

U.S. Department of the Interior
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Effects of Abandoned Coal-Mine Drainage on Streamflow and Water Quality in the Shamokin Creek Basin, Northumberland and Columbia Counties, Pennsylvania, 1999-2001

Water-Resources Investigations Report 03-4311

In cooperation with the
**Northumberland County Conservation District,
Bucknell University
and the
Pennsylvania Department of Environmental Protection**



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by Charles A. Cravotta III and Carl S. Kirby

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**New Cumberland, Pennsylvania
2003**

U.S. DEPARTMENT OF THE INTERIOR
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U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

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CONTENTS

	Page
Abstract	1
Introduction	2
Purpose and scope	2
Geology and mining history	2
Land use	5
Water quality	5
Quality protection and restoration	6
Acknowledgments	7
Methods of water-quality site selection, sampling, and analysis	8
Effects of abandoned mine drainage in the Shamokin Creek Basin	12
Flow and quality of streams	16
Streamflow variability	22
Contaminant concentrations and loads	25
Aquatic ecology	27
Characterization and remediation of abandoned mine drainage	31
Characteristics of AMD sources	31
Remedial priorities and alternatives	35
Flow considerations	42
Summary and conclusions	43
References cited	44
Appendixes

ILLUSTRATIONS

	Page
Figure 1. Map of Shamokin Creek Basin showing locations of municipalities, coalfield, named streams, and corresponding streamwater and mine drainage monitoring network	3.
2. Shaded relief map showing surface extent of abandoned mine workings within the upper Shamokin Creek Basin bounded by Locust Mountain and Mahanoy Mountains on the south and Big Mountain on the north	4
3. Flow chart for selection of passive treatment alternatives modified after Hedin and others (1994), Skousen and others (1998), and Pennsylvania Department of Environmental Protection (1999).	7
4. Graphs showing relation between flow rates and dissolved constituent concentrations at each AMD and streamwater sample site in the Shamokin Creek Basin for low-baseflow and high-baseflow conditions	14
5. Graphs showing relation between total and dissolved concentrations of iron, manganese, and aluminum in high-baseflow AMD and streamwater samples	15
6. Graphs showing relation between measured “hot, peroxide” acidity and computed acidity; measured “hot, peroxide” acidity and computed net alkalinity; and pH and computed net alkalinity on the basis of dissolved metals concentrations for high-baseflow AMD samples	17
7. Maps showing streamflow and concentrations of total acidity, dissolved sulfate, dissolved iron, dissolved manganese, and dissolved aluminum in the mainstem and tributaries of Shamokin Creek during March 2000	18
8. Graphs showing historical and recent streamflow data for Shamokin Creek near Shamokin	23
9. Graphs showing relation between instantaneous streamflow and water-quality data for Shamokin Creek near Shamokin and Sunbury, 1999-2001	24
10. Bar charts showing contributing area, streamflow yields, metals loading, and percentage of AMD metals loading at steam monitoring sites in the Shamokin Creek Basin during low-baseflow and high-baseflow sampling in 1999-2000	26
11. Map of upper Shamokin Creek basin showing abandoned mine discharge locations and corresponding flow rates and loading of iron, manganese, and aluminum during March 2000.	32
12. Graphs showing relation between priority AMD ranking and flow rate, acidity, iron, manganese, and aluminum concentrations for top 25 abandoned mine discharge sites	39
13. Bar charts illustrating priority ranks for top 20 abandoned mine discharge sites	41

TABLES

	Page
Table 1. Description of abandoned mine drainage sites surveyed in 1999-2000 for the Shamokin Creek watershed assessment.	9
2. Description of stream sites surveyed in 1999-2000 for the Shamokin Creek watershed assessment	10
3. Values of selected constituents for streamwater and abandoned mine drainage samples collected for the Shamokin Creek watershed assessment during August 4-6, 1999, and March 14-16, 2000.	13
4. Coliform bacteria and concentrations of dissolved metals and nutrients in water samples from selected sites on Shamokin Creek and its tributaries, August 4, 1999	28
5. Fish species identified during annual ecological surveys of Shamokin Creek and selected tributary streams in October 1999, 2000, and 2001	29
6. Metals concentrations in whole white sucker collected in October 1999 from Shamokin Creek near Shamokin, Pa., and Swatara Creek at Ravine, Pa.	30
7. Rankings and possible remedial alternatives for abandoned mine discharges in Shamokin Creek Basin, Pa.	36

APPENDIXES

	Page
Appendix A. Computation of water quality for the Richard's Shaft discharge using an inverse mixing model with upstream and downstream data	48
B. Hydrological data for abandoned mine drainage and associated stream monitoring sties in the Shamokin Creek Basin, August 1999 to October 2001 (CD rom, only)	
C. Digital reproductions of out-of-print reports (CD rom, only)	
Gannett Fleming Corddry and Carpenter, Inc., 1972, Operation Scarlift project no. SL-113– Mine drainage abatement measures for the Shamokin Creek Watershed: Harrisburg, Pa., Gannett Fleming Corddry and Carpenter, Inc., Engineers.	
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.	
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.	
Wood, C.R., 1996, Water quality of large discharges in the anthracite region of eastern Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 95-4243, 68 p.	

Conversion Factors and Datum

Multiply	By	To obtain
Length		
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m ²)
square mile (mi ²)	2.590	square kilometer (km ²)
Flow rate		
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)
cubic foot per second (ft ³ /s)	1,699	liter per minute (L/min)
gallon per minute (gal/min)	3.785	liter per minute (L/min)
Mass		
ton, short (2,000 lb)	0.9072	megagram (Mg)
Application or loading rate		
pounds per year (lb/yr)	0.4536	kilograms per year (kg/yr)
pounds per acre per day [(lb/acre)/day]	0.1121	grams per square meter per day [(g/m ²)/day]
pounds per acre per day [(lb/acre)/day]	1.121	kilograms per hectare per day [(kg/ha)/day]
pounds per acre per year [(lb/acre)/yr]	1.121	kilograms per hectare per year [(kg/ha)/yr]

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

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$$

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

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Specific conductance of water reported as microsiemens per centimeter at 25 °C.

Symbols are used to indicate less than (<), less than or equal to (≤), greater than (>), greater than or equal to (≥), equal to (=), and approximately equal to (≈).

Effects of Abandoned Coal-Mine Drainage on Streamflow and Water Quality in the Shamokin Creek Basin, Northumberland and Columbia Counties, Pennsylvania, 1999-2001

by Charles A. Cravotta III, U.S. Geological Survey, New Cumberland, Pa.,
and Carl S. Kirby, Bucknell University, Lewisburg, Pa.

Abstract

This report assesses the contaminant loading, effects to receiving streams, and possible remedial alternatives for abandoned mine drainage (AMD) within the upper Shamokin Creek Basin in east-central Pennsylvania. The upper Shamokin Creek Basin encompasses an area of 54 square miles (140 square kilometers) within the Western Middle Anthracite Field, including and upstream of the city of Shamokin. Elevated concentrations of acidity, metals, and sulfate in the AMD from flooded underground anthracite coal mines and (or) unreclaimed culm (waste rock) piles degrade the aquatic ecosystem and water quality of Shamokin Creek to its mouth and along many of its tributaries within the upper basin. Despite dilution by unpolluted streams that more than doubles the streamflow of Shamokin Creek in the lower basin, AMD contamination and ecological impairment persist to its mouth on the Susquehanna River at Sunbury, 20 miles (32 kilometers) downstream from the mined area.

Aquatic ecological surveys were conducted by the U.S. Geological Survey (USGS) in cooperation with Bucknell University (BU) and the Northumberland County Conservation District (NCCD) at six stream sites in October 1999 and repeated in 2000 and 2001 on Shamokin Creek below Shamokin and at Sunbury. In 1999, fish were absent from Quaker Run and Shamokin Creek upstream of its confluence with Carbon Run; however, creek chub (*Semotilus atromaculatus*) were present within three sampled reaches of Carbon Run. During 1999, 2000, and 2001, six or more species of fish were identified in Shamokin Creek below Shamokin and at Sunbury despite elevated concentrations of dissolved iron and iron-encrusted streambeds at these sites.

Data on the flow rate and chemistry for 46 AMD sources and 22 stream sites throughout the upper basin plus 1 stream site at Sunbury were collected by the USGS with assistance from BU and the Shamokin Creek Restoration Alliance (SCRA) during low base-flow conditions in August 1999 and high base-flow conditions in March 2000. The water-quality data were used to determine priority ranks of the AMD sources on the basis of loadings of iron, manganese, and aluminum and to identify possible remedial alternatives, including passive-treatment options, for consideration by water-resource managers. The ranking sequence for the top AMD sources based on the high base-flow data generally matched that based on the low base-flow data. The contaminant loadings generally increased with flow, and 10 previously identified intermittent AMD sources were not discharging during the low base-flow sampling period. The top 3 AMD sources (SR19, SR12, and SR49) on the basis of dissolved metals loading in March 2000 accounted for more than 50 percent of the metals loading to Shamokin Creek, whereas the top 15 AMD sources accounted for more than 98 percent of the metals loading. When sampled in March 2000, these AMD sources had flow rates ranging from 0.7 to 19 cubic feet per second (1,138 to 32,285 liters per minute) and pH from 3.5 to 6.1 standard units. Only 1 of the top 15 AMD sources (SR21) was net alkaline (alkalinity > acidity); the others were net acidic and will require additional alkalinity to facilitate metals removal and maintain near-neutral pH. For the top 15 AMD sources, dissolved iron was the principal source of acidity and metals loading; concentrations of iron ranged from 10 to 57 milligrams per liter. Dissolved manganese ranged from 1.9 to 7.4 milligrams per liter. Dissolved aluminum exceeded 3.9 milligrams per liter at seven of the sites but was less than 0.2 milligram per liter at seven others.

2 Effects of Abandoned Coal-Mine Drainage on Streamflow and Water Quality in the Shamokin Creek Basin

Alkalinity can be acquired by the dissolution of limestone and (or) bacterial sulfate reduction within various passive-treatment systems including anoxic or oxic limestone drains, limestone-lined channels, or compost wetlands. Subsequently, the gradual oxidation and consequent precipitation of iron and manganese can be accommodated within settling ponds or aerobic wetlands. Assuming an iron removal rate of 180 pounds per acre per day (20 grams per square meter per day), constructed treatment wetlands at the top 15 AMD sites would require a minimum area ranging from 0.7 to 17.8 acres (590 to 71,670 square meters). Implementation of passive treatment would not be feasible at most of the top 15 and many lower priority AMD sites considering the proximity of many discharges to streams, roads, or railroads, and the limited availability or access to land at the discharge location. The reduction of infiltration and removal of culm waste and (or) the relocation of the discharge to nearby areas could decrease the AMD quantities and facilitate treatment at some of the priority AMD sites.

Introduction

Shamokin Creek is a tributary of the Susquehanna River that drains 137 square miles (mi²), or 355 square kilometers (km²), in east-central Pennsylvania. Shamokin Creek originates near Centralia in Columbia County, flows westward approximately 10 mi (16 km) through Northumberland County into the city of Shamokin, and then approximately 20 mi (32 km) northward through gaps in Big Mountain and Little Mountain and westward to its mouth on the Susquehanna River at Sunbury (figs. 1 and 2). The Shamokin Creek Basin includes 1 municipality in Columbia County and 13 municipalities in Northumberland County. Ten of the municipalities, including the city of Shamokin, are in the upper 54 mi² (140 km²) of the Shamokin Creek Basin south of Big Mountain. This area is underlain by the Western Middle Anthracite coalfield (mining region) (fig. 1), where anthracite was extensively mined from about 1840-1950 (Reed and others, 1987). Contaminated runoff and discharges from numerous abandoned anthracite mines throughout the upper Shamokin Creek Basin have degraded Shamokin Creek and many of its tributaries. Consequently, Shamokin Creek is designated a “high priority watershed” on the Pennsylvania Department of Environmental Protection degraded watershed list (Pennsylvania Department of Environmental Protection, 1996, 1998).

Purpose and Scope

In order to assess the effects of AMD sources and to identify possible remedial alternatives, the U.S. Geological Survey (USGS), in cooperation with the Pennsylvania Department of Environmental Protection (PaDEP), Bucknell University (BU), and Northumberland County Conservation District (NCCD), began a study in 1999. This report assesses the current contaminant loading, effects to receiving streams, and possible reme-

dial alternatives for AMD within the upper Shamokin Creek Basin on the basis of data collected during 1999-2001. Data on the flow rate and quality of water were collected at all known AMD sites and at selected stream sites within the Shamokin Creek Basin during low base-flow conditions in August 1999 and then repeated during high base-flow conditions in March 2000. The basin-wide synoptic monitoring of flow and water quality during stable base-flow conditions was performed to (1) identify site-specific characteristics including temporal variability associated with seasonal changes in base flow, (2) indicate spatial variability and relative effects of the AMD throughout the basin, and (3) avoid complications in data collection and interpretation associated with rainfall or other short-term weather events. Additionally, during October 1999, 2000, and 2001, data on the diversity and biomass of fish species were collected at a subset of the sampled stream sites, and streamflow of Shamokin Creek below Shamokin was recorded continuously. The supplemental surveys of streamflow and aquatic ecology documented the effects of the AMD on streamwater resources. The project data were compiled into a digital database and geographic information system (GIS). The data were used to compute contaminant loading rates, to determine the potential effects of the AMD on aquatic ecology, and to identify possible remedial priorities and alternatives for watershed rehabilitation. The PaDEP, NCCD, and the Shamokin Creek Restoration Alliance (SCRA) will use study results for choosing remediation alternatives.

Geology and Mining History

The Western Middle Anthracite coalfield underlies the upper Shamokin Creek Basin and parts of the neighboring Mahanoy Creek Basin (Reed and others, 1987). The coalfield is a synclinal basin, or “canoe-shaped” structure, that has been subdivided by parallel faults. Sandstone, siltstone, and conglomerate are the dominant lithologies surrounding the coalbeds; limestone has not been mapped within the coalfield (Wood and others, 1986; Berg and others, 1989; Eggleston and others, 1999). In the Shamokin area, a total of 24 coalbeds of the Llewellyn and Pottsville Formations of Pennsylvanian Age with average thicknesses from 0.6 to 8.3 ft (0.2 to 2.5 m) have been identified and mined to depths exceeding 2,500 ft (762 m) below land surface (Reed and others, 1987). Most anthracite mines were developed as large underground complexes or “collieries” in the valleys, where shafts and tunnels connected mine drifts and slopes within multiple coalbeds. Generally, mining was conducted by the room-and-pillar method, with barrier pillars left intact between adjacent collieries.

Anthracite production in Pennsylvania peaked in 1917 at more than 100 million short tons, including 6.2 million tons from the Shamokin Creek Basin (Gannett Fleming Corddry and Carpenter, Inc., 1972; Pennsylvania Department of Environmental Protection, 2001a; Pennsylvania Coal Association, 2001). During the period of peak production, 95 percent of the anthracite was obtained from underground mines. In 2000, less

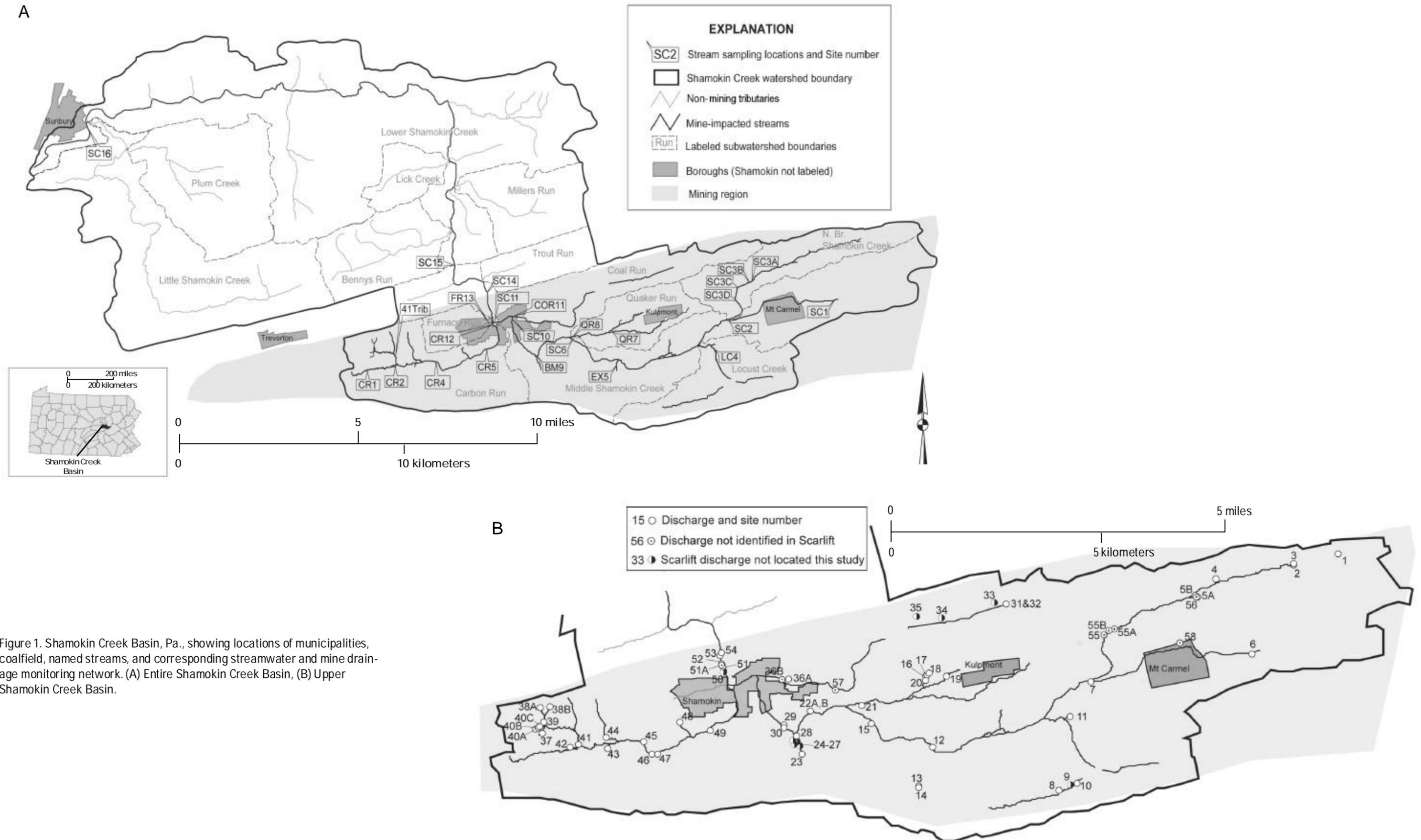


Figure 1. Shamokin Creek Basin, Pa., showing locations of municipalities, coalfield, named streams, and corresponding streamwater and mine drainage monitoring network. (A) Entire Shamokin Creek Basin, (B) Upper Shamokin Creek Basin.

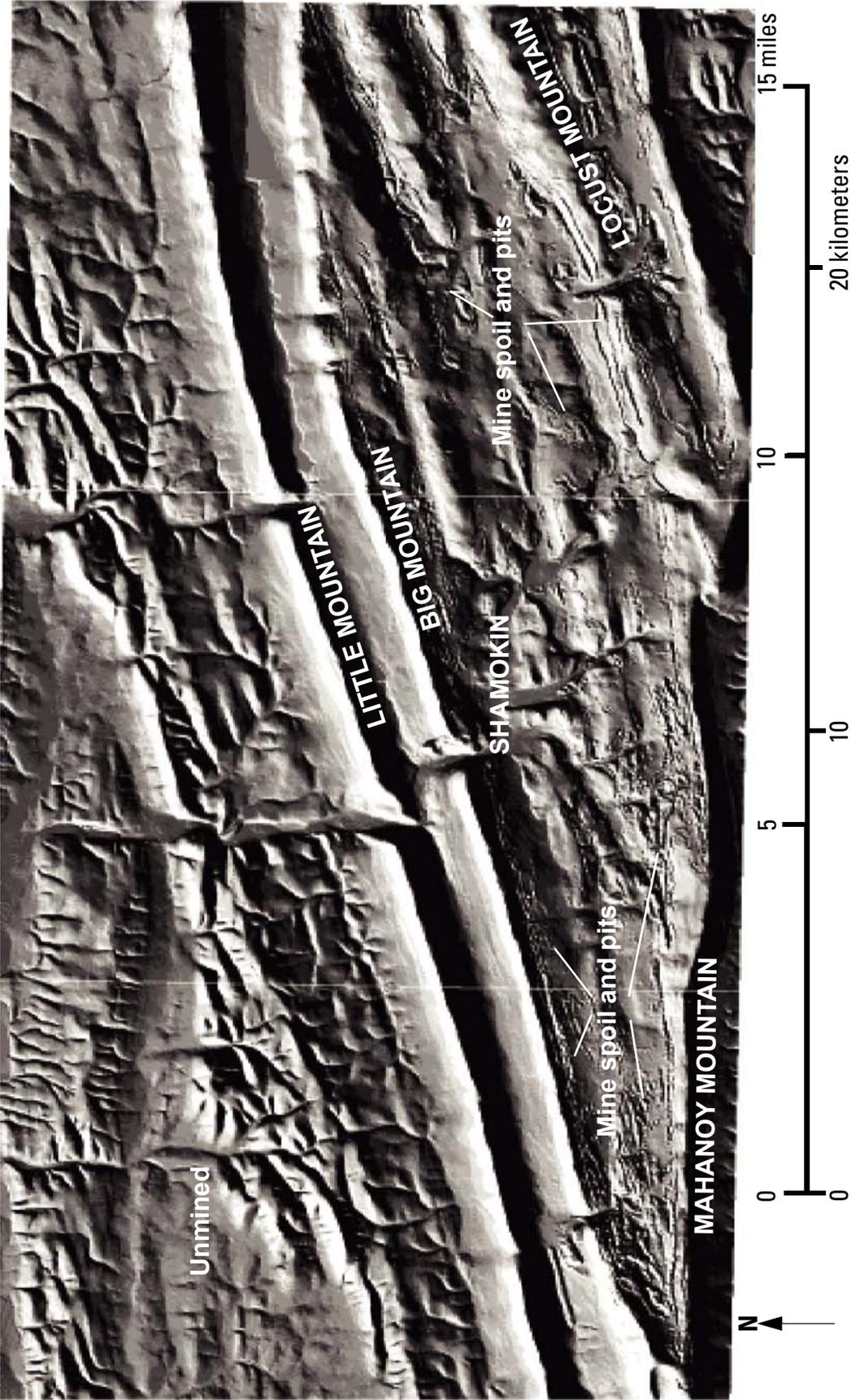


Figure 2. Shaded relief map showing the upper Shamokin Creek Basin, Pa., bounded by Locust Mountain and Mahanoy Mountains on the south and Big Mountain on the north. The surface extent of abandoned mine workings within the basin is apparent at the map scale. Relief based on U.S. Geological Survey 10-meter digital elevation model (DEM) for the Trevorton, Shamokin, and Mount Carmel quadrangles.

than 6 million tons of anthracite were produced in Pennsylvania; only 5.5 percent was obtained from underground mines (Pennsylvania Coal Association, 2001). Only a few surface and deep mines presently are active in the Shamokin Creek Basin. Most mines were closed before 1960 and the mines flooded when ground-water pumping ceased.

Within the upper Shamokin Creek Basin, the underground mine complexes extended beneath most of the North Branch Shamokin Creek, Locust Creek, Quaker Run, and Coal Run, as well as extensive parts of Carbon Run and Shamokin Creek upstream from Shamokin (Gannett Fleming Corddry and Carpenter, Inc., 1972; Reed and others, 1987). Mining-induced subsidence and fracturing have promoted leakage of water to and from the underground mines. When the mines were active, some stream channels were lined artificially to reduce leakage and to reduce the costs of pumping ground water from the mines. Nevertheless, upon closure of the mines, leakage resumed from sections of these channels and elsewhere, and large volumes of the mine complexes flooded producing underground “mine pools.”

Extensive parts of the abandoned underground mines that underlie the valley are flooded, and numerous areas within the valley and along the valley slopes have not been reclaimed or revegetated. Barren, steep banks of spoil and culm and fine coal debris in overflowing or incised siltation basins are sources of sediment (suspended solids), acidity, metals, and sulfate in water that infiltrates or runs off the surface. In parts of the basin, surface flow is diverted through subsidence pits, fractures, and mine openings to the underground mines (Gannett Fleming Corddry and Carpenter, Inc., 1972; Reed and others, 1987). In downstream reaches, the water resurges as “acidic” or “abandoned” mine drainage (AMD) contaminating Shamokin Creek and its tributaries, while contributing substantially to stream-flow. The AMD constitutes a substantial portion of base flow, especially during low-flow or drought conditions (Becher, 1991).

Discharges typically emanate from tunnels, slopes, air shafts, and other passages, including fractures in stream channels, and other topographically low points overlying the mine complex. Many of the same streams that lose water to underground mines in the upper reaches, gain water from mine discharges in their lower reaches. In some cases, the mine complexes extended beyond surface-water divides, enabling the transfer of surface and ground water between adjacent stream basins. For example, water originating in the Shamokin Creek Basin discharges to the Mahanoy Creek Basin from the Douthville, Helfenstein, Locust Gap, and Centralia Mine Discharges, whereas water is conveyed from the Mahanoy Creek Basin through interconnected mine complexes to become part of the overflow from the Henry Clay Stirling discharge (SR49) in the Shamokin Creek Basin (Reed and others, 1987). Because the underground mine complexes were extensive, their discharge volumes tend to be substantially greater and more continuous than those from less extensive surface mines or spoil piles.

