ulrich, J.E., and Asmussen, M.P., 2005. Estimates of ground-water recharge based on streamflow-hydrograph methods, Pennsylvania: U.S. Geological Survey Open-File Report 2005-1333, 30 p. (http://pa.water.usgs.gov/recharge/)

Rutledge, A.T., 1998. Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow data – update: U.S. Geological Survey Water-Resources Investigations Report 98-4148, 43 p. (http://water.usgs.gov/ogw/part/)

Saskowsky, I.D., and White, W.B., 1993. Geochemistry of the Obey River Basin, north-central Tennessee--a case of acid mine water in a karst drainage system: Journal of Hydrology, v. 146, p. 29-48. http://dx.doi.org/10.1016/0022-1694(93)90268-E.

U.S. Environmental Protection Agency, 2002. National recommended water quality criteria—2002: U.S. Environmental Protection Agency, EPA 822-R-02-047, 33 p.

U.S. Geological Survey, 2006. Flooding in Pennsylvania--June 27-29, 2006. (http://pa.water.usgs.gov/flooding_06_06.html).

Watzlaf G.R., Schroeder K.T., Kleinmann R.L.P., Kairies C.L., and Nairn R.W., 2004. The passive treatment of coal mine drainage: U.S. Department of Energy DOE/NETL-2004/1202 (http://www.netl.doe.gov/technologies/coalpower/ewr/water/pdfs/Passive%20Treatment.pdf)

Way, J.H., 1999. Appalachian Mountain section of the Ridge and Valley province. In, Schultz, C.H. (ed.), The geology of Pennsylvania: Pennsylvania Geological Survey, 4th series, Special Publication 1, p. 352-361.

White, W.B., 1988. Geomorphology and hydrology of karst terrains: Oxford University Press, 456 p.

Wood, C.R., 1996. Water quality of large discharges from mines in the anthracite region of eastern Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 95-4243, 69 p.

Wood, G.H., Jr., Kehn, T.M., and Eggleston, J.R., 1986. Deposition and structural history of the Pennsylvania Anthracite region. In, Lyons, P.C. and Rice, C.L. (eds.), Paleoenvironmental and tectonic controls in coal-forming basins of the United States: Geological Society of America Special Paper 210, p. 31-47. http://dx.doi.org/10.1130/SPE210-p31.

Wood, W.W., 1976. Guidelines for the collection and field analysis of ground-water samples for selected unstable constituents: U.S. Geological Survey Techniques of Water-Resources Investigations, book 1, chap. D2, 24 p.