Land Use

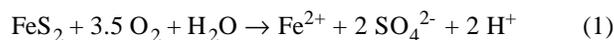
The Shamokin Creek Basin lies in the Appalachian Mountains section of the Ridge and Valley Physiographic Province (Way, 1999). This area is characterized by complexly deformed strata and elongate, northeast-southwest trending ridges that bound narrow valleys. Because of their steep slopes and thin rocky soils, the ridges tend to be forested and sparsely developed. Urban, industrial, and agricultural land uses predominate in the valleys. The northwestern two-thirds, or lower part, of the Shamokin Creek Basin is in the Northern Shale Valleys and Slopes Ecoregion where agricultural land use predominates (Pennsylvania Department of Environmental Protection, 2001a). The southeastern third, or upper part, of the basin is in the Anthracite Coal Ecoregion (Pennsylvania Department of Environmental Protection, 2001a).

Land use in the 137-mi² (350-km²) Shamokin Creek Basin has been classified as 61 percent forested, 32 percent agricultural, and 7 percent “barren, mined” or urban (Myers and Bishop, 1999; U.S. Geological Survey, 2000). Nevertheless, this land-use classification may be misleading because, in the upper basin, abandoned underground mines extend beneath much of the surface and “natural” reforestation conceals large tracts of unreclaimed spoil. Considering the extent of “spoil” and other land-use patterns depicted by USGS topographic maps, land use in the upper 54-mi² (140 km²) Shamokin Creek Basin could be classified as 57 percent forested, 38 percent “mine spoils,” 5 percent urban, and less than 1 percent agricultural. Hence, although the anthracite industry largely is inactive, mining could be considered a major land use within the valley of the upper basin.

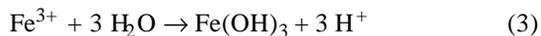
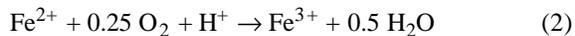
Water Quality

The Shamokin Basin contains 413 mi (661 km) of streams, of which 113 mi (181 km) or 27 percent are listed as degraded by AMD (Pennsylvania Department of Environmental Protection, 1996, 1998, 2001a, 2001b). The streams affected by AMD include the North Branch Shamokin Creek, Locust Creek, Quaker Run, Coal Run, and Carbon Run, as well as Shamokin Creek (fig. 1). Despite dilution by unaffected tributaries in the lower basin, the AMD has degraded the aquatic habitat of Shamokin Creek to its mouth on the Susquehanna River (Gannett Fleming Corddry and Carpenter, Inc., 1972; Reed and others, 1987; Pennsylvania Department of Environmental Protection, 2001a, 2001d).

Generally, AMD can have low pH and elevated concentrations (above background) of dissolved sulfate (SO₄²⁻), iron (Fe²⁺, Fe³⁺), manganese (Mn²⁺), aluminum (Al³⁺), and other metals that result from the oxidation of pyrite (FeS₂) and the dissolution of carbonate, oxide, and aluminosilicate minerals by acidic water (Rose and Cravotta, 1998).

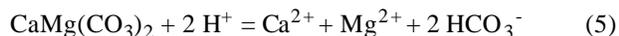


6 Effects of Abandoned Coal-Mine Drainage on Streamflow and Water Quality in the Shamokin Creek Basin



Pyrite oxidation (reaction 1) takes place where oxygen (O_2) and moisture are available. Infiltrating water or surface runoff can dissolve and transport the acidic oxidation products. In contrast with SO_4^{2-} , which is transported primarily as a dissolved ion, Fe can be transported as ferrous (Fe^{2+}) and ferric (Fe^{3+}) ions and as suspended Fe(III) solids. In the presence of O_2 , highly soluble Fe^{2+} tends to oxidize to relatively insoluble Fe^{3+} (reaction 2). At $\text{pH} > 3$, concentrations of Fe^{3+} tend to be limited by the formation of Fe(III) oxyhydroxides and related solids (reaction 3). The complete, stoichiometric oxidation of pyrite is indicated by combining reactions 1, 2, and 3. Half of the protons (H^+), or acid, produced by the complete oxidation of pyrite results from the oxidation of pyritic sulfur to SO_4^{2-} (reaction 1) and the other half results from the oxidation of Fe^{2+} to Fe^{3+} and its consequent precipitation as $\text{Fe}(\text{OH})_3$ (reactions 2 and 3).

The acid produced by pyrite oxidation or by hydrolysis can be neutralized by reaction with calcite (CaCO_3), dolomite [$\text{CaMg}(\text{CO}_3)_2$], and other calcareous minerals.



These calcareous minerals are the dominant components of limestone and can occur in nodules, cementing agents, or fractures in sandstone, siltstone, shale, and associated strata of coal-bearing rocks. Alkalinity, represented by bicarbonate (HCO_3^-), and base cations, including calcium (Ca^{2+}) and magnesium (Mg^{2+}), are common products of neutralization by these calcareous minerals. Where absent or deficient at a mine site, the addition of limestone or other alkalinity-producing materials to mine spoil or mine drainage can be effective for prevention or neutralization of AMD and the attenuation of metals transport. As the pH increases to near-neutral values, concentrations of Fe^{3+} , Al^{3+} , and various other metals in AMD generally will decline; however, concentrations of SO_4^{2-} , Fe^{2+} , and Mn^{2+} generally will not be affected (Blowes and Ptacek, 1994; Cravotta and Trahan, 1999; Cravotta and others, 1999).

The pH of AMD at its point of emergence can be unstable because of a general tendency for the exsolution of dissolved carbon dioxide (CO_2) and hydrogen sulfide (H_2S), the dissolution of O_2 , and the consequent oxidation and hydrolysis of dissolved iron and manganese (Rose and Cravotta, 1998; Cravotta and others, 1999). AMD that initially has near-neutral pH (from 6 to 7) ultimately could have acidic pH (< 4.5) after its complete oxidation. The “hot” acidity measures the sum of all acidity that must be neutralized to successfully treat the AMD. This summed acidity is due to the oxidation and (or) hydrolysis of dissolved iron (reactions 2 and 3), manganese, aluminum, and other cations (Greenberg and others, 1992; Rose and Cravotta, 1998). The final pH of a water after oxidation and hydrolysis can be estimated by measuring the pH of water after peroxide

has been added and the sample left open to the atmosphere for 3 to 5 days. Net-alkaline samples with alkalinity in excess of acidity (negative acidity) tend to remain near neutral; however, net-acidic samples with acidity in excess of alkalinity (positive acidity) tend to have acidic pH after complete oxidation. Hence, the characterization of AMD as acidic or neutral and the evaluation of appropriate remediation should consider the pH, hot acidity, alkalinity, and concentrations of dissolved metals.

Although sewage-treatment facilities serve the larger municipalities in the study area, direct discharges of raw sewage and leaky on-lot septic systems degrade local stream sections throughout the basin (Pennsylvania Department of Environmental Protection, 2001a, 2001d). A plan to address the large number of combined sewer overflows currently is under development for some municipalities in the basin (Leanne Bjorklund, Shamokin Creek Restoration Alliance, oral commun., 2003). Agricultural practices likely affect the quality of streamwater in parts of the western subbasin. However, AMD from abandoned anthracite mines is the overwhelming source of stream impairment in the upper basin (Pennsylvania Department of Environmental Protection, 2001a, 2001d).

Quality Protection and Restoration

Pennsylvania has adopted water-quality criteria intended to protect the anticipated uses of streams for (1) the maintenance and propagation of cold-water and warm-water fish; (2) water supply for domestic, industrial, livestock, wildlife, and irrigation purposes; (3) boating, fishing, and water-contact sports; (4) power; and (5) treated waste assimilation (Commonwealth of Pennsylvania, 2002). The main stem Shamokin Creek is designated a warm-water fishery (WWF) and its tributaries are designated cold-water fisheries (CWF) (Commonwealth of Pennsylvania, 2002). To meet the WWF and CWF designations, the following criteria must be met (Commonwealth of Pennsylvania, 2001a, 2002):

- temperature during July and August not to exceed 66°F (18.9°C) or 87°F (30.6°C) for CWF and WWF, respectively;
- dissolved oxygen concentration greater than 5.0 mg/L for CWF and 4.0 mg/L for WWF;
- alkalinity not less than 20 mg/L as CaCO_3 , except where natural conditions are less;
- pH not less than 6.0 or greater than 9.0;
- total iron concentration not to exceed 1.5 mg/L as 30-day average;
- dissolved iron concentration not to exceed 0.3 mg/L;
- total manganese concentration not to exceed 1.0 mg/L; and
- total aluminum concentration not to exceed 0.75 mg/L.

The above criteria for chemical constituents have been incorporated in recently developed “total maximum daily loads” (TMDLs) for Shamokin Creek and its tributaries (Pennsylvania Department of Environmental Protection, 2001a, 2001b). The intent of the TMDLs is to identify the amount of a contaminant that a stream can assimilate without exceeding its

water-quality standards. TMDLs have been calculated for each of the above contaminants documented as causing impairment. However, the criteria for TMDLs are limited to only a few of the constituents that may have adverse effects to aquatic organisms or humans. Trace metals such as cobalt, nickel, zinc, and cadmium commonly are found in AMD at levels that are above background concentrations and may be toxic (Elder, 1988; Hyman and Watzlaf, 1997; Rose and Cravotta, 1998; Cravotta and others, 2001). Guidelines for the protection of freshwater aquatic organisms and human health from these trace metals and other contaminants have been established by the U.S. Environmental Protection Agency (1997, 2002a, 2002b) and adopted by the Commonwealth of Pennsylvania (2001b).

The restoration of water quality in mining affected areas generally involves a combination of re-mining, land reclamation, and AMD treatment. Re-mining includes reprocessing of culm to separate previously uneconomic coal from waste rock and surface mining or “daylighting” of old underground mine complexes. Such re-mining currently is done under stricter environmental regulations than in the past, and it can result in reduced infiltration to underground mines and (or) improved water quality. Land reclamation can involve the filling of open pits or shafts, the removal and (or) revegetation of coal spoil or culm banks, and the restoration of stream channels and stream-flow. Where reclamation of a mine or mining-related surface effects is not possible, treatment of AMD may be necessary to neutralize acidity and remove dissolved and suspended metals from the hydrologic system. The conventional treatment for metal-laden effluent that has excess acidity involves aeration and the addition of strong alkaline chemicals (Skousen and others, 1998). Although effective, this “active” treatment approach can be expensive because of the high cost of chemical reagents, operation, and maintenance. Alternative treatment methods for AMD include wetlands and limestone-based systems (Hedin and others, 1994; Skousen and others, 1998; Watzlaf and others, 2000). Generally, for net-acidic AMD, limestone-based treatments such as anoxic limestone drains (ALDs), successive alkalinity producing systems (SAPS), or open limestone channels (OLCs) could be appropriate to add alkalinity (fig. 3). For net-alkaline AMD, oxidation ponds or aerobic wetlands are useful to remove metals as solids. These “passive” treatment systems generally require little maintenance but are limited by slower rates of neutralization and contaminant removal and, consequently, may require larger land area than for conventional “active” treatments. Nevertheless, passive systems can be cost effective where water chemistry meets suggested criteria and land and component materials are available locally (Skousen and others, 1998).

Operation Scarlift project SL-113 (Gannett Fleming Cordry and Carpenter, Inc., 1972) identified 54 mine discharges and presented 5 possible plans (including preventative measures and active chemical treatment) to remediate AMD and erosion problems in the upper Shamokin Creek Basin. The report stated that the recommended plan would remove 92 percent of the iron load and 99 percent of the acidity at a cost of \$13.4 million (1972 dollars). Another proposal to solve the

problem would flood the entire valley behind a large dam, presumably by preventing acid formation and diluting the contaminated water (Rahn, 1992). However, because these proposals were too costly or impractical, little has been done to mitigate the AMD.

Major changes have occurred in the flow and quality of the mine discharges and in the quality of Shamokin Creek in the decades since the Operation Scarlift report was completed in 1972 (Reed and others, 1987; Wood, 1996; Kirby, 1995, 1998). Furthermore, passive-treatment systems that recently have been developed could be lower cost alternatives to remediate AMD compared to active treatment methods. An updated assessment of the hydrological and chemical characteristics of the AMD and hydrological, chemical, and biological characteristics of the receiving streams in the basin is needed to determine the relative effects, priorities, and alternatives for AMD remediation.

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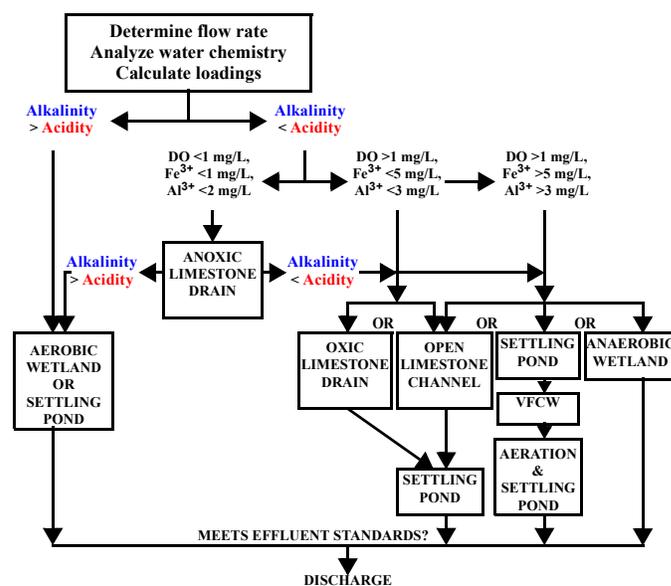


Figure 3. Flow chart for selection of passive treatment alternatives modified from Hedin and others (1994), Skousen and others (1998), and Pennsylvania Department of Environmental Protection (1999). Vertical flow compost wetland (VFCW), also known as SAPS or RAPS.

Methods of Water-Quality Site Selection, Sampling, and Analysis

Before the basin-wide synoptic monitoring was initiated, precise locations of the AMD sources and previously sampled stream sites were determined. Published data on the locations of AMD and stream monitoring sites as reported by Gannett Fleming Corddry and Carpenter, Inc. (1972), Growitz and others (1985), Reed and others (1987), and Wood (1996) and unpublished data from SCRA (Kirby, 1995, 1998) were reviewed, compiled, and mapped. Then, during May and June 1999, an attempt was made to access each AMD site and document its location by use of a global positioning system (GPS). Field measurements of flow rate, pH, and specific conductance were recorded during the preliminary site visit to assist in the identification of AMD sources. Subsequently, plans were developed for synoptic sampling at all the AMD and stream sites by two teams and for resumption of streamflow gaging on Shamokin Creek.

To determine the range of hydrologic conditions during the assessment, continuous streamflow data were collected at the USGS gaging station near Shamokin (station 01554500; SC15). This station had been maintained during 1932-1992 by the USGS but had been discontinued until the present study. During the assessment, stream stage was measured continuously using a chart recorder, and streamflow was measured at various stages to verify previous stage-discharge relations for the computation of discharge (Rantz and others, 1982a, 1982b).

A total of 60 AMD sites were identified from various documents; however, only 46 AMD sites ultimately could be located and surveyed for the assessment (table 1; fig. 1).¹ Additionally, 23 stream sites were surveyed (table 2; fig. 1). The sampled sites that had been surveyed previously for the Scarlift investigation are identified by local identification numbers from 1 to 54 in column 1 of table 1. Some of the Scarlift site identification numbers have been modified by adding a suffix "A" or "B" indicating distinctive seeps or discharges at a specific location. A few Scarlift sites are indicated with hyphenated numbers because previously distinctive, nearby AMD sources had been combined or could no longer be distinguished. Additional sites identified by SCRA and not been reported previously were assigned local identification numbers greater than 54 in column 1 of table 1. Those AMD sites that had been sampled and reported by the USGS (Growitz and others, 1985; Reed and others, 1987; Wood, 1996) are indicated by the USGS local identification numbers in columns 2 and 3 of table 1. One of the previous USGS sample sites could not be located for this study. Finally, a unique USGS station identification number was assigned to identify each of the sampled sites in the USGS

National Water Information System (NWIS) database (column 4 of tables 1 and 2). Generally, previously published coordinates were used to assign the station numbers for ground-water or AMD sites. In some cases, these station numbers differ slightly from the reported latitude and longitude because of inconsistency between the current GPS measurement and previously mapped locations or published coordinates. Stream or other surface-water sites were assigned USGS station numbers based on the relative downstream order within a given watershed (table 2). A few AMD sites had been assigned surface-water station numbers because they appeared as flowing or standing water within a channel or pit. Nevertheless, because of their brevity and their widely adopted use by the local authorities (PaDEP, SCRA), the local SCRA site identification numbers are used hereafter.

Water-quality and flow data for the synoptic surveys were collected during low base-flow (August 4-6, 1999) and (or) high base-flow (March 14-16, 2000) conditions at the AMD and stream sites (tables 1 and 2). Three teams of two persons each were deployed to assigned sites with identical sets of monitoring equipment. In accordance with standard methods, each team measured the flow rate, temperature, specific conductance (SC), dissolved oxygen (DO) concentration, pH, and redox potential (Eh) when samples were collected using field-calibrated instruments (Wood, 1976; Rantz and others, 1982a, 1982b; U.S. Geological Survey, 1997 to present). Water samples were collected as 1-liter grab samples as close as possible to the discharge location or where streamflow was well mixed, avoiding bottom sediments and other debris. The grab samples immediately were split into subsamples for field filtration and preservation as appropriate. Unfiltered samples for analysis of alkalinity, acidity, and major anions were stored in sample-rinsed polyethylene bottles filled to exclude head space. Samples for dissolved (0.45- μm filter) and total recoverable (whole-water; in-bottle nitric and hydrochloric acid digestion) metal analysis were stored in acid-rinsed polyethylene bottles and acidified with nitric acid (HNO_3). Ferrous iron samples were preserved with hydrochloric acid (HCl). Nutrient samples were preserved with sulfuric acid (H_2SO_4). Bacteria samples were stored in sterilized, amber glass bottles. All samples were stored at 4°C until laboratory analyses could be completed.

Major ions, metals, and nutrients in the low and high base-flow water samples were analyzed at the USGS National Water-Quality Laboratory in Denver, Colo., and the PaDEP Laboratory in Harrisburg, Pa., respectively, by inductively coupled plasma atomic emission spectrometry (ICP-AES), ion chromatography (IC), colorimetry, and electrometric titration following methods of Greenberg and others (1992), Fishman and Friedman (1989), and Fishman (1993). Each of the AMD samples was analyzed for major ions and dissolved metals; the

¹Only 39 of the 54 AMD sites identified in the Scarlift report (Gannett Fleming Corddry and Carpenter, Inc., 1972) could be located and sampled for the current assessment. The AMD sites that could not be located had been reported previously to have small flow rates, ranging from 0 to 0.015 ft³/s (254 L/min). The Scarlift site locations were shown on maps; however, the map projections and site coordinates were not provided. Some of the previously reported sites simply could not be found; others currently may not exist.

Table 1. Description of abandoned mine drainage sites surveyed in 1999-2000 for the Shamokin Creek watershed assessment, Pennsylvania [-, not applicable; SCRA, Shamokin Creek Restoration Alliance; WRI, USGS Water Resources Investigations Report; latitude and longitude listed without degree, minute, and second symbols; 404918.4 represents 40°49'18.4" north latitude and 76°22'21.7" west longitude]

SCRA Site No. ^a	WRI 85-4038 ^b	WRI 83-4274 ^c	USGS Station Identification Number	Latitude	Longitude	Site Name	Water-shed ^d	Sample ^e Low	Sample ^e High
1	--	--	01554200	404929.0	762127.4	North Branch Shamokin Creek at Aristes (SR1)	NBSC	Yes	Yes
2	81	78	404917076222101	404918.4	762221.7	Mid Valley Mine seep at Wilburton (SR2)	NBSC	Yes	Yes
3	--	--	01554220	404919.4	762224.6	Unn trib to NB Shamokin Cr at Wilburton (SR3)	NBSC	Yes	Yes
4	82	79	404905076235501	404905.2	762356.5	Mid Valley Mine Tunnel 4 at Wilburton No 1 (SR4)	NBSC	Yes	Yes
5A	--	--	01554260	404849.5	762414.9	Mid Valley Mine overflow at Wilburton No 1 (SR5A)	NBSC	Dry	Yes
5B	83	80	404848076242401	404848.5	762421.7	Mid Valley Mine Tunnel at Wilburton No 1 (SR5B)	NBSC	Yes	Yes
6	--	--	404757076231201	404757	762312	Sayre-Sioux Mine discharge (SR6)	USC	No	Yes
8	--	--	404546076270201	404547.0	762702.4	Locust Gap Mine discharge at Locust Gap (SR8)	LC	Dry	Yes
10	--	--	404554076264701	404554.1	762647.8	Locust Gap Mine discharge at Locust Gap (SR10)	LC	Yes	Yes
11	89	82	404656076265001	404655.8	762650.6	Alaska Mine seep at Locust Gap (SR11)	MSC	Dry	Yes
12	90	87	404625076293701	404625.5	762936.4	Excelsior Mine pit overflow at Excelsior (SR12)	MSC	Yes	Yes
13	--	--	404549076295301	404548.6	762953.0	Mine seep nr Locust Gap Mine (SR13)	MSC	No	Yes
14	--	--	404552076310001	404552.9	763100.2	Mine discharge at Excelsior (SR14)	MSC	No	No
15	96	89	404646076305301	404646.4	763051.0	Corbin Water Level drift at Ranshaw (SR15)	MSC	Yes	Yes
19	86-87	84-85	404739076291901	404731.5	762920.8	Scott Ridge Mine Tunnel at Kulpmont (SR19)	QR	Yes	Yes
20	88	86	404726076294101	404726.6	762948.0	Colbert Mine Breach nr Kulpmont (SR20)	QR	Yes	Yes
21	95	88	404703076305201	404703.2	763103.5	Maysville Mine Borehole at Ranshaw (SR21)	QR	Yes	Yes
22A	97	90	404657076320501	404656.5	763205.3	Royal Oak Mine seep at Marshallton (SR22B)	MSC	Yes	Yes
22B	97	90	404657076320502	404656.5	763206.1	Royal Oak Mine seep at Marshallton (SR22A)	MSC	Yes	Yes
23	98	91	404619076321901	404617.0	763215.4	Big Mtn Mine No 1 Slope at Big Mountain (SR23)	MSC	Yes	Yes
28	--	--	404634076322301	404634	763223	Henry Clay Stirling Mine seepage nr Big Mountain (SR27)	MSC	Yes	Yes
29	--	--	404643076323801	404643.6	763238.0	Royal Oak Mine discharge at Shamokin (SR29)	MSC	Yes	Yes
30	--	--	404641076323701	404641	763238	Royal Oak Mine seep at Shamokin (SR30)	MSC	Yes	Yes
31-32	--	--	404838076281001	404838.4	762810.1	Greenough Mine discharge nr Marion Heights (SR31-32)	QR	Yes	Yes
31A	--	--	--	404840	762810	Natalie Mine drift nr Marion Heights	QR	No ^f	No
36	99	--	404728076340901	404728	763409	Nielson Mine Drainage Tunnel at Shamokin (SR36)	COR	No	No
36A	--	--	404725076323501	404725.8	763235.1	Luke Fiddler Mine discharge at Shamokin (SR36A)	COR	Dry	Dry ^g
36B	--	--	404724076324201	404725.0	763242.7	Royal Oak Mine discharge at Shamokin (SR36B)	COR	Yes	Yes
37	--	--	404631076373001	404631.9	763731.0	Bear Valley Mine discharge nr Kulpms (SR37)	CR	Yes	Yes
38A	109	101	404754076372801	404654.3	763732.0	Bear Valley Mine seep nr Kulpms (SR38A)	CR	Yes	Yes
39	110	102	404642076373001	404642.5	763729.1	Bear Valley strip pool overflow nr Kulpms (SR39)	CR	Yes	Yes
40B	--	--	404636076373501	404637.4	763735.7	Bear Valley Mine discharge nr Kulpms (SR40B)	CR	Yes	Yes
40C	--	--	404637076373401	404637.8	763734.0	Bear Valley Mine discharge nr Kulpms (SR40C)	CR	Yes	Yes
41	--	--	404622076364601	404622.7	763646.4	KMK Coal Co. No. 14, vein s, nr Kulpms (SR41)	CR	Yes	Yes
42	108	100	404618076365901	404619.3	763656.4	Bear Valley Mine, N Mtn Tunnel nr Kulpms (SR42)	CR	Yes	Yes
43	--	--	404618076361001	404618.3	763610.8	Bear Valley Mine discharge nr Shamokin (SR43)	CR	Yes	Yes
44	--	--	404628076361201	404628.5	763613.0	Bear Valley Mine discharge nr Kulpms (SR44)	CR	No	Yes
45	--	--	404625076352701	404625.3	763527.1	Henry Clay Stirling Mine discharge nr Shamokin (SR45)	CR	Yes	Yes
46	107	99	404614076351101	404615.4	763513.1	Bear Valley Mine seep at Bear Valley (SR46)	CR	Yes	Yes
47	--	--	404614076351001	404614.7	763510.2	Bear Valley Mine discharge at Bear Valley (SR47)	CR	Yes	Yes
48	106	98	404643076344701	404644.4	763444.1	Henry Clay Stirling Mine seep at Shamokin (SR48)	CR	Yes	Yes
49	105	97	404637076340701	404638.2	763405.0	Henry Clay Stirling Mine Pump Slope at Shamokin (SR49)	CR	Yes	Yes
50	103	95	404730076335201	404730	763352	Cameron Mine seepage at Shamokin (SR50)	LSC	No	No
51	104	96	404731076334601	404737.7	763353.9	Cameron Mine discharge at Shamokin (SR51)	LSC	Yes	Yes
51A	101	93	404737076335501	404737.7	763353.1	Cameron Mine Drift at Shamokin (SR51A)	LSC	Yes	Yes
52	102	94	404735076335401	404738.1	763354.1	Cameron Mine discharge at Shamokin (SR52)	LSC	No	Yes
53	100	92	404744076335901	404746.9	763356.4	Cameron Mine Air Shaft at Shamokin (SR53)	LSC	Yes	Yes
54	--	--	404748076335701	404748.3	763357.7	Cameron Mine seep at Shamokin (SR54)	LSC	Yes	Yes
55	--	--	404817076261201	404817	762612	Richard's Shaft Mine Drift nr Atlas (SR55)	NBSC	Dry	Yes ^h
56	--	--	404848076241801	404848.2	762418.9	Mid Valley Mine discharge at Wilburton (SR56)	NBSC	Yes	Yes

a. Shamokin Creek Restoration Alliance (SCRA) site numbers based on Scarlift report of Gannett Fleming Corddry and Carpenter, Inc. (1972). Locations of these sites and some additional sites from the Scarlift report that were not sampled are shown in figure 1.

b. Reed and others (1987).

c. Growitz and others (1985). These numbers also were reported by Wood (1996).

d. Watershed areas are shown in figure 1. NBSC=North Branch Shamokin Cr.; MSC=Upper Shamokin Cr.; LSC=Lower Shamokin Cr.; COR=Coal Run; CR=Carbon Run; LC=Locust Cr.; QR=Quaker Run.

e. Water-quality and flow data collected for low base-flow conditions on August 4-6, 1999, and (or) high base-flow conditions on March 14-16, 2000.

f. Natalie Mine drift not found; presumably combined with Greenough Mine discharge as site 31-32.

g. Luke Fiddler Mine discharge not flowing when visited in August 1999 and March 2000. However, substantial flow was sampled in April 2000 by Shamokin Creek Restoration Alliance.

h. Sample was not collected but was estimated on the basis of samples from upstream and downstream sites (SC3B, SC3D) on North Branch Shamokin Creek.

Table 2. Description of stream sites surveyed in 1999-2000 for the Shamokin Creek watershed assessment, Pennsylvania [n.a., not applicable; latitude and longitude listed without degree, minute, and second symbols; 404821.1 represents 40°48'21.1" north latitude and 762548.2 represents 76°25'48.2" west longitude]

SCRA Site Number ^a	AMD Sources ^b	USGS Station Identification Number	Latitude	Longitude	Site Name	Sample ^c	
						Low	High Fish
SC1	None	n.a.	404757	762312	Shamokin Creek nr Mount Carmel (SC1)	Dry	No
SC2	6-7	01554300	404729	762626.8	Shamokin Creek at Atlas (SC2)	Dry	Yes
SC3A	1-4,5A-B,56	01554270	404821.1	762548.2	North Branch Shamokin Cr at Mount Carmel (SC3A)	No	Yes
SC3B	(SC3A)	01554271	404821	762546	North Branch Shamokin Cr at Mount Carmel (SC3B)	No	Yes
SC3C	(SC3B)	01554273	404814	762606	North Branch Shamokin Cr at Mount Carmel (SC3C)	No	No
SC3D	(SC3C),55	01554280	404755.5	762611.4	North Branch Shamokin Cr nr Mount Carmel (SC3D)	Yes	Yes
LC4	8-10	01554452	404651	762652.6	Locust Creek at Locust Gap (LC4)	Dry	Yes
EX5	13,14	01554456	404620.6	762946.6	Unnamed tributary to Shamokin Cr at Excelsior (EX5)	Dry	Yes
SC6	(SC3D,SC2,LC4,EX5),11,12,15	01554460	404700.6	763120	Shamokin Creek at Ranshaw (SC6)	Yes	Yes
QR7	None	01554462	404713	763000	Quaker Run nr Kulpmont (QR7)	Yes	No
QR8	(QR7),16-21	01554465	404701.4	763120.6	Quaker Run at Ranshaw (QR8)	Yes	Yes
BM9	23-28	01554469	404636.1	763223.3	Big Mountain Mine (Buck Run), nr Shamokin (BM9)	Yes	Yes
SC10	(SC6,QR8,BM9),22A-B,29,30	01554471	404729.7	763311.4	Shamokin Creek at Shamokin (SC10)	Yes	No
COR11	31-35,36A-B,57	01554478	404729.8	763311.4	Coal Run at Shamokin (COR11)	Yes	No
SC11	(SC10,COR11)	01554479	404721.4	763346.3	Shamokin Creek ab Carbon Run at Shamokin (SC11)	No	Yes
TR41	37-41	01554481	404622.7	763646.4	Unnamed tributary to Carbon Run nr Shamokin (TR41)	No	Yes
CR1	None	01554482	404614.7	763732.2	Carbon Run nr Trevorton (CR1)	Dry	Yes
CR2	None	01554483	404620	763643	Carbon Run ab unnamed tributary nr Shamokin (CR2)	No	Yes
BU Pond ^d	42	01554484	404619.3	763641.2	Unnamed pond along Carbon Run nr Shamokin	Yes	No
CR4	(CR2, TR41), 42-44	01554486	404625.5	763527.8	Carbon Run nr Shamokin (CR4)	No	No
CR5	(CR4),45-48	01554488	404637.7	763408.2	Carbon Run at Shamokin (CR5)	No	No
CR12	(CR5),49	01554489	404721.4	763346.4	Carbon Run at Shamokin (CR12)	Yes	Yes
FR13	None	01554490	404721.4	763346.5	Furnace Run at Shamokin (FR13)	Yes	No
SC14	(SC ab CR, CR12, FR13), 50-54	01554492	404808	763403	Shamokin Creek at Uniontown (SC14)	Yes	No
SC15	(SC14)	01554500	404837	763504	Shamokin Creek nr Shamokin (SC15)	No	Yes
SC16	(SC15)	01554578	405145	764636	Shamokin Creek nr Sunbury (SC16)	Yes	Yes

a. Shamokin Creek Restoration Alliance (SCRA) site numbers based on Scarlift report of Gannett Fleming Corddry and Carpenter, Inc. (1972) .
 b. AMD sources identified by SCRA site numbers in table 1. If the site is downstream from another stream monitoring site, the AMD associated with that site, in parentheses, also applies.
 c. Water-quality and flow data collected for low base-flow conditions on August 4-6, 1999, and (or) high base-flow conditions on March 14-16, 2000. Aquatic ecological survey conducted during normal base-flow conditions October 6, 1999.
 d. Treated effluent from vertical-flow compost wetland system at SR42 is discharged to BU Pond.

high base-flow samples also were analyzed for total recoverable metals. The streamwater samples were analyzed for the same suite of constituents as the AMD samples plus inorganic nitrogen (ammonia, nitrate, and nitrite) and phosphorus. Charge imbalances were calculated as the difference between cation and anion equivalents relative to the mean of cation and anion equivalents, and routinely were less than 10 percent. Duplicates and USGS Standard Reference Water Samples that were submitted with each set of samples indicated overall precision and accuracy within 5 percent for all constituents. Deionized water blanks and filter blanks routinely indicated concentrations below detection for all analytes.

Selected low base-flow samples were analyzed simultaneously for total coliform and *Escherichia coli* bacteria using standard membrane-filtration techniques and the m-ColiBlue24 Broth nutritive medium (Hach Company, 1999). Commercially sterilized and individually wrapped 0.45- μm gridded filters, media, and petri dishes were used. Samples were collected using glass bottles and stainless-steel filtration apparatus that had been sterilized by autoclaving. A 100-ml sample was vacuum filtered, and the filter immediately was placed on the nutritive media in a disposable petri dish, covered, inverted, and stored at 4°C for up to 5 hours. After collection, the inverted samples were incubated at 35°C for 24 hours in a portable incubator. Red colonies were counted as total coliform and blue colonies were counted as *E. coli*.

Fish were collected by electrofishing over a 500-ft (150-m) reach consisting of mixed riffle, run, and pool habitats at selected stream sites, held for measurement and identification, checked for anomalies, and then released in accordance with methods described by Meador and others (1993a, 1993b), U.S. Environmental Protection Agency (1993), and Bilger and others (1999). In 1999, selected large specimens (>25-cm) of white sucker (*Catostomus commersoni*) from the reach below the USGS streamflow-gaging station on Shamokin Creek below Shamokin were sacrificed for analysis of trace metals in whole fish. Six specimens were frozen for transport to the laboratory in accordance with preparation protocols (Hoffman, 1996). The whole-fish samples were homogenized to form a single composite, and a subsample was dried and acid-extracted for analysis of trace metals by ICP-AES, inductively coupled plasma-mass spectrometry, or cold vapor-atomic absorption spectrophotometry at the USGS NWQL in Denver, Colo. (Hoffman, 1996).

The data assembled for the assessment were incorporated into digital databases, including the USGS NWIS, spreadsheets, and a GIS. These data are summarized by site in appendix B. The water-quality data also are accessible on the World Wide Web as an organized project on Pennsylvania Spatial Data

Access (PASDA; <http://www.pasda.psu.edu/access/sham-crk.shtml>) or for selected stations and dates on the USGS NWIS (<http://www.pah2o.er.usgs.gov/>).

Relative ranks of AMD sites were determined and compared on the basis of ranks of contaminant loads during low and high base-flow conditions. Because acidity of AMD is largely a function of the pH and dissolved metal concentrations, prioritization methods evaluated acidity or metals loading for ranking the AMD sources using an approach similar to that of Williams and others (1996, 1999). The metals loading was computed as the product of flow rate and the sum of concentrations of the metals as

$$\text{Metal load (Mg/yr)} = fQ(C_{\text{Fe}} + C_{\text{Mn}} + C_{\text{Al}}), \quad (6)$$

where Q is the instantaneous flow rate in cubic feet per second and C with a subscript Fe, Mn, or Al indicates iron, manganese, or aluminum concentration, respectively, in milligrams per liter. For these units of measure, the conversion factor, $f = 0.894$, yields annual loading in kilograms, whereas $f = 1.97$ yields annual loading in pounds.

Although acidity was measured on refrigerated, tightly sealed samples by hot peroxide titration for the high base-flow samples (Greenberg and others, 1992) and by cold peroxide titration for the low base-flow samples (Fishman and Friedman, 1989), the interpretation of these measured acidities for AMD can be debated (Kirby, 2002). Therefore, acidity for all the samples was computed from pH and dissolved metals concentrations in milligrams per liter as

$$\text{Acidity}_{\text{computed}} \text{ (mg/L CaCO}_3\text{)} = 50 \cdot (10^{(3-\text{pH})}) + 2C_{\text{Fe}}/55.85 + 2 \cdot C_{\text{Mn}}/54.94 + 3 \cdot C_{\text{Al}}/26.98. \quad (7)$$

The computed acidity avoids issues of different analytical methods, the lack of reporting negative values, or an assumed value of zero for near-neutral pH samples. However, it also involves assumptions regarding valence or speciation of the dissolved metals.² The net alkalinity was computed by subtracting the computed acidity from measured alkalinity as

$$\text{Net alkalinity (mg/L CaCO}_3\text{)} = \text{Alkalinity} - \text{Acidity}_{\text{computed}}. \quad (8)$$

The net alkalinity on the basis of computed acidity (equations 7 and 8) should be similar to the measured "hot" acidity where acid added at the start of the titration is subtracted from the total base consumed and negative values of the acidity for high-pH samples are reported.

The physical setting (area available for treatment, slope), maximum measured flow, and specific water-quality data for

²Equivalents as H^+ (OH^- neutralizing capacity) of 2 per mole of Fe and Mn and 3 per mole of Al were assumed considering the potential for the dissolved metals to hydrolyze over a pH range from 2.5 to 8.0, on the basis of hydrolysis constants, pK_1 and pK_2 , at 25°C from Ball and Nordstrom (1991). Uncomplexed ferrous (Fe^{2+}) and manganous (Mn^{2+}) ions have 2 equivalents per mole and tend to be dominant species in AMD with $\text{pH} < 9$ ($\text{pK}_1 = 9.5$, $\text{Fe}^{2+} \rightarrow \text{Fe}(\text{OH})^+$; $\text{pK}_1 = 10.6$, $\text{Mn}^{2+} \rightarrow \text{Mn}(\text{OH})^+$). At $\text{pH} > 2.2$, dissolved ferric iron has less than 3 equivalents per mole because of the tendency for Fe^{3+} to form hydroxyl complexes ($\text{pK}_1 = 2.2$, $\text{Fe}^{3+} \rightarrow \text{Fe}(\text{OH})^{2+}$; $\text{pK}_2 = 3.5$, $\text{Fe}(\text{OH})^{2+} \rightarrow \text{Fe}(\text{OH})_2^+$). At $\text{pH} < 5$, uncomplexed aluminum (Al^{3+}) ions, with 3 equivalents per mole, are prevalent ($\text{pK}_1 = 5.0$, $\text{Al}^{3+} \rightarrow \text{Al}(\text{OH})^{2+}$; $\text{pK}_2 = 5.2$, $\text{Al}(\text{OH})^{2+} \rightarrow \text{Al}(\text{OH})_2^+$).

each AMD source including minimum net alkalinity (equation 8) and maximum concentrations of dissolved oxygen and metals for the low and high base-flow samples were used to determine feasibility of remediation. Guidelines similar to those introduced by Hedin and others (1994) and modified by Skousen and others (1998) were used for the identification of appropriate remedial alternatives (fig. 3). Consideration was given to remaining or removal of culm banks, various passive-treatment technologies, active treatment, and the “no-action” alternative. Computed wetland size, based on the 180 lb/acre/day (20 g/m²/d) iron-loading rate criteria of Hedin and others (1994), was compared with available land area to indicate feasibility for implementation of passive treatment at each site.

Effects of Abandoned Mine Drainage in the Shamokin Creek Basin

Data for flow rate, pH, acidity, alkalinity, and metals concentrations in samples from each AMD and stream site surveyed for the Shamokin Creek watershed assessment during low base-flow conditions in August 1999 and high base-flow conditions in March 2000 are summarized in table 3 and figure 4. All data on the concentrations of major ions, nutrients, and additional constituents are documented in appendix B.

Instantaneous streamflow ranged from 0 to 301 ft³/s (0 to 511,459 L/min); the medians for the low and high base-flow surveys were 2.7 and 7.4 ft³/s (4,587 to 12,574 L/min), respectively (table 3, fig. 4). Corresponding flow rates of AMD ranged from 0 to 19 ft³/s (0 to 32,285 L/min); the medians for the low and high base-flow surveys were 0.01 and 0.18 ft³/s (17 to 306 L/min), respectively. With few exceptions, the flow rate at each stream and AMD site during March 2000 exceeded that during August 1999 (fig. 4). Despite differences in flow rates, the pH and other chemical characteristics of water at a given AMD or stream site generally were similar for low and high base-flow conditions (table 3, fig. 4). Furthermore, the concentrations of “dissolved” metals in 0.45- μ m-filtered high base-flow samples were similar to the concentrations of “total recoverable” metals in corresponding unfiltered samples (fig. 5).

Sulfate concentrations in the low and high base-flow AMD samples ranged from 8 to 800 mg/L (fig. 4). Sulfate concentrations in streamwater samples did not exceed 630 mg/L. The maximum concentration of sulfate in AMD or streamwater samples was recorded for high base-flow conditions. Median concentrations of sulfate for AMD or streamwater samples for low and high base-flow conditions were equivalent. Generally, sulfate concentrations for a particular site were similar or greater during high base-flow than low base-flow conditions (fig. 4). Greater sulfate concentration at high base-flow than at low base-flow conditions indicates that recharge during the winter 1999 and spring 2000 was effective mobilizing pyrite oxidation products and was not effective as a diluting agent.

Iron concentrations in the low and high base-flow AMD samples ranged from 0.02 to 57.4 mg/L, and in streamwater

samples ranged from 0.07 to 22.0 mg/L (fig. 4, table 3). Generally, iron concentrations for a particular site were similar or greater during high base-flow than low base-flow conditions. For samples containing more than 1.0 mg/L (1,000 μ g/L) dissolved iron, the concentrations of dissolved and total iron were equivalent (fig. 5). More than two-thirds of streamwater samples exceeded the Commonwealth of Pennsylvania (2002) instream criteria for total recoverable iron (1.5 mg/L) and dissolved iron (0.3 mg/L). Most streamwater samples also exceeded continuous exposure criteria for protection of aquatic life from dissolved iron (1 mg/L) (U.S. Environmental Protection Agency, 2002a). Approximately half the AMD samples exceeded the Commonwealth of Pennsylvania (1998a, 1998b) criteria for maximum concentration of iron in effluent from an active mine (6 mg/L).

Manganese concentrations in the low and high base-flow AMD samples ranged from <0.01 to 10 mg/L, and in streamwater samples ranged from 0.05 to 7.6 mg/L (fig. 4, table 3). Generally, manganese was present as a dissolved constituent in the streamwater and AMD samples (dissolved = total), and concentrations for a particular site were similar during high base-flow and low base-flow conditions. More than two-thirds of the streamwater samples exceeded the Commonwealth of Pennsylvania (2002) instream criteria for total recoverable manganese (1.0 mg/L) (fig. 5). About one-fifth of the AMD samples exceeded the Commonwealth of Pennsylvania (1998a, 1998b) criteria for maximum concentration of manganese in effluent from an active mine (4.0 mg/L).

Aluminum concentrations in the low and high base-flow AMD samples ranged from <0.01 to 57 mg/L, and in streamwater samples ranged from 0.01 to 7.0 mg/L (fig. 4, table 3). Generally, aluminum concentrations for a particular site were similar during high base-flow and low base-flow conditions. Maximum and highest median concentrations were associated with AMD at low base-flow conditions. For samples containing more than 1.0 mg/L (1,000 μ g/L) dissolved aluminum, the concentrations of dissolved and total aluminum were equivalent (fig. 5). More than three-fourths of the streamwater samples and three-fourths of the AMD samples exceeded the Commonwealth of Pennsylvania (2002) instream criteria for total recoverable aluminum (0.75 mg/L). Most streamwater samples also exceeded continuous exposure criteria for protection of aquatic life from dissolved aluminum (0.087 mg/L) (U.S. Environmental Protection Agency, 2002a).

Although criteria for water-quality protection apply to the total metals concentrations (Commonwealth of Pennsylvania, 1998a, 1998b, 2001a, 2002), the dissolved concentrations generally are considered to be bioavailable (Elder, 1988; U.S. Environmental Protection Agency, 2002a). Thus, the “dissolved concentration” data for the 0.45- μ m filtered samples can be evaluated directly with respect to aquatic-toxicity criteria. Furthermore, the dissolved metals loading is required for the selection and sizing of AMD treatment systems (fig. 3) and, as indicated by equations 7 and 8, the dissolved metals concentrations are included in the measurement and evaluation of acidity and net alkalinity. Thus, hereinafter, dissolved metals concentra-

Table 3. Values of selected constituents for streamwater and abandoned mine drainage samples collected for the Shamokin Creek watershed assessment, Pennsylvania, August 4-6, 1999, and March 14-16, 2000
 [ID, identification number; 0, not flowing or dry; n.d., no data; <, less than; ft³/s, cubic feet per second; L/min, liters per minute; mg/L, milligrams per liter; Mg/yr, megagrams per year]

SCRA Site ID ^a	Flow rate (ft ³ /s) ^b	Flow rate (L/min)	Oxygen (mg/L)	pH (standard units)	Net alkalinity ^c (mg/L CaCO ₃)	Iron (mg/L Fe)	Aluminum (mg/L Al)	Manganese (mg/L Mn)	Sulfate (mg/L SO ₄)	Nitrogen ^d (mg/L N)	Fe, Al, and Mn load ^e (Mg/yr)													
												Aug99	Mar00											
Streamwater (SW)																								
SC2	0	0.54	0	918	n.d.	5.8	n.d.	6.6	n.d.	25	n.d.	0.89	n.d.	<0.20	n.d.	0.26	n.d.	45	n.d.	n.d.	1.2	0	0.62	
SC3B	n.d.	7.4	n.d.	12,574	n.d.	8.6	n.d.	3.9	n.d.	-41	n.d.	6.6	n.d.	3.4	n.d.	2.1	n.d.	190	n.d.	n.d.	.12	n.d.	96.1	
SC3D	2.2	14	3,738	23,789	8.9	9.6	3.2	5.2	-64	-30	2.7	11.	4.2	1.5	2.4	2.4	160	190	190	.08	.17	18.3	199.	
LC4	0	1.8	0	3,059	n.d.	11.3	n.d.	3.9	n.d.	-30	n.d.	.43	n.d.	3.8	n.d.	.88	n.d.	120	n.d.	n.d.	.47	0	7.91	
EX5	0	1.9	0	3,228	n.d.	10.9	n.d.	4.9	n.d.	-1	n.d.	.11	n.d.	.27	n.d.	.17	n.d.	12	n.d.	n.d.	.10	0	4.04	
SC6	12	34	20,390	57,773	9.9	9.9	6.3	6.1	-28	-32	16.	16.	.02	<20	2.9	2.5	220	190	190	.96	.95	203.	593.	
QR7	2	n.d.	3,398	n.d.	9.8	n.d.	6.2	n.d.	-45	n.d.	22.	n.d.	.02	n.d.	3.6	n.d.	260	n.d.	n.d.	.63	n.d.	45.8	n.d.	
QR8	7.5	22	12,744	37,382	10.0	9.1	6.3	6.5	-25	-17	17.	19.	.07	<20	3.4	3.3	250	250	250	.88	.93	137.	484.	
BM9	.93	4.1	1,580	6,967	9.3	9.7	3.3	3.7	-101	-99	13.	21.	7.0	6.8	7.6	7.2	480	630	630	.18	.28	22.9	119.	
SC10	19	59	32,285	100,253	9.3	9.5	6.5	6.3	-19	-28	8.2	15.	.03	<20	3.4	2.9	250	230	230	.86	.89	198.	986.	
COR11	.1	1.5	170	2,549	7.1	8.2	6.5	6.4	72	51	.92	2.9	.01	<20	1.5	1.3	170	140	140	1.4	1.9	.22	8.12	
SC11	n.d.	64	n.d.	108,749	n.d.	9.1	n.d.	6.4	n.d.	-27	n.d.	15.	n.d.	<20	n.d.	3.1	n.d.	240	n.d.	n.d.	.98	n.d.	1,161.	
TR41	n.d.	.92	n.d.	1,563	n.d.	11.8	n.d.	5.8	n.d.	5	n.d.	.14	n.d.	<20	n.d.	.07	n.d.	52	n.d.	n.d.	n.d.	n.d.	.69	
CR1	0	.24	0	408	n.d.	11.8	n.d.	4.3	n.d.	-6	n.d.	.10	n.d.	.57	n.d.	.62	n.d.	36	n.d.	n.d.	.21	0	.17	
CR12	3.2	18	5,437	30,586	9.5	9.7	6.5	6.6	-9	-7	11.	15.	.01	1.4	3.9	2.5	350	280	280	.96	.85	42.7	320.	
FR13	.1	.8	170	1,359	8.9	10.2	7.0	6.9	64	23	.07	.09	.01	<20	.08	.05	24	20	20	1.2	2.0	.01	.28	
SC14	30	85	50,976	144,432	9.6	9.4	5.9	6.2	-34	-30	15.	19.	.05	<20	3.8	3.1	310	290	290	1.0	1.0	505.	1,702.	
SC15	n.d.	84	n.d.	142,733	n.d.	9.1	n.d.	6.3	n.d.	-25	n.d.	14.	n.d.	<20	n.d.	2.7	n.d.	260	n.d.	n.d.	1.1	n.d.	1,532.	
SC16	34	301	57,773	511,459	8.9	9.9	4.0	6.5	-15	6	.23	1.3	.67	<20	3.3	.54	280	63	63	1.8	3.1	128.	683.	
Abandoned Mine Drainage (GW)																								
1	0.01	0.2	17	340	10.0	9.4	3.0	3.3	-384	-111	6.5	2.1	57.	14.	2.9	1.1	540	220	220	0.52	0.43	0.59	3.27	
2	.04	.1	68	170	8.0	7.1	3.1	2.9	-198	-265	2.9	4.0	26.	33.	4.7	5.4	390	710	710	.15	n.d.	1.2	3.39	
3	.01	.08	10	136	.4	.2	3.5	3.2	-206	-275	15.	20.	28.	36.	4.4	5.1	490	760	760	n.d.	n.d.	.25	4.28	
4	.5	1.3	850	2,209	8.4	9.1	3.6	3.5	-41	-52	1.1	3.7	4.3	4.6	1.8	1.9	99	150	150	n.d.	n.d.	3.22	11.5	
5A	0	1.4	0	2,379	n.d.	.5	n.d.	3.8	n.d.	-51	n.d.	10.	n.d.	3.9	n.d.	2.2	n.d.	160	160	160	.12	0	24.7	
5B	2.7	5	4,588	8,496	.4	.7	4.0	3.8	-54	-51	12.	9.9	4.3	3.9	2.2	2.2	140	160	160	n.d.	n.d.	44.6	85.2	
6	n.d.	.02	n.d.	34	n.d.	5.2	n.d.	4.7	n.d.	-6	n.d.	.97	n.d.	.42	n.d.	1.6	n.d.	16	16	16	n.d.	n.d.	n.d.	.03
8	0	.68	0	1,155	5.9	11.5	3.3	3.4	-120	-52	1.6	.25	15.	5.3	5.0	1.3	360	160	160	n.d.	n.d.	0	3.63	
10	.01	.04	9	68	5.1	11.2	2.6	2.6	-373	-305	14.	16.	38.	26.	6.0	3.6	690	630	630	n.d.	n.d.	.26	1.59	
11	0	.25	0	425	n.d.	12.6	n.d.	3.5	n.d.	-115	n.d.	.25	n.d.	17.1	n.d.	2.2	n.d.	370	n.d.	n.d.	n.d.	0	3.92	
12	7.2	14	12,234	23,789	4.1	6.5	5.8	5.7	-8	-31	28.	30.	.06	<20	2.9	3.2	230	240	240	n.d.	.40	199.	464.	
13	n.d.	.02	n.d.	34	n.d.	3.0	n.d.	4.7	n.d.	-2	n.d.	.20	n.d.	.35	n.d.	.36	n.d.	25	n.d.	n.d.	n.d.	n.d.	.01	
15	.92	2.5	1,563	4,248	2.3	4.8	4.2	4.4	-123	-138	35.	46.	8.6	8.3	5.0	4.8	380	510	510	n.d.	n.d.	40.	130.	
19	9.4	19	15,972	32,285	1.9	1.4	5.9	5.8	-20	-20	24.	30.	.09	<20	3.5	3.7	230	270	270	n.d.	n.d.	232.	520.	
20	1.9	1.6	3,228	2,719	.3	7.9	6.0	6.0	-18	-23	26.	30.	.05	<20	3.7	3.7	260	270	270	n.d.	n.d.	50.5	50.3	
21	.56	4.3	952	7,307	4.1	5.6	6.1	6.4	45	69	18.	23.	.01	<20	2.6	2.8	230	240	240	n.d.	n.d.	10.3	88.8	
22A	.01	.22	17	374	.8	.6	5.8	5.8	-4	16	16.	13.	.04	<20	2.5	2.4	260	240	240	.15	n.d.	.17	2.73	
22B	.01	.9	9	1,529	2.3	2.8	5.8	5.9	4	13	14.	11.	.01	<20	2.3	2.2	240	230	230	.28	n.d.	.07	9.89	
23	.51	3.6	867	6,117	4.0	.1	3.7	4.1	-112	-106	25.	28.	7.8	7.0	7.4	7.1	470	630	630	n.d.	n.d.	18.3	134.	
28	.01	.14	17	238	6.5	5.2	3.4	3.4	-72	-67	.27	.13	6.9	6.2	7.1	6.9	440	560	560	n.d.	n.d.	.13	.8	
29	.5	.26	850	442	1.1	.7	5.4	5.5	-10	-11	9.5	11.	.07	<20	2.4	2.7	190	200	200	.20	n.d.	5.35	3.76	
30	.01	.01	9	17	7.0	9.8	3.6	3.6	-28	-53	1.5	4.0	1.2	4.9	3.6	3.7	450	460	460	.15	n.d.	.03	.11	
31-32	.01	.04	17	68	7.7	7.9	3.4	3.5	-48	-77	.08	.18	4.5	10.	1.4	1.7	160	270	270	n.d.	n.d.	.05	.4	
36A	0	0	0	0	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0	0	
36B	.01	.02	9	34	1.6	2.4	5.4	4.4	-26	-8	13.	.04	.04	.69	1.1	1.1	170	200	200	.95	n.d.	.06	.02	
37	0	.01	0	17	n.d.	6.6	n.d.	5.1	n.d.	-5	n.d.	.32	n.d.	.48	n.d.	1.2	n.d.	83	83	83	n.d.	n.d.	0	.01
38A	.04	.03	68	51	6.4	8.0	6.5	6.7	18	21	.02	.08	.01	<20	<.01	.01	32	34	34	n.d.	n.d.	0	.01	
39	.01	.07	9	119	4.9	4.8	6.2	6.0	18	6	.05	10.	.01	<20	.08	3.3	66	100	100	n.d.	n.d.	0	.74	
40B	0	.04	0	68	n.d.	5.8	n.d.	5.8	n.d.	6	n.d.	.19	n.d.	<20	n.d.	.25	n.d.	68	68	68	n.d.	n.d.	0	.04
40C	.01	.08	17	136	40.0	5.9	6.2	6.0	15	6	.24	.10	<.01	<20	.54	.16	73	68	68	n.d.	n.d.	.01	.03	
41	0	.01	0	17	n.d.	4.4	n.d.	5.9	n.d.	1	n.d.	3.7	n.d.	<20	n.d.	1.2	n.d.	30	30	30	n.d.	n.d.	0	.05
42	.4	1.1	680	1,869	1.4	4.4	5.2	5.9	-8	-14	6.7	14.	.01	<20	1.9	1.8	160	150	150	n.d.	n.d.	3.08	15.6	
43	0	.04	0	68	n.d.	9.0	n.d.	4.2	n.d.	-17	n.d.	.14	n.d.	1.61	n.d.	2.8	n.d.	220	n.d.	n.d.	n.d.	0	.07	
44	n.d.	.02	n.d.	34	n.d.	8.4	n.d.	5.8	n.d.	4	n.d.	1.5	n.d.	<20	n.d.	.22	n.d.	8	8	8	n.d.	n.d.	n.d.	.04
45	0	.01	0	17	n.d.	8.9	n.d.	4.6	n.d.	-4	n.d.	.12	n.d.	.62	n.d.	.83	n.d.	110	110	110	n.d.	n.d.	0	.01
46	.01	.2	9	340	.6	7.2	3.3	3.8	-50	-58	.21	.10	3.7	8.0	2.0	3.1	180	320	320	n.d.	n.d.	.03	1.47	
47	0	.03	0	51	n.d.	5.2	n.d.	3.2	n.d.	-117	n.d.	.68	n.d.	14.	n.d.	2.8	n.d.	n.d.	n.d.	n.d.	n.d.	0	.4	
48	.02	.2	34	340	6.0	.2	6.4	6.4	44	62	.82	11.	.											

14 Effects of Abandoned Coal-Mine Drainage on Streamflow and Water Quality in the Shamokin Creek Basin

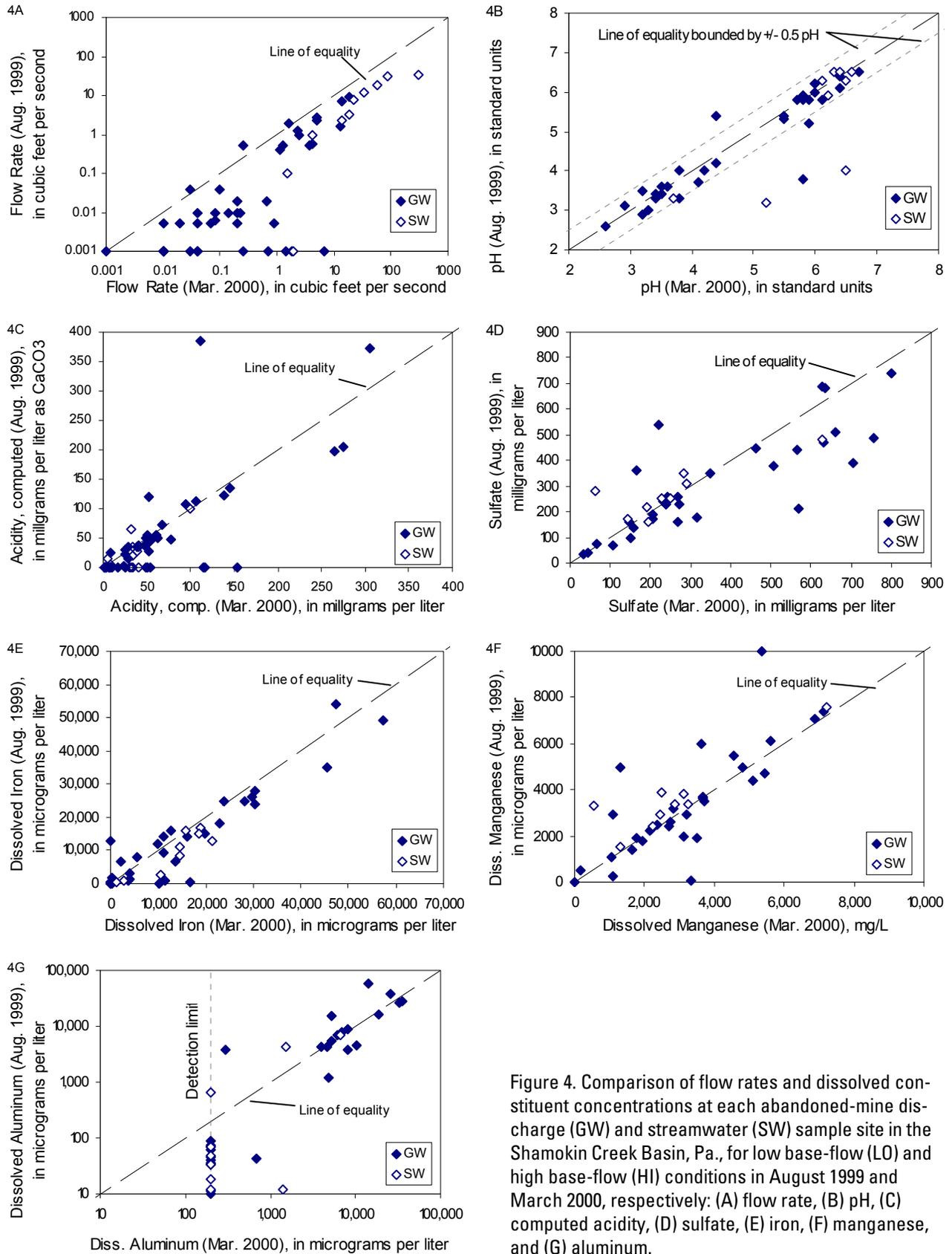


Figure 4. Comparison of flow rates and dissolved constituent concentrations at each abandoned-mine discharge (GW) and streamwater (SW) sample site in the Shamokin Creek Basin, Pa., for low base-flow (LO) and high base-flow (HI) conditions in August 1999 and March 2000, respectively: (A) flow rate, (B) pH, (C) computed acidity, (D) sulfate, (E) iron, (F) manganese, and (G) aluminum.

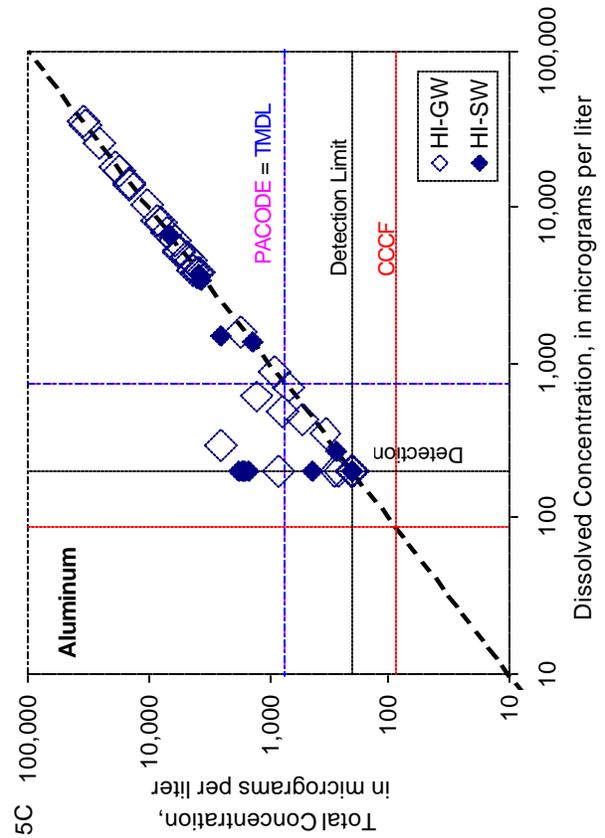
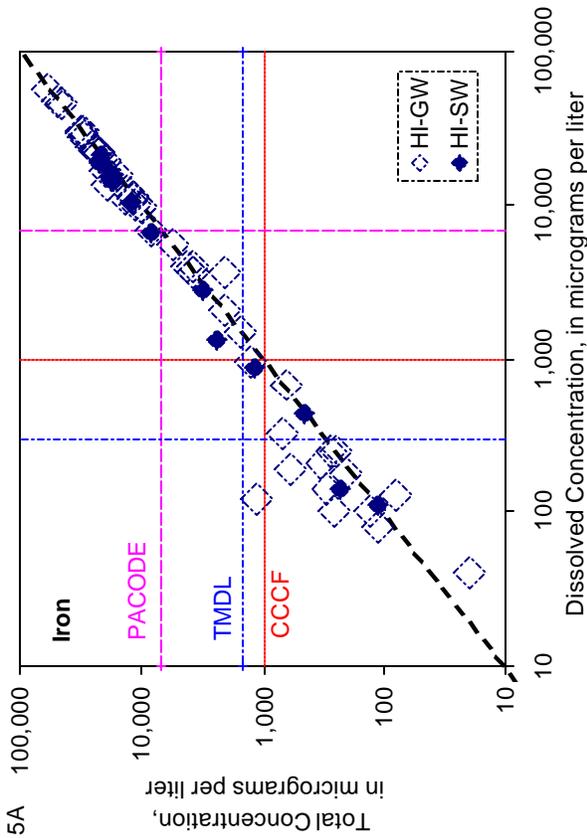
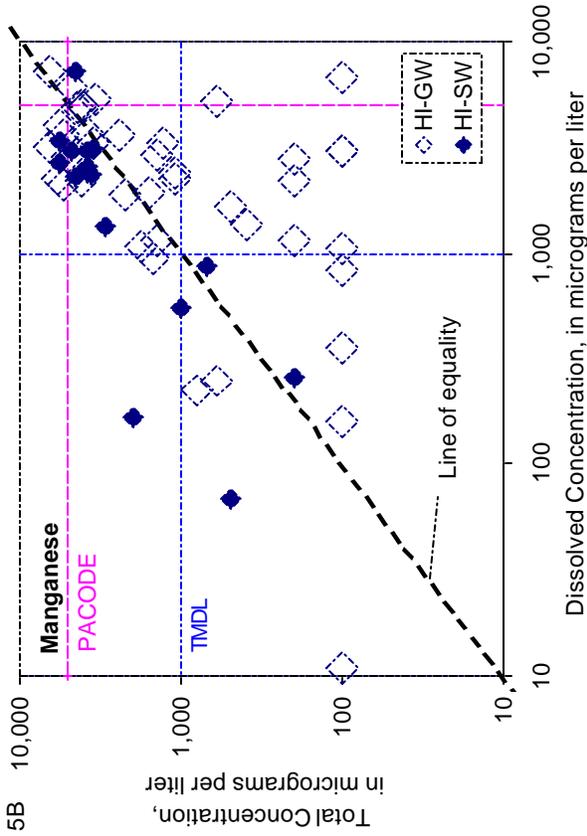


Figure 5. Comparison of total and dissolved concentrations of (A) iron, (B) manganese, and (C) aluminum in high base-flow abandoned-mine discharge (HI-GW) and streamwater (HI-SW) samples collected in Shamokin Creek Basin, Pa., March 2000. PACODE indicates effluent limitation for active surface or underground coal mine in Pennsylvania (Commonwealth of Pennsylvania, 2000, 2001a); TMDL indicates total maximum daily load stream-quality criteria (Commonwealth of Pennsylvania, 1998a, b); and CCCF indicates continuous contaminant concentration exposure tolerated by freshwater aquatic organisms without unacceptable effect (U.S. Environmental Protection Agency, 2002a).

tions and corresponding computed values for metals loading, acidity, and net alkalinity will be emphasized.

Computed acidity (equation 7) of AMD ranged from 0 to 384 mg/L. Median acidities for low and high base-flow conditions were equivalent for AMD samples and for streamwater samples. With few exceptions, acidity at a particular site was similar during low and high base-flow conditions. In contrast, the highest alkalinity concentration for the AMD or streamwater samples was less than 75 mg/L (fig. 6).

Plots of measured “hot” acidity relative to computed acidity, net alkalinity, and pH indicate (a) the pH and dissolved metals concentrations adequately explain the acidity and (b) the pH has a bimodal frequency distribution for the water-quality data as a whole as described by Cravotta and others (1999) (fig. 6). Approximately half of the samples had near-neutral pH (>5.5), whereas the other half had acidic pH (<4.5). The minimum pH value of 2.6 for AMD was observed during both low and high base-flow conditions. Few AMD or streamwater samples for this survey had pH less than 3. The maximum pH value for AMD samples was 6.7 for high base-flow and 6.5 for low base-flow conditions. The minimum and maximum pH values for streamwater samples were greater than those for AMD samples, but consistent with the bimodal frequency distribution. Notably, two stream sites, North Branch Shamokin Creek (SC3D) and Shamokin Creek at Sunbury (SC15), and one AMD site, the Cameron Mine discharge (SR51), had acidic pH during low base-flow conditions but near-neutral pH during high base-flow conditions. The low pH at these sites for low base-flow conditions can be attributed to various possible factors, including the concentration of solutes by evaporation, increased rate of pyrite oxidation associated with increased air flow to the subsurface as the water table declined during drought, increased rate of Fe^{2+} oxidation associated with warmer temperature, and more complete oxidation and hydrolysis associated with longer transport or detention times at slower flow rates.

Acidity was measured in the laboratory on refrigerated, tightly sealed samples by hot peroxide titration for the high base-flow survey and by cold peroxide titration for the low base-flow survey. Assuming a charge of +3 on dissolved aluminum and +2 on dissolved iron and manganese per equation 7, computed acidity and corresponding values of net alkalinity generally agree well with the “hot” peroxide acidity measured for high base-flow samples (fig. 6). Most AMD sources consistently were acidic (alkalinity < acidity) or net alkaline (alkalinity > acidity) on the basis of samples collected during low and high base-flow conditions (figs. 4 and 6, appendix B). A majority of the samples that had pH >4.5 was “net acidic” because of the elevated concentrations of Fe^{2+} and Mn^{2+} . Many of the net acidic, high-pH samples had elevated concentrations of sulfate, indicating their origin as acidic AMD that had been neutralized. Although a majority of samples that had pH greater than 6 had positive net alkalinity, a few AMD and streamwater samples with high pH were net acidic. Generally, samples that had pH less than 5.6 were net acidic.

Note that some samples with field pH greater than 5.6 were reported to have “hot” acidity concentration of zero (acidity was

not measured); however, the actual acidity, if as computed, could be as much as 50 mg/L for one or more of these near-neutral samples (fig. 6). The negative value of computed net alkalinity is similar to the hot acidity for samples with pH less than 5.6. Larger values of cold acidity than computed acidity result from temporary acidity from CO_2 and H_2S that is included in the cold acidity measurement but that largely will be eliminated by aeration and exsolution of these dissolved gases under atmospheric conditions in the environment or by boiling during hot acidity titration.

In summary, a majority of base-flow streamwater samples during the study met Commonwealth of Pennsylvania (2001b, 2002) water-quality standards for pH (6.0 to 9.0); however, few met criteria for net alkalinity (20 mg/L as CaCO_3) and concentrations of dissolved iron (0.3 mg/L) and total manganese (1.0 mg/L) (figs. 4, 5, and 6). The characteristics at individual streamwater sites and specific source(s) of impairment are summarized in the next section.

Flow and Quality of Streams

The flow and quality of low and high base-flow samples for each of the primary stream monitoring locations are described below, in approximate downstream order, by the local site identification number and the corresponding TMDL site identification number (Pennsylvania Department of Environmental Protection, 2001a, 2001b), if applicable. The dominant upstream AMD sources and selected water-quality data are listed in tables 1, 2, and 3 and figure 7.

SC2 (*TMDL-SC1*) is on Shamokin Creek upstream of the confluence with North Branch Shamokin Creek and includes the Sayre-Sioux Mine discharge (SR6) and drainage from the borough of Mount Carmel. In August 1999, the sampled reach for SC2 was dry. However, in March 2000, water was flowing at 0.54 ft³/s (918 L/min) through the grass-and shrub-choked channel. The water had pH of 6.6, net alkalinity of 25 mg/L, and a relatively small load of dissolved metals (0.6 Mg/yr) (table 3; fig. 7). The concentration of dissolved nitrogen in Shamokin Creek at SC2 was 1.2 mg/L (table 3). These data indicate that the area sampled by SC2 is affected by losses of flow, but the water quality largely is unaffected by AMD.

SC3D (*TMDL-NB1*) is on North Branch Shamokin Creek 0.8 mi (1.3 km) upstream of its confluence with Shamokin Creek and includes discharges from the Mid Valley Mine (SR2; SR4; SR5A,B; SR56) and Richard’s Shaft (SR55). In August 1999, the sampled reach for SC3D was flowing at 2.2 ft³/s (3,738 L/min) with pH of 3.2, net alkalinity of -64 mg/L, and a relatively large metal load (18.3 Mg/yr) accentuated by elevated concentration of aluminum (4.2 mg/L) but relatively low concentration of iron (2.7 mg/L) (table 3). The entire streamflow and metals loading could have originated from the Mid Valley Mine tunnel discharge (SR5B); associated discharges had substantially lower flow rates and metals loading. The Richard’s Shaft Mine Drift near Atlas (SR55), immediately upstream from SC3D, was not flowing in August 1999. However, in

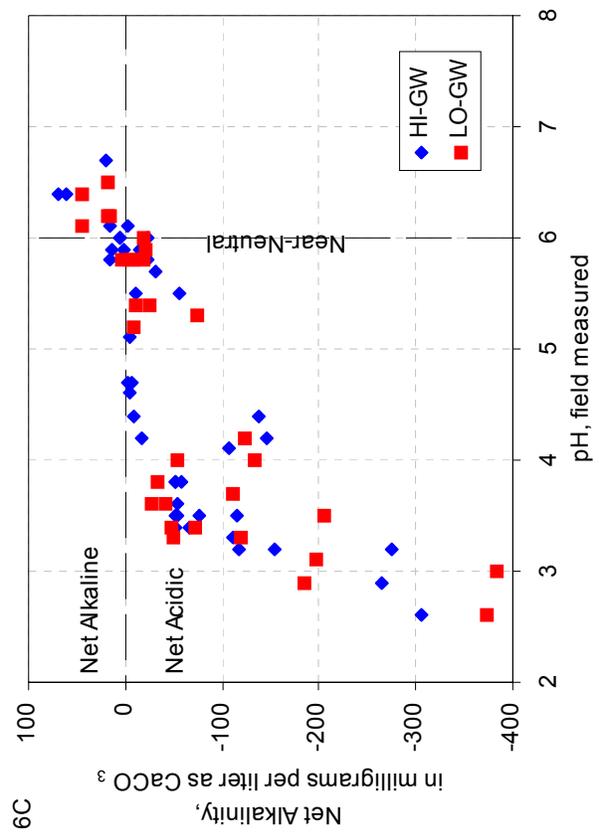
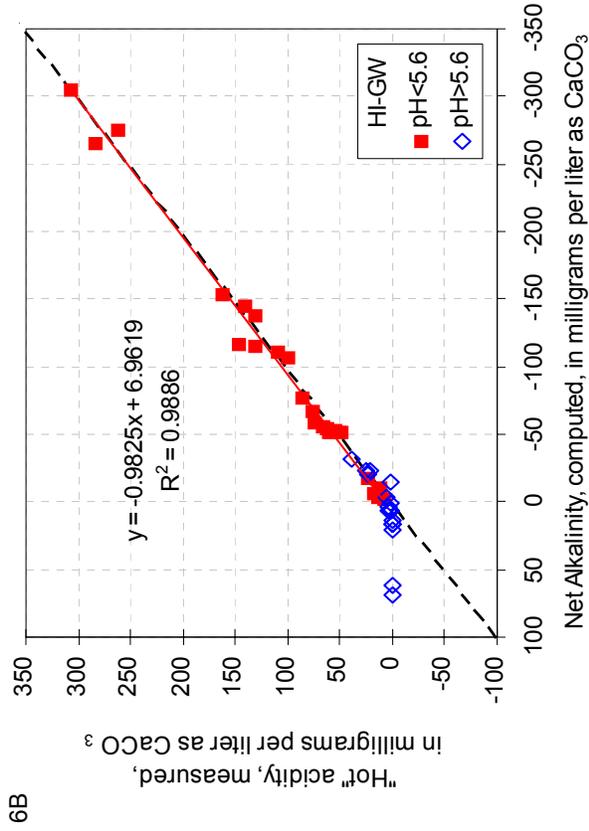
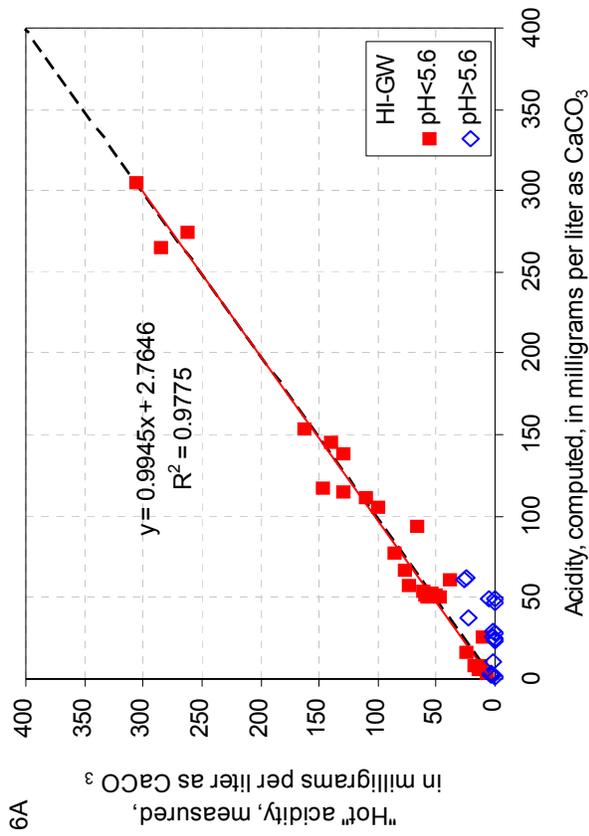


Figure 6. Comparison of (A) measured "hot, peroxide" acidity and computed acidity, (B) measured "hot, peroxide" acidity and computed net alkalinity, and (C) pH and computed net alkalinity on the basis of dissolved metals concentrations for high base-flow AMD (HI-GW) samples, March 2000, Shamokin Creek Basin, Pa. In 6C, data also are plotted for low base-flow AMD (LO-GW) samples, August 1999; reference lines at pH of 6 and net alkalinity of 0 are shown to distinguish net acidic and net alkaline or near-neutral samples.

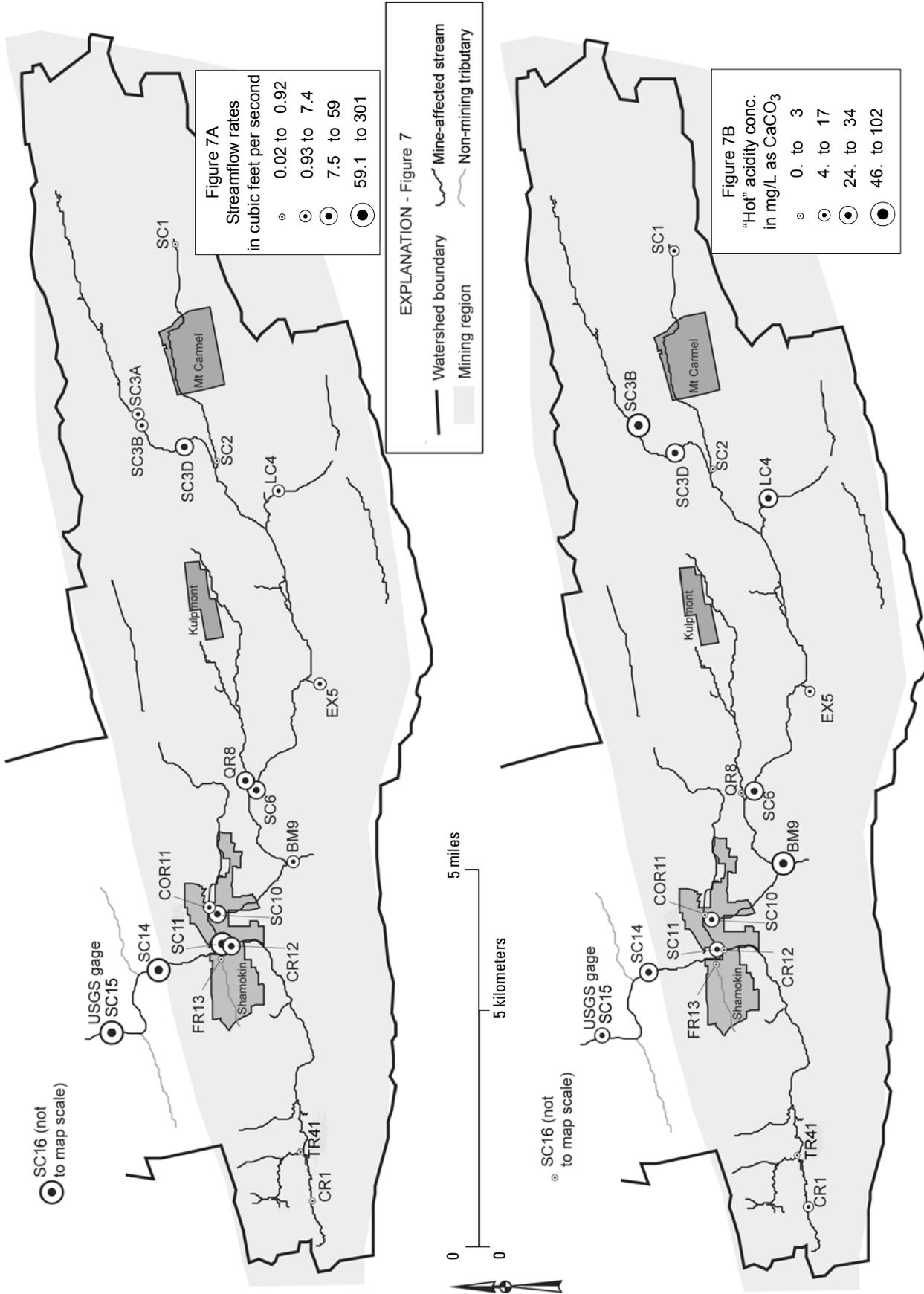


Figure 7. Maps of Shamokin Creek, Pa., showing: (A) streamflow in cubic feet per second, (B) acidity, (C) dissolved sulfate, (D) dissolved iron, (E) dissolved manganese, and (F) dissolved aluminum in the mainstem and tributaries March 2000.

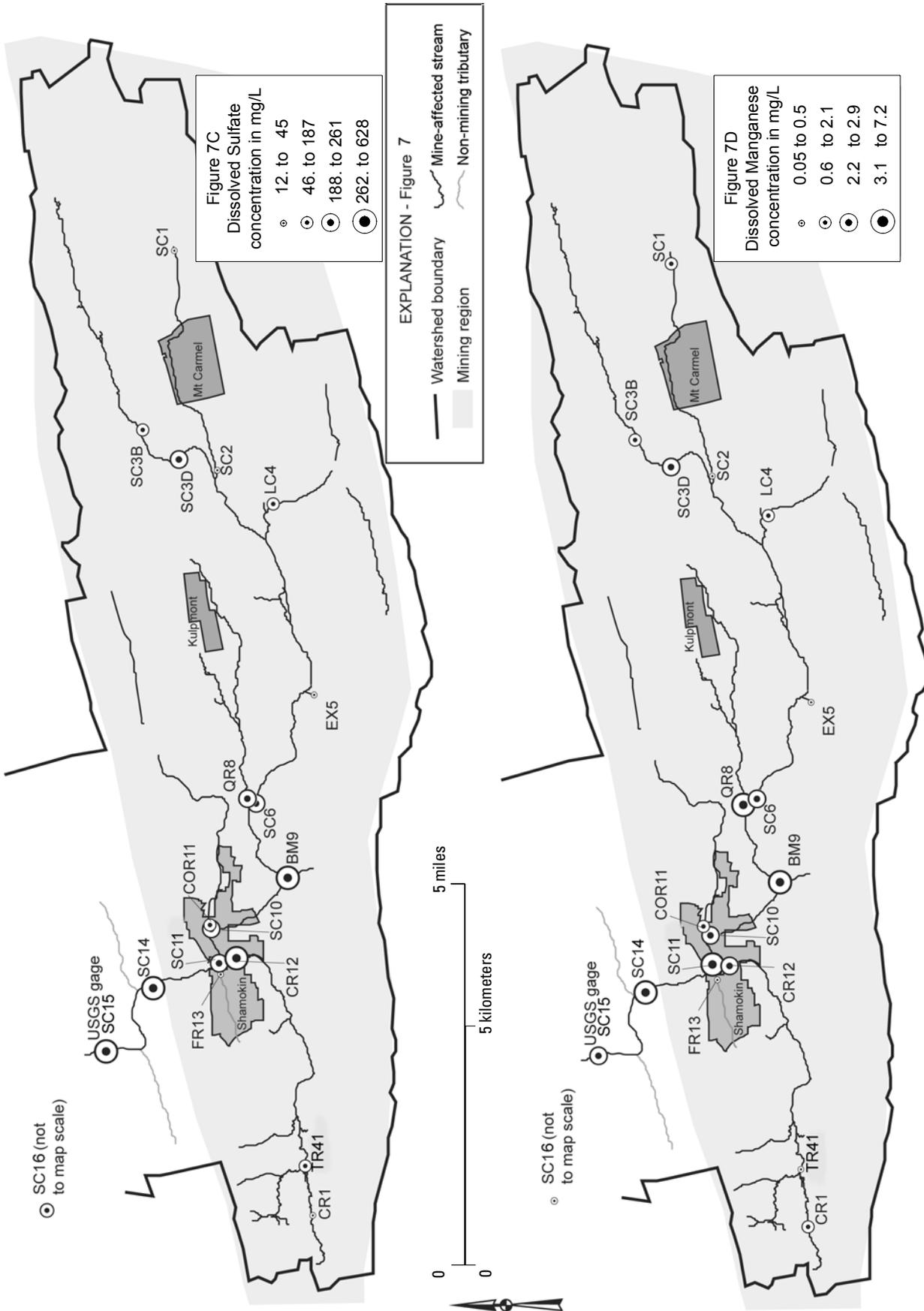


Figure 7. Maps of Shamokin Creek, Pa., showing: (A) streamflow in cubic feet per second, (B) acidity, (C) dissolved sulfate, (D) dissolved iron, (E) dissolved manganese, and (F) dissolved aluminum in the mainstem and tributaries March 2000 (continued).

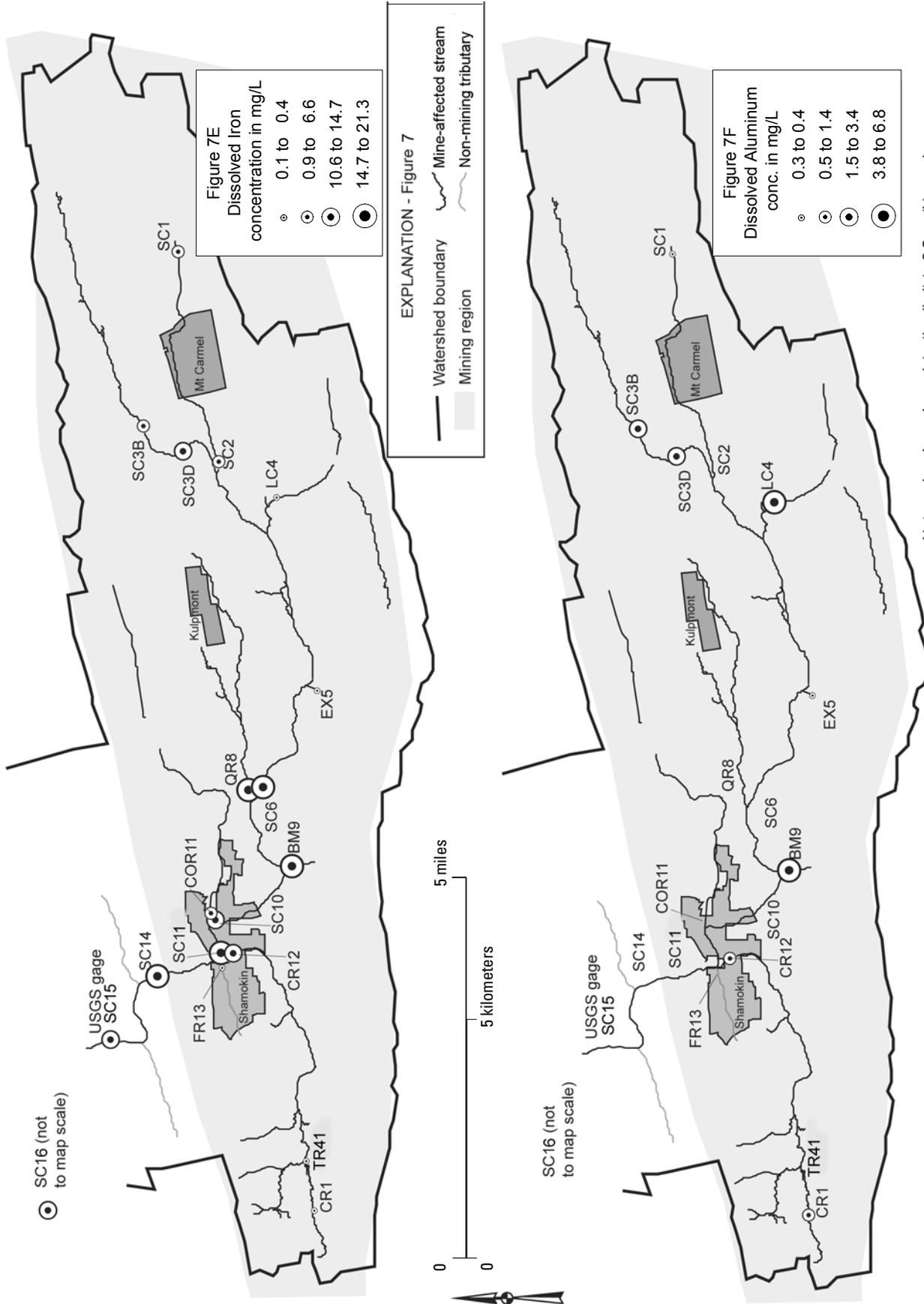


Figure 7. Maps of Shamokin Creek, Pa., showing: (A) streamflow in cubic feet per second, (B) acidity, (C) dissolved sulfate, (D) dissolved iron, (E) dissolved manganese, and (F) dissolved aluminum in the mainstem and tributaries March 2000 (continued).

March 2000, all the upstream AMD sources including SR55 were flowing, contributing to the flow rate at SC3D of 14 ft³/s (23,789 L/min) with pH of 5.2 and elevated concentration of iron (10.6 mg/L) and moderate concentration of aluminum (1.5 mg/L) (table 3, fig. 7). Discharge from SR55 was not visible at its presumed location 0.5 mi (0.8 km) upstream of SC3D because the discharge and surrounding area of the stream channel were inundated by a beaver pond. Nevertheless, just above the ponded area, at SC3B on North Branch Shamokin Creek, the flow rate was only 7.4 ft³/s with pH of 3.9 and elevated aluminum (3.4 mg/L) (table 3). The large increase in flow and change in quality between SC3B and SC3D resulted from the iron-laden, intermediate-pH water from SR55. Following the synoptic survey, the beaver dam was found to be breached and the discharge from SR55 was confirmed at the location indicated. Dissolved nitrogen concentration was less than 0.2 mg/L at SC3B and SC3D (table 3). The data for North Branch Shamokin Creek indicate that the area sampled by SC3D is affected both by losses of flow and by loading of acidity and metals from continuous and intermittent AMD sources.

LC4 is near the mouth of Locust Creek. Various small AMD sources collectively referred to as the Locust Gap Mine discharges (SR8-SR10) contribute flow to this intermittent stream. In August 1999, the sampled reach for LC4 was dry, despite small flows from upstream AMD sources. In March 2000, water sampled at LC4 flowed at rate of 1.8 ft³/s (3,059 L/min) with pH of 3.9, net alkalinity of -30 mg/L, and moderate metals loading accentuated by elevated concentration of aluminum (3.8 mg/L) (table 3, fig. 7). The concentration of dissolved nitrogen was 0.5 mg/L in the high base-flow samples at LC4 (table 3). These data indicate that the area sampled by LC4 is affected by decreases in flow and by loading of acidity and metals from small, intermittent AMD sources.

EX5 is near the mouth of an unnamed tributary to Shamokin Creek at Excelsior. Various small AMD sources (SR13-SR14) contribute flow to this intermittent stream, which is concrete-lined along its lower reach. In August 1999, the sampled reach for EX5 was dry. In March 2000, water sampled at EX5 had a flow rate of 1.9 ft³/s (3,228 L/min) with pH of 4.9, net alkalinity of -1 mg/L, and low concentrations of metals (table 3). The concentration of dissolved nitrogen was 0.1 mg/L in the high base-flow samples at EX5 (table 3). These data indicate that the area sampled by EX5 is affected by losses of flow and by minor loading of acidity and metals from small, intermittent AMD sources.

SC6 is on Shamokin Creek west of Ranshaw, upstream of Quaker Run and downstream of Locust Creek and North Branch Shamokin Creek. In addition to the flows from these tributaries, Shamokin Creek at SC6 receives substantial contributions from the Excelsior Mine Pit overflow (SR12) and the Corbin Water Level Drift discharge (SR15) plus various small seeps. In August 1999 and March 2000, flows were 12 and 34 ft³/s (20,390 and 57,773 L/min), respectively (table 3). The quality of these low and high base-flow samples was relatively constant with pH of 6.3 and 6.1, net alkalinity of -28 and -32 mg/L, and concentrations of dissolved iron of 16 mg/L, manga-

nese of 2.9 and 2.5 mg/L, and aluminum of <0.2 mg/L (table 3, fig. 7). The large loads of metals at SC6 result mainly from SR12. The concentration of dissolved nitrogen in Shamokin Creek at SC6 was 1.0 mg/L during low and high base-flow conditions (table 3).

QR8 (*TMDL-QR1*) is at the mouth of Quaker Run west of Ranshaw. Most water flowing from Quaker Run to Shamokin Creek originates at three discharges, the Scott Ridge Mine Tunnel (SR19) and Colbert Mine Breach discharges (SR20), which become a tributary locally called Dark Run, and the Maysville Mine Borehole discharge (SR21) that flows into lower Quaker Run after its confluence with Dark Run. Although discrete AMD sources had not been identified in its upper watershed area before its confluence with Dark Run, the upper reach of Quaker Run at QR7 had relatively high concentrations of iron (22 mg/L) and was net acidic (pH 6.2; net alkalinity -45 mg/L) (table 3). The upper reaches of Quaker Run and Dark Run also receive effluent from the Borough of Kulpmont Wastewater Treatment Plant and the Borough of Marion Heights. In August 1999 and March 2000, flows at QR8 were 7.5 and 22 ft³/s (12,744 and 37,382 L/min), respectively (table 3). The quality of the low and high base-flow samples at QR8 was relatively constant with pH of 6.3 and 6.5, net alkalinity of -25 and -17 mg/L, and concentrations of dissolved iron of 17 and 19 mg/L, manganese of 3.4 and 3.3 mg/L, and aluminum of <0.2 mg/L (table 3, fig. 7). The concentration of dissolved nitrogen was 0.9 mg/L during low and high base-flow conditions (table 3). According to reports from SCRA, this stream channel loses water but regains flow upstream of the sewage-treatment plant.

BM9 is at the mouth of the unnamed tributary, locally called Buck Run, south of the city of Shamokin. Buck Run is formed almost entirely of AMD discharged from the Big Mountain Mine No. 1 slope (SR23) approximately 2,100 ft (640 m) upstream. In August 1999 and March 2000, flows were 0.93 and 4.1 ft³/s (1,580 and 6,967 L/min), respectively (table 3). With the exception of dissolved iron, the quality of the low and high base-flow samples was relatively constant with pH of 3.3 and 3.7, net alkalinity of -101 and -99 mg/L, and concentrations of dissolved iron of 13 and 21 mg/L, manganese of 7.6 and 7.2 mg/L, and aluminum of 7.0 and 6.8 mg/L (table 3, fig. 7). The concentration of dissolved nitrogen was <0.3 mg/L during low and high base-flow conditions (table 3). Wide variations in the flow rate of the SR23 discharge recently documented by the SCRA (Leanne Bjorklund, Shamokin Creek Restoration Alliance, oral commun., 2003) may have resulted in greater fluctuations in flow and chemistry at BM9 than indicated by the data reported above.

SC10 (*TMDL-SC2*) is on Shamokin Creek near the eastern limit of the city of Shamokin, downstream of sites SC6, QR8, and BM9 and upstream of Coal Run. In August 1999 and March 2000, flows were 19 and 59 ft³/s (32,285 and 100,253 L/min), respectively (table 3). With the exception of dissolved iron, the quality of the low and high base-flow samples was relatively constant with pH of 6.5 and 6.3, net alkalinity of -19 and -28 mg/L, and concentrations of dissolved iron of 8.2 and 15 mg/L, manganese of 3.4 and 2.9 mg/L, and aluminum of <0.2 mg/L

(table 3, fig. 7). The concentration of dissolved nitrogen was 0.9 mg/L during low and high base-flow conditions (table 3).

COR11 is at the mouth of Coal Run. Water flowing in Coal Run originates from various small mine discharges including the Greenough Mine discharge (SR31-32) and the Nielson Mine (SR36A) and Luke Fiddler Mine (SR36B) discharges. In August 1999 and March 2000, flows were 0.1 and 1.5 ft³/s (170 and 2,549 L/min), respectively (table 3). The quality of the low and high base-flow samples was relatively constant with pH of 6.4 and 6.5, net alkalinity 72 and 51 mg/L, and concentrations of dissolved iron of 0.9 and 2.9 mg/L, manganese of 1.5 and 1.3 mg/L, aluminum of <0.2 mg/L, and nitrogen of 1.4 and 1.9 mg/L (table 3, fig. 7). Coal Run is the largest of surveyed streams that had consistently net-alkaline water quality. Nevertheless, as described below, this stream tends to lose water along its lower reaches by leakage to underground mines.

SC11 (*TMDL-SC3*) is on Shamokin Creek upstream of the mouth of Carbon Run and downstream of Coal Run. This section includes effects from the city of Shamokin. Water-quality samples were collected at this site only during the ecological survey in October 1999 and the high base-flow survey in March 2000. In March 2000, flow was 64 ft³/s (108,749 L/min), with pH of 6.4, net alkalinity of -27 mg/L, and concentrations of dissolved iron of 15 mg/L, manganese of 3.1 mg/L, aluminum of <0.2 mg/L, and nitrogen of 1.0 mg/L (table 3, fig. 7).

CR12 (*TMDL-CAR1*) is on Carbon Run upstream of its confluence with Shamokin Creek and downstream of all known AMD sources in the Carbon Run subbasin. Much of the Carbon Run watershed is composed of spoil piles and abandoned surface mines. The stream disappears underground at various points in its headwaters area and reemerges downstream. The Henry-Clay Stirling Mine Pump Slope discharge (SR49) is the largest AMD source in the Carbon Run watershed, contributing half or more of the total flow and associated AMD contaminants. In August 1999 and March 2000, flows at CR12 were 3.2 and 18 ft³/s (5,437 and 30,586 L/min), respectively (table 3). The quality of the low and high base-flow samples was relatively constant with pH of 6.5 and 6.6, net alkalinity of -9 and -7 mg/L, and concentrations of dissolved iron of 11 and 14 mg/L, manganese of 3.9 and 2.5 mg/L, aluminum of 0.01 and 1.4 mg/L, and nitrogen of 1.0 and 0.9 mg/L (table 3, fig. 7).

SC14 (*TMDL-SC4*) is on Shamokin Creek near the Glen Burn Colliery at the southern base of Big Mountain, downstream of Carbon Run (CR12), Furnace Run (FR13), the city of Shamokin, and the Cameron Drift (SR51A) and the Cameron Air Shaft (SR53) discharges. In August 1999 and March 2000, flows at SC14 were 30 and 85 ft³/s (50,976 and 144,432 L/min), respectively (table 3). The quality of the low and high base-flow samples was relatively constant with pH of 5.9 and 6.2, net alkalinity of -34 and -30 mg/L, and concentrations of dissolved iron of 15 and 19 mg/L, manganese of 3.8 and 3.1 mg/L, aluminum of <0.2 mg/L, and nitrogen of 1.0 and 1.0 mg/L (table 3, fig. 7).

SC15 (*TMDL-SC6*) is at the USGS gaging station on Shamokin Creek downstream of the city of Shamokin and Big Mountain and Little Mountain and downstream of the unim-

paired tributaries Trout Run, Eagle Run, Benny's Run, and Millers Run. Water-quality samples were collected at this site during the ecological surveys in October 1999-2001 and the high base-flow survey in March 2000. Generally, the quality of streamwater is similar to that at SC14, however, concentrations of acidity and metals are slightly lower at SC15 because of dilution by the unimpaired tributaries and precipitation of metals. The quality of streamwater at SC15 varied considerably during the assessment and is discussed in detail below.

SC16 (*TMDL-SC8*) is near the mouth of Shamokin Creek in the city of Sunbury downstream of Little Shamokin Creek and various unnamed tributaries. Some of these tributaries historically have been affected by agricultural activities and carry large loads of nutrients and sediment (Pennsylvania Department of Environmental Protection, 2001a, 2001b). In August 1999 and March 2000, flows at SC16 were 34 and 301 ft³/s (57,773 and 511,459 L/min), respectively (table 3). The quality of streamwater at SC16 varied considerably during the assessment and is discussed in detail below.

Streamflow Variability

Wide ranges in flow rates at water-quality sampling sites during 1999-2001 resulted from leakage to and discharge from abandoned mines in the upper Shamokin Creek Basin. These interactions were amplified by drought conditions during the study period (figs. 8 and 9). During August 1999, a total of 41 of the 50 AMD sites were surveyed; 12 of the 41 surveyed AMD sources were "dry," including the Richard's Shaft Mine Drift near Atlas that was the fourth largest AMD source sampled during March 2000 (tables 1 and 3). Four stream survey sites on Shamokin Creek at Atlas (SC2), Locust Creek at Locust Gap (LC4), the unnamed tributary at Excelsior (EX5), and Carbon Run near Trevorton (CR1) also were dry in August 1999 (table 2, appendix B). In contrast, during the high base-flow survey in March 2000, all the stream survey sites were flowing and only 1 of the 46 sampled AMD sources, the Luke Fiddler Mine discharge (SR36A) was dry (table 3, fig. 4). Shortly after the high base-flow survey was completed, the SCRA sampled a large flow from SR36A (Leanne Bjorklund, Shamokin Creek Restoration Alliance, oral commun., 2003). Four of the 50 AMD sites listed in table 2 could not be located and were not sampled during the study.

To provide context for the data collected for the assessment, the long-term streamflow data for Shamokin Creek at the USGS gaging station near Shamokin (SC15; USGS station 01554500) during 1940-1992 and 1999-2001 were examined (figs. 8 and 9). During the 1999-2001 study period, the average streamflow of Shamokin Creek generally was lower than normal because of drought conditions in 1999 and 2001.

The low base-flow survey in August 1999 was conducted during drought conditions (figs. 8 and 9). Little to no flow in the undermined tributaries to Shamokin Creek and the lack of flow at a many of the AMD sites during the low base-flow conditions are consistent with previous investigations. Of the 54 AMD

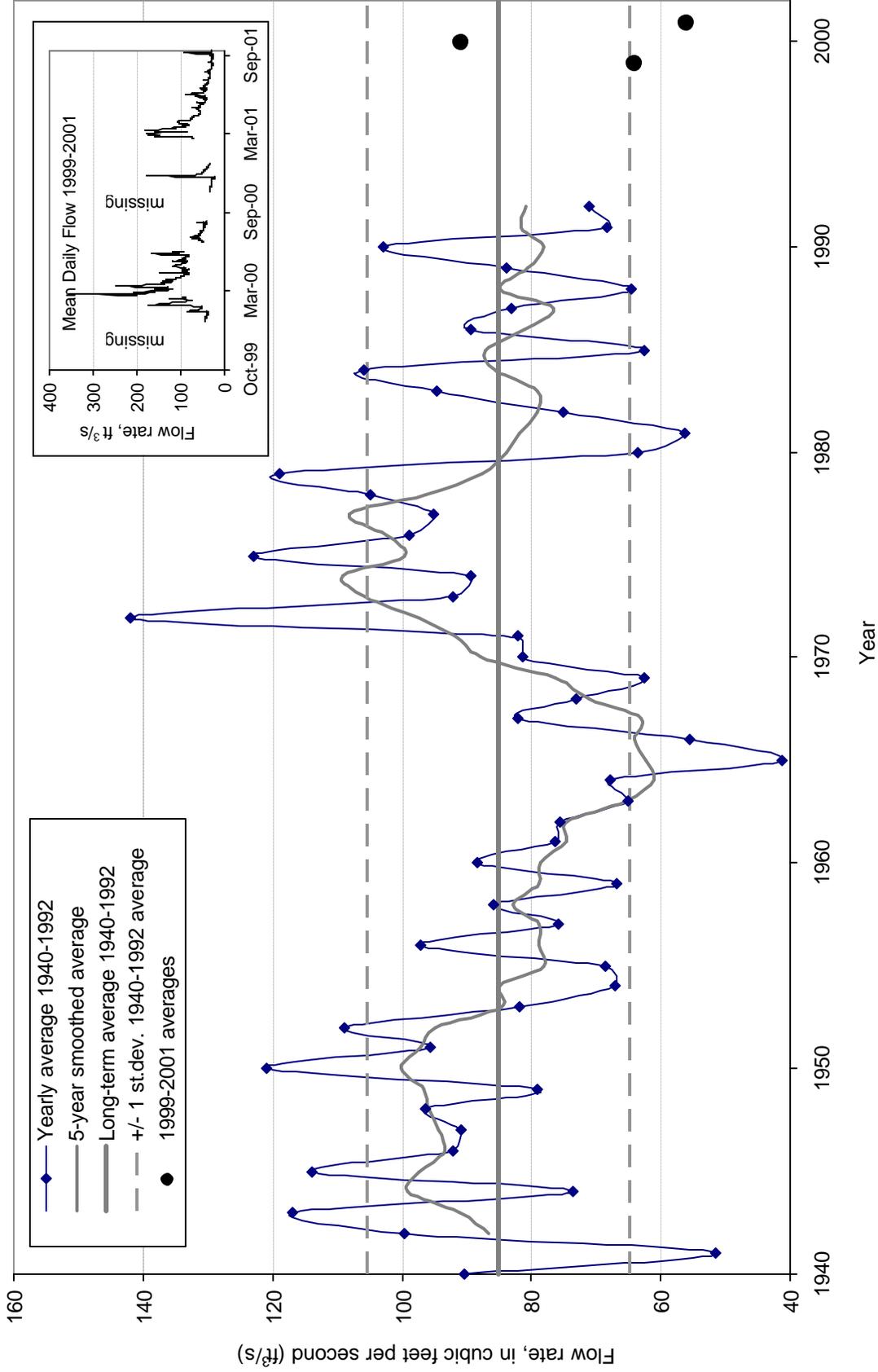


Figure 8. Historical (1940-1992) and recent (1999-2001) streamflow data for Shamokin Creek near Shamokin, Pa. (SC15; USGS station 01554500). Daily mean values were used to generate the hydrographs and to compute the mean and standard deviation (st.dev.) of the long-term average streamflow.

24 Effects of Abandoned Coal-Mine Drainage on Streamflow and Water Quality in the Shamokin Creek Basin

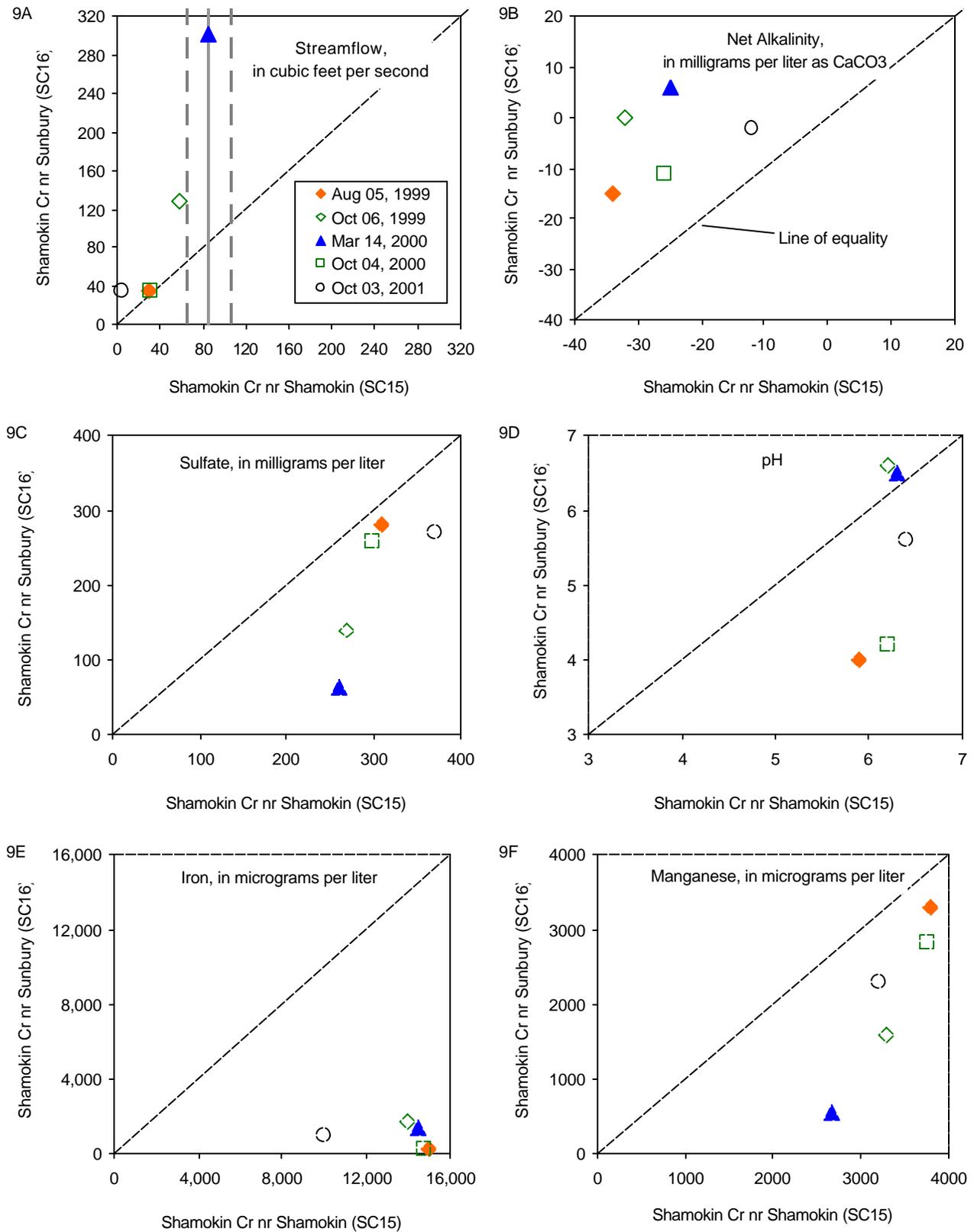


Figure 9. Comparison of instantaneous streamflow and water-quality data for Shamokin Creek near Shamokin (SC15) and Sunbury (SC16), Pa., 1999-2001: (A) streamflow, (B) net alkalinity, (C) sulfate, (D) pH, (E) dissolved iron, and (F) dissolved manganese. Data for SC15 in August 1999 were not available; data for SC14 were substituted for this station on this date.

sites reported from the Scarlift investigation, 20 had been identified previously as intermittently flowing; the other 34 were identified as continuous (Gannett Fleming Corddry and Carpenter, Inc., 1972). Heavy rains associated with tropical storms during mid to late September 1999 abruptly ended the drought. The stream ecological survey during October 1999 followed these tropical storms. Normal rainfall and corresponding recharge resumed through the winter 1999 and spring 2000.

During the high base-flow survey in March 2000, streamflow of Shamokin Creek at the USGS gaging station was equivalent to the long-term average at this location (figs. 8 and 9). Generally, the flow rate of Shamokin Creek increased downstream, from Shamokin (SC15) to Sunbury (SC16), because of inflows from various tributaries in the lower basin that were not affected by mining. However, during August 1999 and October 2000, flow rates increased only marginally downstream (fig. 9).

Despite dilution and the addition of alkalinity by the tributaries in the lower Shamokin Basin, the effects of AMD were not mitigated, particularly during August 1999 and October 2000 when streamflow at SC16 was similar to that at SC15. Dilution and alkalinity loading would have been least for these flow conditions. The pH at SC15 consistently was near neutral, ranging from 5.9 to 6.4. However, the pH at SC16 ranged from 4.0 to 6.6; the lowest pH and highest sulfate concentrations were associated with low base-flow conditions. The decline in pH from SC15 to SC16 can be attributed to the oxidation and hydrolysis of dissolved iron and a corresponding deficiency of alkalinity necessary to buffer the acid generated by these processes. Streamwater quality at Shamokin was relatively constant during the study. However, streamwater quality at Sunbury varied greatly by sample date, with a large range in pH and concentrations of sulfate and metals associated with ecological surveys in October 1999, 2000, and 2001. This observation is supported by the periodic changes in the appearance (ranging from colorless to orange) of the water at SC16 that have been noted for several years.

To determine the magnitude and effects of interbasin ground-water or surface-water diversions, streamflow at points along Shamokin Creek and its tributaries within the upper basin was compared to the drainage area defined by upstream topography. Streamflow values were normalized as the yield, or discharge divided by the contributing area (fig. 10). Streamflow yields for Shamokin Creek near Sunbury (SC16) were larger during the high base-flow and smaller during the low base-flow survey than those for Shamokin Creek near Shamokin (SC15). This result indicates that AMD is a substantial, sustained source of base flow in the upper basin and is consistent with interpretations by Becher (1991). Becher noted that streamflow from the upper Shamokin Creek Basin was sustained at higher levels during drought and had dampened peak flows compared to the nearby basins. A hydrologic budget for the upper Shamokin Creek Basin was computed by Becher (1991) on the basis of long-term streamflow record (1932-1992) for Shamokin Creek near Shamokin (SC15; USGS station 01554500). 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 but greater proportions of runoff contributing to the streamflow.

Compared to Shamokin Creek near Shamokin (SC15) or Sunbury (SC16) during low and high base-flow conditions, various upper tributaries, including North Branch Shamokin Creek (SC3D), Quaker Run (QR8), and Big Mountain or Buck Run (BM9), had high yields (fig. 10). These high yields could result from the interbasin gain of ground water and potentially large effect of AMD. At least one large AMD source was present immediately upstream of each of these stream monitoring stations (sites 55, 21, and 23, respectively) (table 1, fig. 7). In contrast, various other tributaries had consistently smaller yields than those for Shamokin Creek near Shamokin or near Sunbury (fig. 10). These tributaries likely were affected by leakage to underground mines, including Upper Shamokin Creek (SC2), Locust Creek (LC4), the unnamed tributary at Excelsior (EX5), Coal Run (COR11), and tributaries in the upper part of Carbon Run (CR1, TR41).

Contaminant Concentrations and Loads

In addition to the toxicity of dissolved metals, such as aluminum, the metals associated with AMD degrade the aquatic habitat because of their tendency to precipitate on the streambed. The measured dissolved load of metals in streamwater samples typically was less than the sum of metals load from each of the AMD sources upstream of stream survey points during both low and high base-flow conditions (fig. 10). This difference in loading of dissolved metals results from the precipitation of iron, aluminum, and, to a lesser extent, manganese within the stream channel during base-flow conditions. However, the accumulation of metals in the streambed may only temporarily reduce the downstream metal loading. The scour and resuspension of the precipitated metals during high-flow events can result in the non-attainment of water-quality criteria in downstream reaches. This condition has been documented on the basis of stormflow sampling on Swatara Creek (Cravotta and Bilger, 2001). Generally, the non-conservative transport of metals from the AMD sources to downstream monitoring sites invalidates simple computations of load reductions required for TMDL attainment. Correction factors are needed to relate the load reduced from an AMD source to the corresponding downstream load.

Low and high base-flow streamwater samples indicate less mass of metals in transport than had been added by upstream AMD sources. However, various stream sites (SC2, LC4, EX5, BM9, COR11) have greater metals loads, as percentage of total sum of known AMD sources, indicating additional AMD sources in these watersheds (fig. 10). Because these streams have greater metals loading at high base flow compared to low base-flow conditions, the additional AMD sources are likely to be intermittent or ephemeral.

The one AMD sample and eight low base-flow streamwater samples that were analyzed for coliform bacteria had posi-

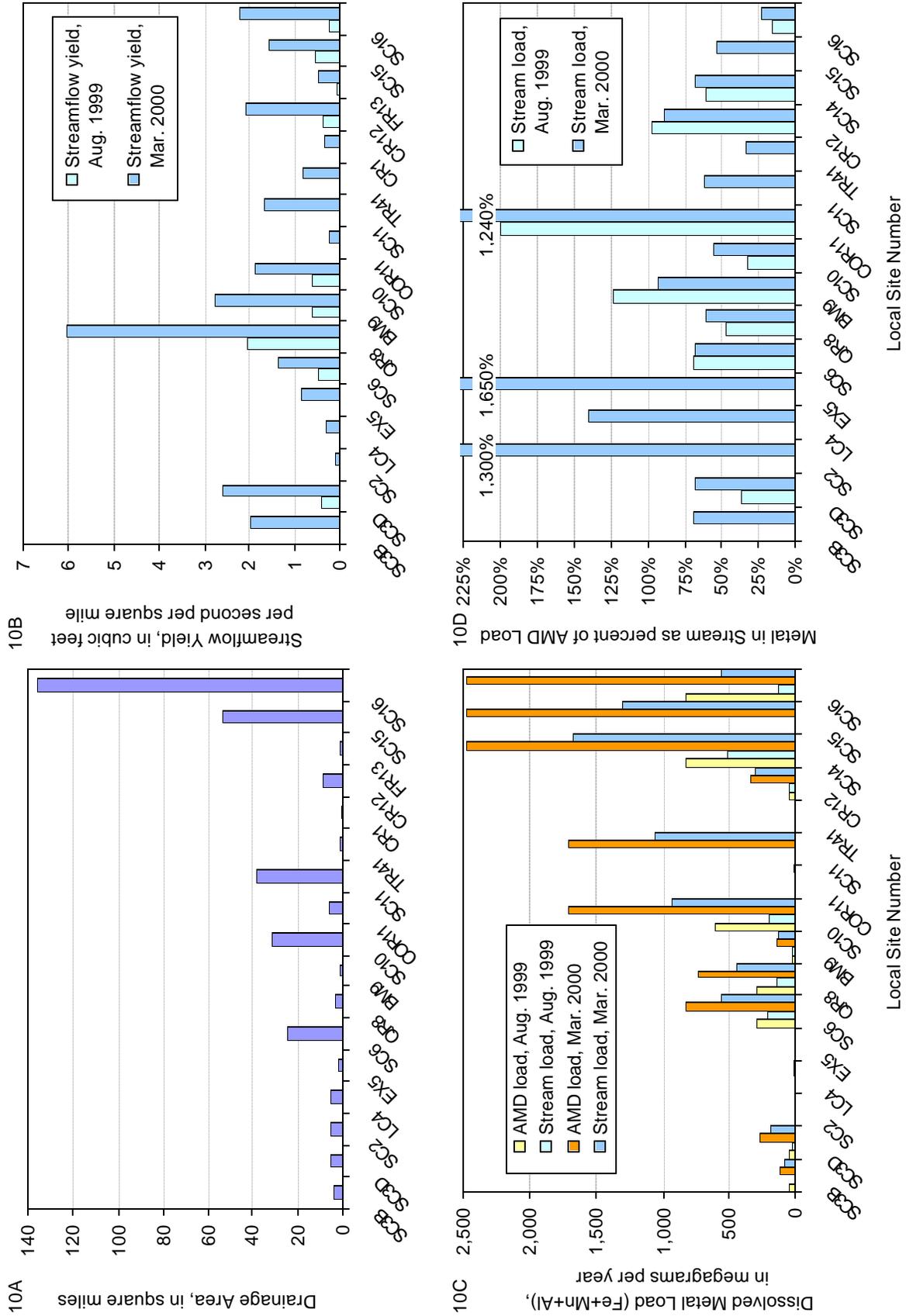


Figure 10. (A) Contributing area, (B) streamflow yields, (C) metals loading, and (D) percentage of AMD metals loading at stream monitoring sites in the Shamokin Creek Basin, Pa., 1999-2000. In 10D, the scale on the ordinate (Y) axis was truncated; values greater than 100 percent indicate the metals loading in streamwater was greater than the sum of metals loading from known AMD sources indicated in figure 1 and tables 1 and 2.

tive counts for total coliform and other sewage-related contaminants, in addition to contaminants associated with coal-mine sources (table 4). The AMD sample (SR23) and upstream sample on Shamokin Creek (SC3D) had relatively low counts for total coliform compared to other sites and did not contain *E. coli*. These samples also had low pH and low concentrations of inorganic nitrogen, chloride, and sodium compared to downstream samples (table 4). In contrast, the streamwater samples from downstream reaches in the watershed contained total coliform and *E. coli* and had near-neutral pH and moderate concentrations of nitrogen, chloride, and sodium. Although raw and (or) treated sewage effluent can be a source alkalinity, nitrogen, chloride, and sodium, bacteria generally are killed by chlorination or ozonation of treated sewage effluent. The presence of viable coliform bacteria in the streamwater samples indicates that raw sewage from combined sewer overflows, leaky sewer pipes, or residences could be a source of contamination. Mixing sewage with AMD has not negated the effect of raw sewage on water quality. Although concentrations of sewage-related contaminants were low in the streamwater compared to typical sewage effluent, a plan to address the combined sewer overflows is under development (Leanne Bjorklund, Shamokin Creek Restoration Alliance, oral commun., 2003). Further study is needed on determining bacteria and nitrogen sources.

Aquatic Ecology

Aquatic ecological surveys were conducted by the USGS at six of the stream sites in October 1999 and repeated annually in 2000 and 2001 on Shamokin Creek below Shamokin and at Sunbury. In 1999, fish were absent from Quaker Run and Shamokin Creek upstream of its confluence with Carbon Run; however, creek chub (*Semotilus atromaculatus*) were present within three sampled reaches of Carbon Run (table 5). During 1999, 2000, and 2001, six or more fish species were identified in Shamokin Creek below Shamokin and at Sunbury, despite elevated metals concentrations and iron-encrusted streambeds at these sites (table 5, fig. 9). Various tributary streams in Shamokin Creek's middle and lower reaches, including Trout Run, Buddys Run, Millers Run, Lick Creek (fig. 1), and those locally known as Kulp Run, Sunnyside Run, and Elysburg Run historically have supported healthy aquatic communities (Gannett Fleming Corddry and Carpenter, Inc., 1972).

The mainstem of Shamokin Creek downstream of the mined area supports fish species that have a range of tolerances of pollution and low pH (table 5). In 1999, 6 species of fish (spotfin shiner, creek chub, fallfish, white sucker, brown bullhead, and pumpkinseed) were captured downstream of the USGS gaging station at SC15, and 10 species of fish (spotfin shiner, fallfish, white sucker, gizzard shad, spottail shiner, northern hog sucker, rock bass, green sunfish, pumpkinseed, and smallmouth bass) were captured at SC16 near Sunbury (table 5). The streamwater at these sites had pH greater than 6 during the October 1999 survey. However, in August 1999, when the low base-flow synoptic survey was completed, and in

October 2000, when another ecological survey was conducted, the pH was 4.2 for Shamokin Creek at Sunbury (table 5; fig. 9). Few, if any, fish species had been documented previously in other freshwater bodies with this water quality (Butler and others, 1973; Earle and Callaghan, 1998; Barbour and others, 1999). Nevertheless, during the October 2000 survey, seven and eight species of fish were identified at the Shamokin and Sunbury sites, respectively. One or more individuals of acid-intolerant (Butler and others, 1973), but moderately pollution tolerant (Barbour and others, 1999), species were found, including fallfish, bluegill, and walleye (Butler and others, 1973; Barbour and others, 1999). Presumably, the fish migrate into and out of Shamokin Creek in response to prevailing water quality or find refuge in noncontaminated influents from tributaries or ground water.

Little macroinvertebrate life is supported by Shamokin Creek and its more severely mining-affected tributaries because of the iron-rich coating of the bottom surfaces (Pennsylvania Department of Environmental Protection, 2001b). Although macroinvertebrate kick-net samples were collected during the ecological surveys in October 1999, identification of specimens has not been completed. Nevertheless, in October 2001, only a single caddisfly (hydropsychid) specimen was found in Shamokin Creek at SC15, whereas none were found at SC16 (Martin Friday, Pennsylvania Department of Environmental Protection, oral commun., 2001). Chironomids have been observed in more acidic waters in the mining region (Robbins and others, 2000) and have been tentatively identified in samples collected from the Shamokin Creek Basin (M.D. Bilger, U.S. Geological Survey, oral commun., 2002). Eidem and Moffe (1998) and Casselggio (2001) sampled macroinvertebrates in Carbon Run and its tributaries.

Metal concentrations in the streambed of mining-affected streams could become elevated in the tissue of inhabitant fish and other aquatic organisms (Winterbourn and others, 2000; Cravotta and Bilger, 2001). Concentrations of metals in the whole-fish (white sucker) sample from Shamokin Creek near Shamokin were similar to those for an equivalent sample collected during the same week in October 1999 from Swatara Creek at Ravine, Pa. (table 6). Iron, manganese, aluminum, strontium, and zinc concentrations were elevated compared to other metals in these whole-fish samples (table 6). In general, because of metals in gut contents and in organs such as the liver, concentrations of most metals in whole fish will be greater than those in fish prepared for consumption (Campbell and others, 1988; Cravotta and Bilger, 2001). None of the metals in the whole white sucker samples exceeded U.S. Environmental Protection Agency (1997) screening values for human consumption (table 6). The following elements were not detected in the fish samples: Sb, As, Be, Cd, Mo, Ag, U, and V (table 6). Nevertheless, the concentrations of zinc exceeded the national average for whole-fish samples (Lowe and others, 1985). Copper and selenium were similar to the national averages, and mercury and lead were lower than the national averages (Lowe and others, 1985).

Table 4. Coliform bacteria and concentrations of dissolved metals and nutrients in water samples from selected sites on Shamokin Creek and its tributaries, August 4, 1999
[ft³/s, cubic feet per second; L/min, liters per minute; °C, degrees Celsius; mg/L, milligrams per liter; colonies/100 ml, colonies per 100 milliliters]

SCRA Site Identification Number ^a	Flow rate ^b (ft ³ /s)	Temperature (°C)	Oxygen (mg/L)	pH	Acidity ^c (mg/L as CaCO ₃)	Iron	Manganese	Aluminum	Sulfate	Sodium	Chloride	Phosphorus	Inorganic Nitrogen			Bacteria		
													Total ^d	Ammonia	Nitrite + Nitrate	Total Coli-	<i>E. coli</i> form	
SR23	0.51	11.5	1.8	3.5	123	0	29	7.4	7.6	520	2.9	3.1	0.005	0.25	0.25	<0.05	23	0
SC3D	2.2	20.5	8.9	3.2	64	0	2.7	4.2	160	4.8	5.8	<0.04	.08	.08	<.05	210	0	
SC6	12	16.0	9.9	6.3	34	6	16	2.9	.018	220	8.5	12	<0.04	.96	.90	.06	>250	25
QR7	2.0	13.5	9.8	6.2	46	1	22	3.6	.022	260	7.9	12	n.a.	.63	.39	.24	>300	23
QR8	7.5	14.5	10.0	6.3	37	12	17	3.4	.069	250	8.4	13	.094	.88	.39	.49	220	200
SC10	19	18.0	9.3	6.5	21	2	8.2	3.4	.034	250	7.8	11	.006	.86	.56	.30	>500	97
COR11	.1	15.5	7.1	6.5	4	76	.92	1.5	.012	170	18	37	.008	1.4	1.2	.18	>1,000	>100
CR12	3.2	17.5	9.5	6.5	37	18	11	3.9	.012	350	5.8	5.8	<.004	.96	.96	<.05	>500	>500
FR13	.1	21.5	8.9	7.0	0	64	.07	.082	.010	24	33	55	.039	1.2	.19	1.00	>3,000	>3,000

^a Shamokin Creek Restoration Alliance (SCRA) site numbers based on Scarlift report of Gannett Fleming Corrdry and Carpenter, Inc. (1972). Site locations are shown in figure 1. Complete data for sampled sites are given in appendix A.

^b For convenience, flow rate is given in English units, only; 1 ft³/s = 1,699 L/min.

^c Acidity computed using equation 7.

^d Total inorganic nitrogen computed as sum of ammonia, nitrate, and nitrite, all expressed as nitrogen.

Table 5. Fish species identified during annual ecological surveys of Shamokin Creek, Pennsylvania, October 1999, 2000, and 2001^a

[pollution tolerance: I (intolerant), M (moderate), T (tolerant); pH at time of survey shown in column heading for annual species counts at Shamokin and Sunbury, Pa.]

Taxa		Minimum pH in Pa. ^b	Pollu- tion Toler- ance ^c	Shamokin			Sunbury			
ORDER Family Genus species	Common Name			1999 ^d pH 6.2	2000 pH 6.2	2001 pH 6.4	1999 pH 6.6	2000 pH 4.2	2001 pH 5.5	
CLUPEIFORMES										
Clupeidae										
	<i>Dorosoma cepedianum</i>	Gizzard shad	6.5	M	0	0	0	1	0	0
CYPRINIFORMES										
Cyprinidae										
	<i>Campostoma anomalum</i>	Stoneroller	6.0	M	0	0	1	0	0	0
	<i>Cyprinella analostana</i>	Spotfin shiner	6.4	M	33	0	31	88	0	5
	<i>Notemigonus crysoleucas</i>	Golden shiner	4.6	T	0	2	0	0	0	0
	<i>Notropis hudsonius</i>	Spottail shiner	6.4	M	0	0	0	2	0	0
	<i>Semotilus atromaculatus</i>	Creek chub	5.2	T	32	9	48	0	0	1
	<i>Semotilus corporalis</i>	Fallfish	6.1	M	2	0	0	6	2	24
Catostomidae										
	<i>Catostomus commersoni</i>	White sucker	4.6	T	29	64	74	16	3	14
	<i>Hypentelium nigricans</i>	Northern hog sucker	6.0	I	0	0	0	1	0	0
SILURIFORMES										
Ictaluridae										
	<i>Ameiurus natalis</i>	Yellow bullhead	6.5	T	0	0	2	0	0	0
	<i>Ameiurus nebulosus</i>	Brown bullhead	4.6	T	2	10	0	0	1	2
	<i>Noturus insignis</i>	Margined madtom	5.9	M	0	0	0	0	0	3
SALMONIFORMES										
Esocidae										
	<i>Esox niger</i>	Chain pickerel	4.6	M	0	0	0	0	0	5
Salmonidae										
	<i>Oncorhynchus mykiss</i>	Rainbow trout	6.5	M	0	0	1	0	0	0
	<i>Salvelinus fontinalis</i>	Brook trout	5.0	M	0	1	0	0	0	0
PERCIFORMES										
Centrarchidae										
	<i>Ambloplites rupestris</i>	Rock bass	6.0	M	0	1	0	1	1	2
	<i>Lepomis auritus</i>	Redbreast sunfish	6.2	M	0	8	0	0	1	0
	<i>Lepomis cyanellus</i>	Green sunfish	6.4	T	0	0	5	2 ^e	0	1
	<i>Lepomis gibbosus</i>	Pumpkinseed	4.6	M	2	0	7	1	1	6
	<i>Lepomis macrochirus</i>	Bluegill	6.5	M	0	0	0	0	2	1
	<i>Micropterus dolomieu</i>	Smallmouth bass	6.0	M	0	0	0	35	0	46
Percidae										
	<i>Etheostoma olmstedii</i>	Tessellated darter	5.9	M	0	0	0	0	0	1
	<i>Stizostedion vitreum</i>	Walleye	6.5	M	0	0	0	0	1	1
Total number of individuals collected:					100	95	169	153	12	112
Total number of species identified:					6	7	8	10	8	14

a. Fish collected by electrofishing, identified, and released by M. D. Bilger and R. A. Brightbill of the U.S. Geological Survey on October 6, 1999, October 4, 2000, and October 3, 2001.

b. Minimum pH of occurrence in freshwater in Pennsylvania as reported by Butler and others (1973).

c. Pollution tolerance adapted from Barbour and others (1999)

d. In 1999, electrofishing surveys were conducted at the above stations on Shamokin Creek below Shamokin (SC15) and at Sunbury (SC16) plus seven other stations. No fish were found at North Branch Shamokin Creek (SC3D), Shamokin Creek at Ranshaw (SC6), Quaker Run at Ranshaw (QR8), and Shamokin Creek above Carbon Run at Shamokin (SC11). Creek chub (*Semotilus atromaculatus*) were the only species found at Carbon Run at the confluence with Shamokin Creek (CR12; 7 individuals), Carbon Run at unnamed tributary near Shamokin (CR ab TR41; 67 individuals), and unnamed tributary to Carbon Run near Shamokin (TR41; 73 individuals).

e. One of the two fish counted as green sunfish (*Lepomis cyanellus*) was identified as a green sunfish hybrid.

30 Effects of Abandoned Coal-Mine Drainage on Streamflow and Water Quality in the Shamokin Creek Basin

Table 6. Metals concentrations for whole white sucker (*Catostomus commersoni*) collected in October 1999 from Shamokin Creek near Shamokin and Swatara Creek at Ravine, Pa.

[concentrations reported as micrograms per gram ($\mu\text{g/g}$) dry and wet weight for six-fish composite sample; water and solids content in weight percent (%); <, less than; --, not applicable]

Constituent	Element Symbol	Shamokin Cr. nr Shamokin ^a		Swatara Cr. at Ravine ^a		Consumption Advisory ^b	National Geometric Mean Concentration, ^c	
		White Sucker, Whole		White Sucker, Whole			Wet Weight	
		Dry	Wet	Dry	Wet		1978-79	1980-81
Aluminum	Al	44.72	13.92	46.90	11.07	--	--	--
Antimony	Sb	<.15	<.05	<.20	<.05	--	--	--
Arsenic	As	<.15	<.05	<.20	<.05	3.0	--	--
Barium	Ba	1.73	.54	4.20	.99	--	--	--
Beryllium	Be	<.15	<.05	<.20	<.05	--	--	--
Boron	B	.37	.12	.40	.09	--	--	--
Cadmium	Cd	<.15	<.05	<.20	<.05	10.0	--	--
Chromium	Cr	.97	.30	1.90	.45	--	--	--
Cobalt	Co	.23	.07	.80	.19	--	--	--
Copper	Cu	2.45	.76	3.60	.85	--	0.86	0.68
Iron	Fe	186.84	58.16	103.00	24.31	--	--	--
Lead	Pb	.37	.12	.20	.05	--	.19	.17
Manganese	Mn	15.78	4.91	70.60	16.66	--	--	--
Mercury	Hg	.068	.021	.100	.024	.6	.11	.11
Molybdenum	Mo	<.15	<.05	<.20	<.05	--	--	--
Nickel	Ni	.44	.14	1.20	.28	--	--	--
Selenium	Se	1.56	.49	2.30	.54	50.0	.46	.47
Silver	Ag	<.15	<.05	<.20	<.05	--	--	--
Strontium	Sr	37.92	11.81	62.80	14.82	--	--	--
Uranium	U	<.15	<.05	<.20	<.05	--	--	--
Vanadium	V	<.15	<.05	<.20	<.05	--	--	--
Zinc	Zn	39.89	12.42	70.00	16.52	--	.26	.24
Water/Solids	--	68.9%	31.1%	76.4%	23.6%	--	--	--

a. Shamokin Creek near Shamokin, Pa. (SC15); site described in table 2. Swatara Creek at Ravine, Pa. (U.S. Geological Survey station 01571820); site described by Cravotta and Bilger (2001).

b. Human consumption advisory screening levels from U.S. Environmental Protection Agency (1997a). Note that concentrations are on dry weight basis.

c. National Contaminant Biomonitoring Program data for 1978-81 from Lowe and others (1985). Note that concentrations are on wet weight basis.

Characterization and Remediation of Abandoned Mine Drainage

Numerous AMD sources have been identified as sources of acidity, metals, and other contaminants in Shamokin Creek and its tributaries in the upper basin. However, the effects on streamwater quality can vary depending on the characteristics of the AMD sources and the receiving stream. Hence, the primary goals of this study were to assess and rank the effects of individual AMD sources and to identify possible remedial alternatives, including passive treatment options that could be applied in the basin.

Characteristics of Abandoned Mine Drainage Sources

The water-quality data for low base-flow samples collected in August 1999 and high base-flow samples collected in March 2000 are summarized below for the largest AMD sources on the basis of flow volume, in approximate east-to-west (or downstream) order. The large discharges are identified by site number and distinguished by larger symbols in figure 11 on the basis of their metal loadings.³ The TMDL report identified the AMD sources by name and not site identification number (Pennsylvania Department of Environmental Protection, 2001a, 2001b). Most of the large AMD sources are along the valley bottom near perennial streams. Many AMD sources contribute substantially to base flow of the receiving stream. The tributary stream basin that receives the AMD is identified in table 2. On the basis of previous reports by Gannett Fleming Corddry and Carpenter, Inc. (1972) or Reed and others (1987), the approximate recharge area for each of the AMD sources has been delineated along with other mine features as part of the GIS developed for the project (<http://www.pasda.psu.edu/access/shamcrk.shtml>). Possible treatment alternatives on the basis of the AMD water quality (fig. 3) and the proximity of the AMD source to nearby streams, roads, and other land-use features have been noted below for consideration by resource managers and land owners that may be involved in decisions to implement remediation. No attempt has been made in this study to evaluate the feasibility for remediation or treatment of the AMD sources.

Mid Valley Tunnel (SR5B) and Mid Valley overflow (SR5A) discharges are at Wilburton No. 1, approximately 2.8 mi (4.5 km) upstream of the mouth of North Branch Shamokin Creek and 2.1 mi (3.4 km) upstream from SC3D. In August

1999 and March 2000, flows at SR5B were 2.7 and 5.0 ft³/s (4,588 and 8,496 L/min), respectively; the flows at SR5A were 0 and 1.4 ft³/s (4,588 and 8,496 L/min), respectively (table 3). When both discharges were flowing in March 2000, the quality of AMD from SR5B and SR5A was nearly identical (table 3), implying a common source. The quality of the low and high base-flow AMD from SR5B was relatively constant with pH of 4.0 and 3.8, net alkalinity of -54 and -51 mg/L, and concentrations of dissolved iron of 12 and 9.9 mg/L, manganese of 2.2 mg/L, aluminum of 4.3 and 3.9 mg/L, and oxygen of 0.4 and 0.7 mg/L (table 3, fig. 11). Various smaller discharges from the Mid Valley Mine, including SR56 and SR4, also have water quality similar to that at SR5B. The large flow and high concentrations of aluminum and iron coupled with the remote location of SR5B could complicate the implementation of passive treatment. Flushable limestone-based systems and active treatment could be considered. Ideally, the flow rate and metals loading could be reduced by remining or reprocessing of culm and restoration of streamflow in the recharge area.

Richard's Shaft Mine Drift (SR55) is near Atlas, approximately 2.4 mi (3.8 km) upstream of the confluence of North Branch Shamokin Creek and Shamokin Creek. Although the Richard's Mine shaft location was shown on mine maps compiled for the assessment, this intermittent discharge was not reported previously by Gannett Fleming Corddry and Carpenter, Inc. (1972) or Reed and others (1987). In August 1999, SR55 was not flowing, and a nearby shaft along the streambank below SR55 and above SC3D was intercepting streamwater. In March 2000, the nearby shaft was discharging a small volume of water with quality identical to that in the stream. Downstream of SR55, the North Branch Shamokin Creek at SC3D had a flow rate of 14 ft³/s, pH of 5.2, concentrations of dissolved iron of 11 mg/L and aluminum of 1.5 mg/L. However, upstream from SR55, the flow rate at SC3B was only 7.4 ft³/s with pH of 3.9, concentrations of dissolved iron of 6.6 mg/L and aluminum of 3.4 mg/L. On the basis of these upstream and downstream measurements, the flow rate at SR55 was computed to be 6.6 ft³/s (11,215 L/min), with pH of 5.5, net alkalinity of -11 mg/L, and concentrations of dissolved iron of 22 mg/L, manganese of 2.4 mg/L, and aluminum of 0.9 mg/L (table 3, appendix A)⁴. Additional hydrologic data are needed to document flow and water-quality variations relevant for the selection and design of remediation.

Excelsior Mine Strip Pit Overflow discharge (SR12) receives drainage from the Reliance, Alaska, Enterprise, and Excelsior-Corbin Collieries and is one of the largest discharges in the Shamokin Creek watershed. The discharge floods an

³In figures and tables, the prefix "SR" was omitted from AMD site numbers. The prefix is used in text to distinguish AMD sites from stream sites, dates, and data values.

⁴A mixing model using the data for SC3B and SC3D and the geochemical program PHREEQCI (Parkhurst and Appelo, 1999) was developed to estimate the pH, alkalinity, and other solute concentrations of SR55 considering nonconservative transport of metals (appendix A). The pH, alkalinity, and Ca²⁺ were assumed to be controlled by dissolution of calcite and the concentrations of dissolved Fe³⁺ and Al to be limited by equilibrium with goethite (FeOOH) and amorphous Al(OH)₃, respectively. Generally, the concepts and approach used for this model could be applicable throughout the basin to explain changes in solute concentrations as AMD mixes and reacts with streamwater of varying quality.

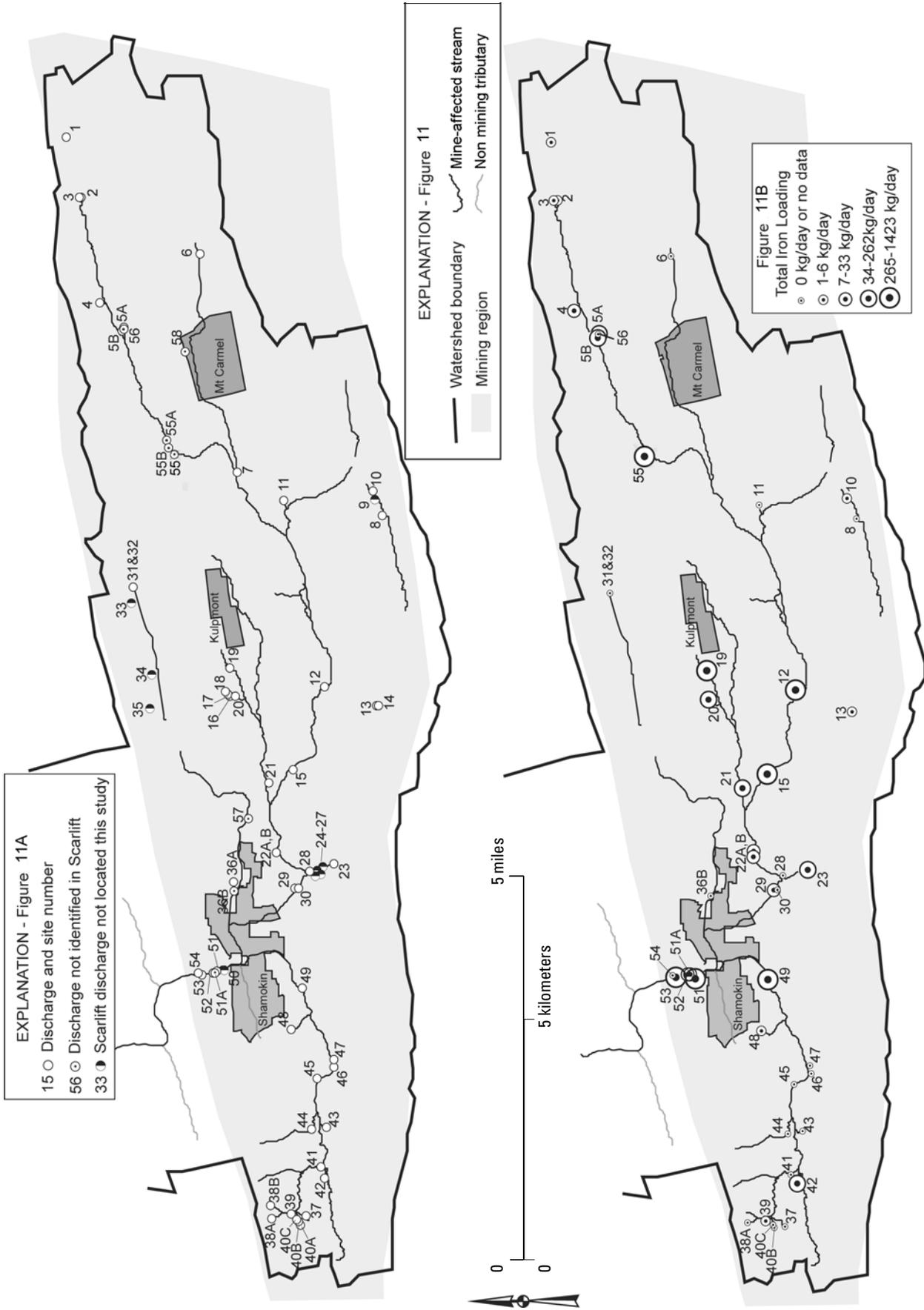


Figure 11. Maps of upper Shamokin Creek Basin, Pa., showing: (A) abandoned mine discharge locations and corresponding flow rates and loading of iron, manganese, and aluminum, March 2000.

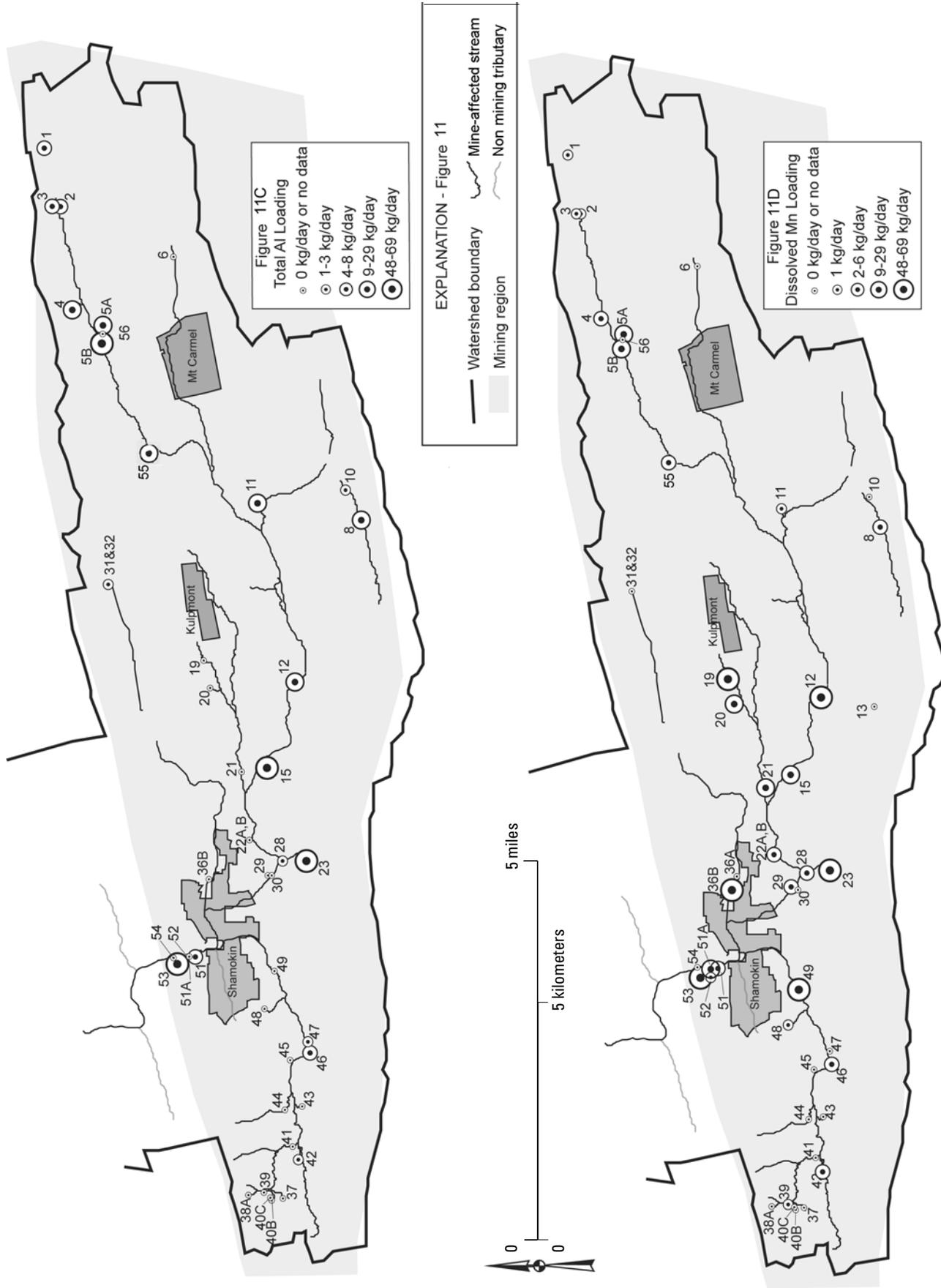


Figure 11. Maps of upper Shamokin Creek Basin, Pa., showing: (A) abandoned mine discharge locations and corresponding flow rates and loading of iron, manganese, and aluminum, March 2000 (continued).

abandoned strip pit forming a 2.9-acre (11,936 m²) pond that spills directly into Shamokin Creek. The flow from SR12 is similar to that of Shamokin Creek at their confluence. In August 1999 and March 2000, flows at SR12 were 7.2 and 14 ft³/s (12,234 and 23,789 L/min), respectively (table 3). The water quality of the AMD was relatively constant with pH of 5.8 and 5.7, net alkalinity of -8 and -31 mg/L, and concentrations of dissolved iron of 28 and 30 mg/L, manganese of 2.9 and 3.1 mg/L, aluminum of <0.2 mg/L, and oxygen of 4.1 and 6.5 mg/L (table 3, fig. 11). The AMD samples were collected at the pond overflow and had been aerated. Unpublished data indicates that dissolved oxygen concentrations are <0.3 mg/L where mine pool water enters the strip pit (Carl Kirby, Bucknell University, written commun., 2003). Because of its large size and its proximity to Shamokin Creek, remediation of SR12 could be difficult. An alternative remediation involves the in-situ addition of limestone (or other alkalinity source) to the flooded pit and subsequent aeration of water to promote the oxidation, hydrolysis, and settling of iron solids prior to its discharge to the creek.

Corbin Water Level Drift discharge (SR15) is at Ranshaw and drains the Excelsior-Corbin Colliery into Shamokin Creek upstream of its confluence with Quaker Run. In August 1999 and March 2000, flows at SR15 were 0.92 and 2.5 ft³/s (1,563 and 4,248 L/min), respectively (table 3). The quality of the AMD was relatively constant with pH of 4.2 and 4.4, net alkalinity of -123 to -138 mg/L, and concentrations of dissolved iron of 35 and 46 mg/L, manganese of 5.0 and 4.8 mg/L, aluminum of 8.6 and 8.3 mg/L, and oxygen of 2.3 and 4.8 mg/L (table 3, fig. 11). Although space for treatment is limited, a vertical-flow wetland system such as that constructed at SR42 may be appropriate for treatment of SR15. The SCRA obtained approval for installation of a system in 2003-2004 (Carl Kirby, Bucknell University, written commun., 2003).

Scott Ridge Mine Tunnel discharge (SR19) is at Kulpmont, approximately 1.2 mi (1.9 km) upstream of the mouth of Quaker Run and drains the Morris Ridge, Sayre, Stuartsville, Sioux, Richards, Greenough, Pennsylvania, Scott, and Natalie Collieries. This discharge had the largest flow rate of any AMD source in the watershed during 1999-2000. The discharge from SR19 surfaces through two different openings and drains into an unnamed tributary locally known as Dark Run. In August 1999 and March 2000, discharge at SR19 was 9.4 and 19 ft³/s (15,972 and 32,285 L/min), respectively (table 3). The quality of the AMD was relatively constant with pH of 5.9 and 5.8, net alkalinity of -20 mg/L, and concentrations of dissolved iron of 24 and 30 mg/L, manganese of 3.5 and 3.7 mg/L, aluminum of <0.2 mg/L, and oxygen of 1.9 and 1.4 mg/L (table 3, fig. 11). Because the metals loading is large and space for a treatment system is limited by proximity of the discharge to streams and roads, consideration could be given to active treatment options such as heterogeneous catalysis of iron oxidation by ferric hydroxide (Dietz and Dempsey, 2002).

Colbert Mine Breach discharge (SR20) is approximately 1.0 mi (1.6 km) upstream of the mouth of Quaker Run near Kulpmont and drains the Morris Ridge, Sayre, Stuartsville, Sioux, Richards, Greenough, Pennsylvania, Scott, and Natalie

Collieries. AMD from SR20 discharges directly into Dark Run. In August 1999 and March 2000, flows at SR20 were 1.9 and 1.6 ft³/s (3,228 and 2,719 L/min), respectively (table 3). The quality of the AMD was relatively constant with pH of 6.0, net alkalinity of -23 to -18 mg/L, and concentrations of dissolved iron of 26 and 30 mg/L, manganese of 3.7 mg/L, aluminum of <0.2 mg/L, and oxygen of 0.3 and 7.9 mg/L (table 3, fig. 11). The quality of AMD at SR20 is similar to that at SR19; however, because the flow rate is much smaller at SR20 than at SR19, passive treatment by anoxic or oxic limestone drains at SR20 may be feasible.

Maysville Mine Borehole discharge (SR21) is approximately 0.3 mi (0.5 km) upstream of the mouth of Quaker Run at Ranshaw and drains the Maysville Colliery. The discharge emerges through a pipe and flows directly into Quaker Run. In August 1999 and March 2000, flows at SR21 were 0.56 and 4.3 ft³/s (952 and 7,307 L/min), respectively (table 3). The quality of the AMD was relatively constant with pH of 6.1 and 6.4, net alkalinity 45 and 69 mg/L, and concentrations of dissolved iron of 18 and 23 mg/L, manganese of 2.6 and 2.8 mg/L, aluminum of <0.2 mg/L, and oxygen of 4.1 and 5.6 mg/L (table 3, fig. 11). This is the largest AMD source in the Shamokin Creek watershed that was consistently net alkaline. AMD with this quality could be treated passively with aerobic ponds. However, the discharge is on the bank of Quaker Run. Anecdotal information suggests that this discharge intentionally has been moved to its current location (Carl Kirby, Bucknell University, written commun., 2003). The discharge possibly could be relocated away from the bank of the stream to enable its passive treatment.

Big Mountain Mine No. 1 slope discharge (SR23) at Big Mountain drains the Big Mountain, Burnside, and Enterprise Collieries and forms the headwaters of an unnamed tributary locally called Buck Run. In August 1999 and March 2000, flows at SR23 were 0.51 and 3.6 ft³/s (867 and 6,117 L/min), respectively (table 3). The quality of the AMD was relatively constant with pH of 3.7 and 4.1, net alkalinity of -112 and -106 mg/L, and concentrations of dissolved iron of 25 and 28 mg/L, manganese of 7.4 and 7.1 mg/L, aluminum of 7.8 and 7.0 mg/L, and oxygen of 4.0 and 0.1 mg/L (table 3, fig. 11). Although flowing during August 1999 and March 2000, this discharge is intermittent (Leanne Bjorklund, Shamokin Creek Restoration Alliance, oral commun., 2003). During 2001, the SCRA reported the discharge at SR23 stopped flowing, while the same quality water began to flow from a nearby capped shaft. Subsequently, the "new" shaft overflow chemistry changed various times, evidenced by alternating precipitation of iron or aluminum hydroxide solids. The SCRA also measured appreciable pH variations. In the late spring of 2003, the SCRA reported that the shaft and the original SR23 discharge were flowing following extensive rains. In the fall 1998, PaDEP data on this permitted discharge also showed a distinct increase in iron and pH associated with aluminum concentration near zero. This discharge probably is connected hydrologically to an active strip mine operation (Blaschak Coal) that uses lime amendments during the reclamation process. The lime amendments could cause the chemistry fluctuations; however, changes in flow

have not been explained. Undeveloped land below the discharge could be available for construction of a treatment system. However, additional hydrologic data are needed to document flow and chemistry variations that would be relevant for the selection and design of remediation. A vertical-flow wetland system or flushable oxic limestone drain could be considered.

Royal Oak Mine discharge (SR22A,B) at Marshallton is approximately 0.7 mi (1.1 km) upstream of the mouth of Coal Run and drains the Buck Ridge #1 and Luke Fidler Collieries. The flow rate at SR22B exceeds or equals that at SR22A; otherwise, the quality is similar (table 3). In August 1999 and March 2000, flows at SR22B were 0.01 and 0.9 ft³/s (9 and 1,529 L/min), respectively (table 3). The quality of the AMD was relatively constant with pH of 5.8 and 5.9, net alkalinity 4 and 13 mg/L, and concentrations of dissolved iron of 14 and 11 mg/L, manganese of 2.3 and 2.2 mg/L, aluminum of <0.2 mg/L, and oxygen of 2.3 and 2.8 mg/L (table 3, fig. 11). AMD with this quality could be treated passively with aerobic ponds. However, the proximity of the discharge to the stream could limit installation of a passive-treatment system.

Henry Clay Stirling Mine Pump Slope discharge (SR49) is southwest of Shamokin approximately 1.5 mi (2.4 km) upstream of the mouth of Carbon Run and drains the Henry Clay, Stirling, Neilson, Bear Valley, Burnside, Royal Oak, and Buck Ridge Collieries. The Henry Clay Stirling Mine Slope discharge is the largest discharge in the Carbon Run watershed and one of the largest in the Shamokin Creek watershed. In August 1999 and March 2000, flows at SR49 were 1.6 and 13 ft³/s (2,719 and 22,090 L/min), respectively (table 3). With the possible exception of alkalinity, the quality of the AMD was relatively constant with pH of 5.8 and 6.1, net alkalinity of -19 and 17 mg/L, and concentrations of dissolved iron of 25 and 24 mg/L, manganese of 3.2 and 2.8 mg/L, aluminum of <0.2 mg/L, and oxygen of 0.3 and 0.4 mg/L (table 3, fig. 11). Land probably is not available for construction of a treatment system. However, additional hydrologic data are needed to document flow and chemistry variations, particularly the alkalinity and acidity, that would be relevant for the selection and design of remediation systems. Direct placement of limestone into the flooded slope could be considered. Alternatively, limestone screenings might be emplaced down an upgradient borehole (USGS NU 146 or NU 147 in Reed and others, 1987). The cover to borehole NU 147 is in a private driveway on State Route 125 right-of-way, and it was recently paved over, presumably by the landowner. Borehole NU 146 has not been located recently.

Cameron Air Shaft discharge (SR53) is the first of a pair of discharges flowing from the Glen Burn Colliery Complex near the northern limit of the city of Shamokin. This discharge also receives drainage from the Hickory Ridge, Colbert, Hickory Swamp, Cameron, Glen Burn, Natalie, and Luke Fidler Collieries. In August 1999 and March 2000, flows at SR53 were 2.3 and 5.0 ft³/s (3,908 and 8,496 L/min), respectively (table 3). The quality of the AMD was relatively constant with pH of 4.0 and 4.2, net alkalinity of -134 and -145 mg/L, and concentrations of dissolved iron of 49 and 57 mg/L, manganese of 6.1 and

5.6 mg/L, aluminum of 5.4 and 5.2 mg/L, and oxygen of 2.4 and 3.4 mg/L (table 3, fig. 11). Because SR53 is situated in the flood plain between State Route 61 and Shamokin Creek, land area is constrained for construction of a treatment system. In this situation, active treatment alternatives warrant consideration.

Cameron Drift discharge (SR51A), a drift opening, is the second in a pair of discharges flowing from the Glen Burn Colliery. This discharge receives drainage from the Hickory Ridge, Colbert, Hickory Swamp, Cameron, Glen Burn, Natalie, and Luke Fidler Collieries. In August 1999 and March 2000, flows at SR51A were 1.2 and 2.3 ft³/s (2,039 and 3,908 L/min), respectively (table 3). The quality of the AMD was relatively constant with pH of 5.3 and 5.5, net alkalinity of -75 and -56 mg/L, and concentrations of dissolved iron of 54 and 47 mg/L, manganese of 5.5 and 4.5 mg/L, aluminum of <0.2 mg/L, and oxygen of 0.3 and 0.2 mg/L (table 3, fig. 11). Although the adjacent land is constrained by its proximity to State Route 61 and Shamokin Creek, an underground, anoxic limestone drain could be considered for treatment of SR51A.

Remedial Priorities and Alternatives

Flow and concentration data for the high base-flow samples collected in March 2000 were used to determine priority ranks of the AMD sources on the basis of loads of dissolved iron, manganese, and aluminum and to indicate the possible size of wetlands for iron removal. The AMD source with the highest loading was assigned a rank of 1, with successively higher ranks assigned to AMD sources in descending order of dissolved metal loading (table 7). To provide context for comparing the AMD sources, the dissolved metals loading at each AMD source was expressed as a percentage of cumulative dissolved metals loading for all the AMD sources in the watershed (table 7). Generally, the AMD sources with the largest flow rates and iron concentrations were ranked among the top 20 AMD sources (fig. 12). However, the AMD ranking generally did not correlate with the acidity or aluminum concentration. The top three AMD sources, SR19, SR12, and SR49, accounted for more than 50 percent of the dissolved metals loading to Shamokin Creek, whereas the top 15 AMD sources accounted for more than 98 percent of the dissolved metals loading (table 7).

The March 2000 high base-flow, dissolved-metal data were considered useful in the evaluation of AMD priorities because (1) flow rates in March 2000 likely were near normal, (2) 10 previously identified intermittent AMD sources were not discharging during the August 1999 low base-flow survey, and (3) acidity is determined largely by dissolved metals concentrations. Ideally, loadings and associated AMD priorities should be determined on the basis of long-term averages, but these data were not available. Data for pH were not used for the ranking computations because pH tends to be an unstable parameter that does not indicate the ultimate potential for acidic conditions, and when pH or hydrogen ion loadings were included in the ranking computations, results were not changed appreciably.

Table 7. Rankings and possible remedial alternatives for abandoned mine drainage (AMD) in Shamokin Creek Basin, Pennsylvania [AMD rank based on instantaneous dissolved metals, net-alkalinity, or sulfate loading during March 14-16, 2000. Remedial alternatives identified in order of preference; any treatment design would require additional data and specific analysis; VFCW, vertical-flow compost wetland; ALD, anoxic limestone drain; OLD, flushable oxic limestone drain; OLC, open limestone channel; ft³/s, cubic feet per second; L/min, liters per minute; mg/L, milligrams per liter; --, no data. *Discharges ranked 43rd are not distinguished from one another by rank because of insufficient data.

SCRA Site Identification Number ^a	AMD Metals Rank ^b	Net Alkalinity Rank	Sulfate Rank	Percentage Dissolved Fe, Al, and Mn load	Cumulative Percentage Fe, Al, and Mn load	Principal Characteristics ^c	Remedial Alternatives ^d					Comments	Wetland Area, acres ^e	
							Remove Culm bank	VFCW	ALD	OLD	OLC			Aerobic Pond(s)
19	1	4	1	23.5	23.5	Very large flow; high Fe, Mn; moderate Al; net acidic; suboxic.						1	Passive methods difficult because of physical layout. Consider active treatment using heterogeneous catalysis of iron oxidation by ferric hydroxide. Additional alkalinity needed to balance acidity and facilitate iron oxidation. Potentially could be treated passively south of Route 61.	17.8
12	2	2	3	17.1	40.6	Very large flow; high Fe, Mn; moderate Al; net acidic; oxic.					?	?	Consider <i>in-situ</i> alkaline addition to present pond (requires introduction of dissolved oxygen into strip pit) or active treatment. PaDEP BAMR considering filling pit to eliminate physical hazard at County's request. (Additional water chemistry and survey data available from C. Kirby in Dept. of Geology, Bucknell University.)	13.1
49	3	43*	2	12.6	53.2	Large flow; high Fe, Mn; moderate Al; net acidic [?] ; anoxic.		1			1	2	May be able to introduce limestone into present pump slope or mine pool through borehole; water must be routed across Carbon Run to ponds. Consider active treatment with no alkaline addition, but using heterogeneous catalysis of iron oxidation by ferric hydroxide. Diminished source of metals during low-flow conditions.	10.0
53	4	1	4	12.3	65.5	Very large flow; very high Fe, Mn; very high Al; net acidic; oxic.		?			?	1	Discharges from culvert under Route 61 immediately into Shamokin Creek; no area for treatment unless discharge relocated. Large flow, high concentrations of metals, and oxic character limit passive treatment options.	8.8
55	5	8	8	6.0	71.5	Intermittent flow; high Fe, Mn; moderate Al; net acidic; suboxic.		?	?		?	?	Additional hydrologic data are needed to understand flow changes. Dry during low-flow conditions. Significant source of alkalinity and iron during high-flow conditions. Access difficult because upwells within ponded area on North Branch Shamokin Creek. However, area may be available for treatment.	4.5
23	6	3	5	5.5	77.0	Large flow; very high Fe, Mn; very high Al; net acidic; oxic.		1	2		1		Additional hydrologic data are needed to understand flow changes. Will be difficult keeping surface runoff out of treatment system. Diminished source of metals during low-flow conditions.	3.1
15	7	5	7	5.3	82.3	Large flow; very high Fe, Mn; very high Al; net acidic; oxic.		1	2		1	3	Area on south side of Shamokin Creek alone insufficient for complete passive treatment; flows as of December 2001 (170 gpm) much lower than those measured during March 2001. As of July 2002, a VFCW and aerobic pond are under construction.	3.5
51A	8	7	6	4.3	86.6	Large flow; very high Fe, Mn; moderate Al; net acidic; anoxic.			1			2	Small area for passive treatment before discharges reaches Shamokin Creek. Substantial source of metals during low-flow conditions.	3.8
21	9	43*	9	4.0	90.6	Large flow; high Fe, Mn; moderate Al; net alkaline; oxic.					2?	1	Discharges immediately into Quaker Run; no area for passive treatment unless discharge relocated; discharge was apparently relocated in the past to reduce flooding in Ranshaw. Consider active treatment with no alkaline addition, but using heterogeneous catalysis of iron oxidation by ferric hydroxide.	3.0
05B	10	6	10	2.9	93.5	Very large flow; high Fe, Mn; high Al; net acidic; anoxic.	?	?	?			?	Site is remote, making active treatment difficult; difficult area for passive treatment; may be able to lower Al concentration by preventing water infiltration up-gradient (Site 1). Water quality similar to Site 5A. Consider treatment within deep mine pool. Substantial source of metals during low-flow conditions.	1.8
20	11	11	11	1.9	95.4	Large flow; high Fe, Mn; moderate Al; net acidic; oxic.			1		1	2	May be anoxic; extreme water turbulence at monitored pipe outlet and sulfide odor makes it uncertain as to whether dissolved oxygen is high at pipe inlet. Water quality similar to Site 19. Marginally net acidic; small additional alkalinity needed for treatment. Substantial source of metals during low-flow conditions.	1.7
05A	12	9	13	0.8	96.2	Intermittent flow; high Fe, Mn; high Al; net acidic; anoxic.	?				?	?	Site is remote, making active treatment difficult; difficult area for passive treatment; may be able to lower Al concentration by preventing water infiltration up-gradient (Site 1). Water quality similar to Site 5B.	0.4
42	13	18	16	0.6	96.8	Large flow; moderate Fe, Mn; moderate Al; net acidic; oxic.					*	*	Treated successfully using VFCW followed by settling ponds. Monitor and maintain treatment; flush VFCW periodically; check erosion problems along Carbon Run.	0.5
51	14	17	12	0.5	97.3	Moderate flow; moderate Fe, Mn; moderate Al; net acidic; oxic.					?	?	Unusually high dissolved oxygen for deep mine discharge. Water chemistry changes substantially with time and flow rate. Small area for treatment unless discharge relocated.	0.3
04	15	10	15	0.5	97.8	Large flow; moderate Fe, Mn; very high Al; net acidic; oxic.		2	1	3	1		Unusually high dissolved oxygen for deep mine discharge implies subsurface aeration. Remote location. Limited area for passive treatment.	0.1
22B	16	42	14	0.4	98.2	Moderate flow; high Fe, Mn; moderate Al; net alkaline [?] ; oxic.					?	?	Remote location. Same water chemistry as 22A. No area for treatment; relocation of discharge unlikely.	0.4
03	17	16	23	0.2	98.4	Small flow; very high Fe, Mn; very high Al; net acidic; anoxic.	1	3	2	4	2		Substantial Al loading to North Branch of Shamokin Creek. Remote location; removal of large culm bank could eliminate source. Ponds could be constructed in old silt pond from which coal fines could be recovered.	<.1
11	18	13	19	0.2	98.6	Intermittent flow; moderate Fe, Mn; very high Al; net acidic; oxic.	1	2	3	4	2		Substantial Al loading to Locust Creek; intermittent to moderate flow; removal of large culm bank could eliminate source.	<.1
29	19	24	24	0.2	98.8	Moderate flow; high Fe, Mn; moderate Al; net acidic; suboxic.	3?		2?	1?	2?		Railroad tracks limit space for treatment.	0.2
08	20	12	17	0.2	99.0	Intermittent flow; moderate Fe, Mn; very high Al; net acidic; oxic.	1	3	2	4	2		Substantial Al loading to Locust Creek; intermittent to moderate flow; removal of large culm bank could eliminate source.	<.1
52	21	29	18	0.2	99.2	Moderate flow; high Fe, Mn; moderate Al; net acidic; oxic.					?	?	Small area for treatment unless discharge relocated.	0.1
02	22	14	21	0.2	99.4	Moderate flow; moderate Fe, Mn; very high Al; net acidic; oxic.	1	2	3	4	1		Remote location; removal of large culm bank could substantially remediate site. Ponds could be constructed in old silt pond from which coal fines could be recovered.	<.1
01	23	15	26	0.1	99.5	Moderate flow; moderate Fe, Mn; very high Al; net acidic; oxic.	1	3			2		Water apparently infiltrates into deep mine pool, contributing substantial Al loading to North Branch of Shamokin Creek at Site 5. Remote location; removal of large culm bank could eliminate source. Stream restoration needed; stream infiltrates completely at low flow.	<.1

Table 7. Rankings and possible remedial alternatives for abandoned mine drainage (AMD) in Shamokin Creek Basin, Pennsylvania (continued) [AMD rank based on instantaneous dissolved metals, net-alkalinity, or sulfate loading during March 14-16, 2000. Remedial alternatives identified in order of preference; any treatment design would require additional data and specific analysis; VFCW, vertical-flow compost wetland; ALD, anoxic limestone drain; OLD, flushable oxalic limestone drain; OLC, open limestone channel; ft³/s, cubic feet per second; L/min, liters per minute; mg/L, milligrams per liter; --, no data. *Discharges ranked 43rd are not distinguished from one another by rank because of insufficient data.

SCRA Site Identification Number ^a	AMD Metals Rank ^b	Net Alkalinity Rank	Sulfate Rank	Percentage Dissolved Fe, Al, and Mn load	Cumulative Percentage Fe, Al, and Mn load	Principal Characteristics ^c	Remedial Alternatives ^d					Comments	Wetland Area, acres ^e		
							Remove Culm bank	VFCW	ALD	OLD	OLC			Aerobic Pond(s)	Active Treatment
22A	24	41	25	0.1	99.6	Moderate flow; high Fe, Mn; moderate Al; net acidic?; anoxic.		?			?		?	Remote location. Same water chemistry as 22B. No area for treatment; relocation of discharge unlikely.	0.1
48	25	43*	30	0.1	99.7	Moderate flow; moderate Fe, Mn; moderate Al; net alkaline; oxid.					*			Treated successfully using aerobic wetlands. Monitor and maintain treatment, especially bank stability.	0.1
10	26	19	27	0.1	99.8	Small flow; high Fe, Mn; very high Al; net acidic; oxid.	1	2	3	4	1			Emanates from small pond in spoil pile; substantial Fe and Al loading to Locust Creek. Stream restoration needed: stream infiltrates completely at low flow.	<1
46	27	20	22	0.1	99.9	Moderate flow; moderate Fe, Mn; high Al; net acidic; oxid.	1	?			2			Intermittent seepage along various locations making passive treatment difficult; substantial source of Al to Carbon Run. Removal of culm bank may eliminate AMD.	<1
28	28	21	20	0.1	100	Moderate flow; moderate Fe, Mn; very high Al; net acidic; oxid.		?			1			Small area available for ponds.	<1
39	29	38	32	<1	100	Small flow; moderate Fe, Mn; moderate Al; net alkaline; oxid.					1			Apparently low dissolved oxygen where discharge emanates – measurements were downflow of discharge. Add limestone to pool of discharge and enhance present wetland.	<1
47	30	22	29	<1	100	Intermittent flow; moderate Fe, Mn; very high Al; net acidic; oxid.	1	?			?			Intermittent seepage along various locations; flow into Carbon Run leaving Small room for passive treatment	<1
31-32	31	23	28	<1	100	Small flow; moderate Fe, Mn; very high Al; net acidic; oxid.	2	2	1	3	1			Main source of water for upper Coal Run; all water at low flow infiltrates into a downflow strip pit; stream restoration needed in addition to water treatment.	<1
54	32	25	33	<1	100	Small flow; moderate Fe, Mn; very high Al; net acidic; oxid.	1	?			2			Low-flow seepage from spoils piles; small area for passive treatment.	<1
56	33	27	38	<1	100	Intermittent flow; high Fe, Mn; very high Al; net acidic; anoxic.	1	1			2			Anaerobic wetland could be appropriate for this water quality, which is similar to adjacent Site 5A. If possible, treat with Site 5A.	<1
30	34	28	35	<1	100	Small flow; moderate Fe, Mn; moderate Al; net acidic; oxid.	3	3	1	2	1			Flushable oxalic limestone drain could be appropriate for this water quality, provided that space and access are available.	<1
43	35	26	31	<1	100	Intermittent flow; moderate Fe, Mn; moderate Al; net acidic; oxid.	2	2	3	1	1			Water enters wetland downstream of emanation; intermittently a substantial source of Al to Carbon Run; water could be diverted into present downstream water-filled strip pit; vertical flow wetland may have to be upflow type.	<1
41	36	35	43*	<1	100	Intermittent flow; moderate Fe, Mn; moderate Al; net alkaline?; oxid.					?			Very small; marginally net alkaline; no treatment suggested.	<1
44	37	36	43*	<1	100	Small flow; low Fe, Mn; moderate Al; net alkaline?; oxid.					?			Very small; no treatment suggested.	<1
40B	38	37	37	<1	100	Intermittent flow; low Fe, Mn; moderate Al; net alkaline; oxid.					?			No treatment suggested.	<1
40C	39	39	34	<1	100	Small flow; low Fe, Mn; moderate Al; net alkaline; oxid.					?			No treatment suggested.	<1
06	40	31	43*	<1	100	Small flow; moderate Fe, Mn; moderate Al; net acidic; oxid.	2	2	3	1	1			Water flows through wetland that could be used for treatment; would need to keep excess runoff from entering treatment system.	<1
36B	41	30	36	<1	100	Small flow; moderate Fe, Mn; moderate Al; net acidic; oxid.					?			Not reported in Scarlift; water quality substantially different from Site 36A.	<1
13	42	32	42	<1	100	Small flow; low Fe, Mn; moderate Al; net acidic; oxid.			2?		1			Likely anoxic as indicated by high Fe concentration and intermediate pH.	<1
37	43*	33	41	<1	100	Intermittent flow					2?	1		OLC would increase alkalinity of tributary.	
36A	43*	43*	43*	<1	100	Intermittent flow; moderate Fe, Mn; moderate Al; net acidic; oxid.	2	2	1		1			Flow alternates between no flow and very high flow, complicating treatment options. Discharge not flowing during USGS sampling in March 2000, but SCRA sampled large flow (2 ft ³ /s) during April 2000.	<1
38A	43*	40	40	<1	100	Small flow; low Fe, Mn; moderate Al; net alkaline; oxid.					2	1		Alternative treatment: add alkaline material to present pond.	<1
45	43*	34	39	<1	100	Intermittent flow; low Fe, Mn; moderate Al; net acidic; oxid.					?			Small flow immediately adjacent to Carbon Run; no treatment suggested.	--
7	43*	43*	43*	<1	100	Intermittent flow.								Discharge not flowing during study.	--
9	43*	43*	43*	<1	100	--								Discharge not located.	--
14	43*	43*	43*	<1	100	Intermittent flow.								Discharge not flowing during study.	--
16	43*	43*	43*	<1	100	Intermittent flow.								Discharge not flowing during study.	--
17	43*	43*	43*	<1	100	Intermittent flow.								Discharge not flowing during study.	--
18	43*	43*	43*	<1	100	Intermittent flow.								Discharge not flowing during study.	--
24	43*	43*	43*	<1	100	--								Not found during sampling; seep located adjacent to or in stream.	--
25	43*	43*	43*	<1	100	--								Not found during sampling; seep located adjacent to or in stream.	--
26	43*	43*	43*	<1	100	--								Not found during sampling; seep located adjacent to or in stream.	--

Table 7. Rankings and possible remedial alternatives for abandoned mine drainage (AMD) in Shamokin Creek Basin, Pennsylvania (continued) [AMD rank based on instantaneous dissolved metals, net-alkalinity, or sulfate loading during March 14-16, 2000. Remedial alternatives identified in order of preference; any treatment design would require additional data and specific analysis; VFCW, vertical-flow compost wetland; ALD, anoxic limestone drain; OLD, flushable oxic limestone drain; OLC, open limestone channel; ft³/s, cubic feet per second; L/min, liters per minute; mg/L, milligrams per liter; --, no data. *Discharges ranked 43rd are not distinguished from one another by rank because of insufficient data.

SCRA Site Identification Number ^a	AMD Metals Rank ^b	Net Alkalinity Rank	Sulfate Rank	Percentage Dissolved Fe, Al, and Mn load	Cumulative Percentage Fe, Al, and Mn load	Principal Characteristics ^c	Remedial Alternatives ^d						Comments	Wetland Area, acres ^e		
							Remove Culm bank	VFCW	ALD	OLD	OLC	Aerobic Pond(s)			Active Treatment	
27	43*	43*	43*	<.1	100	--									Not found during sampling; seep located adjacent to or in stream.	--
33	43*	43*	43*	<.1	100	--									Discharge not located.	--
34	43*	43*	43*	<.1	100	--									Discharge not located.	--
35	43*	43*	43*	<.1	100	--									Discharge not located.	--
40A	43*	43*	43*	<.1	100	--									Small flow during study; no treatment suggested.	--
50	43*	43*	43*	<.1	100	--									Discharge not located.	--
57	43*	43*	43*	<.1	100	--					1?				Undetermined small flow immediately adjacent to Coal Run; insufficient data for determining remedial alternatives.	--

a. Shamokin Creek Restoration Alliance (SCRA) site numbers based on Scarlift report of Gannett Fleming Corddry and Carpenter, Inc. (1972).
 b. Rankings for AMD metals and net-alkalinity considered the instantaneous loading of dissolved iron, aluminum, and manganese; net alkalinity = measured alkalinity - computed acidity per equations 7 and 8.
 c. Principal characteristics based on maxima and minima for flow rate and concentrations of alkalinity, dissolved metals, and oxygen (in mg/L) for samples collected in August 1999 and March 2000. Flow (ft³/s): 'very large' if minimum > 2.0; 'large' if maximum ≤ 2.0; 'moderate' if maximum ≤ 1.0; 'small' if maximum < 0.1; 'Intermittent' if maximum or minimum = 0. Iron and manganese (mg/L): 'very high' if minimum Fe > 12 and minimum Mn > 4; 'high' if minimum Mn > 4; 'moderate' if minimum Fe ≤ 12 and minimum Mn ≤ 4; 'low' if maximum Fe < 3 and maximum Mn < 1. Aluminum (mg/L): 'very high' if maximum > 4; 'high' if maximum > 2; 'moderate' if maximum ≤ 2; 'low' if maximum < 0.2. Net alkalinity (alkalinity - computed acidity; mg/L as CaCO₃): 'net acidic?' if maximum ≤ 5; 'net acidic' if maximum ≤ 0; 'net alkaline?' if minimum > 0 or if missing and minimum pH ≥ 6.4; 'net alkaline' if minimum ≥ 5. Dissolved oxygen (mg/L): 'anoxic' if maximum ≤ 1; 'suboxic' if maximum ≤ 2; 'oxic' if minimum > 2.
 d. Remedial alternatives initially identified on the basis of maxima and minima for flow rate and water quality (in mg/L): 'Remove culmbank' if maximum pH < 4.0; 'Aerobic pond' if minimum net alkalinity ≥ 5; 'VFCW and aerobic pond' if minimum net alkalinity < 5, maximum dissolved oxygen > 1, maximum Al ≥ 2, and maximum Qoifs ≤ 6.5; 'ALD and aerobic pond' if minimum net alkalinity < 5, maximum dissolved oxygen ≤ 1, maximum Al < 2, and maximum flow ≤ 6.5; 'OLD and aerobic pond' if minimum net alkalinity < 5, maximum dissolved oxygen > 1, maximum Al < 3, and maximum flow ≤ 6.5; 'OLC' if minimum net alkalinity < 5, maximum Fe < 10, maximum Al < 5, and maximum flow ≤ 10; 'Active Treatment' if minimum flow > 2 or maximum net alkalinity < -300.
 e. Minimum wetland size computed by dividing the product of maximum flow rate and maximum iron concentration, in grams per day, by 20 g/m²/day (180 lb/acre/day) per Hedlin, R.S., Nairn, R.W., and Kleinmann, R.L.P. (1994).

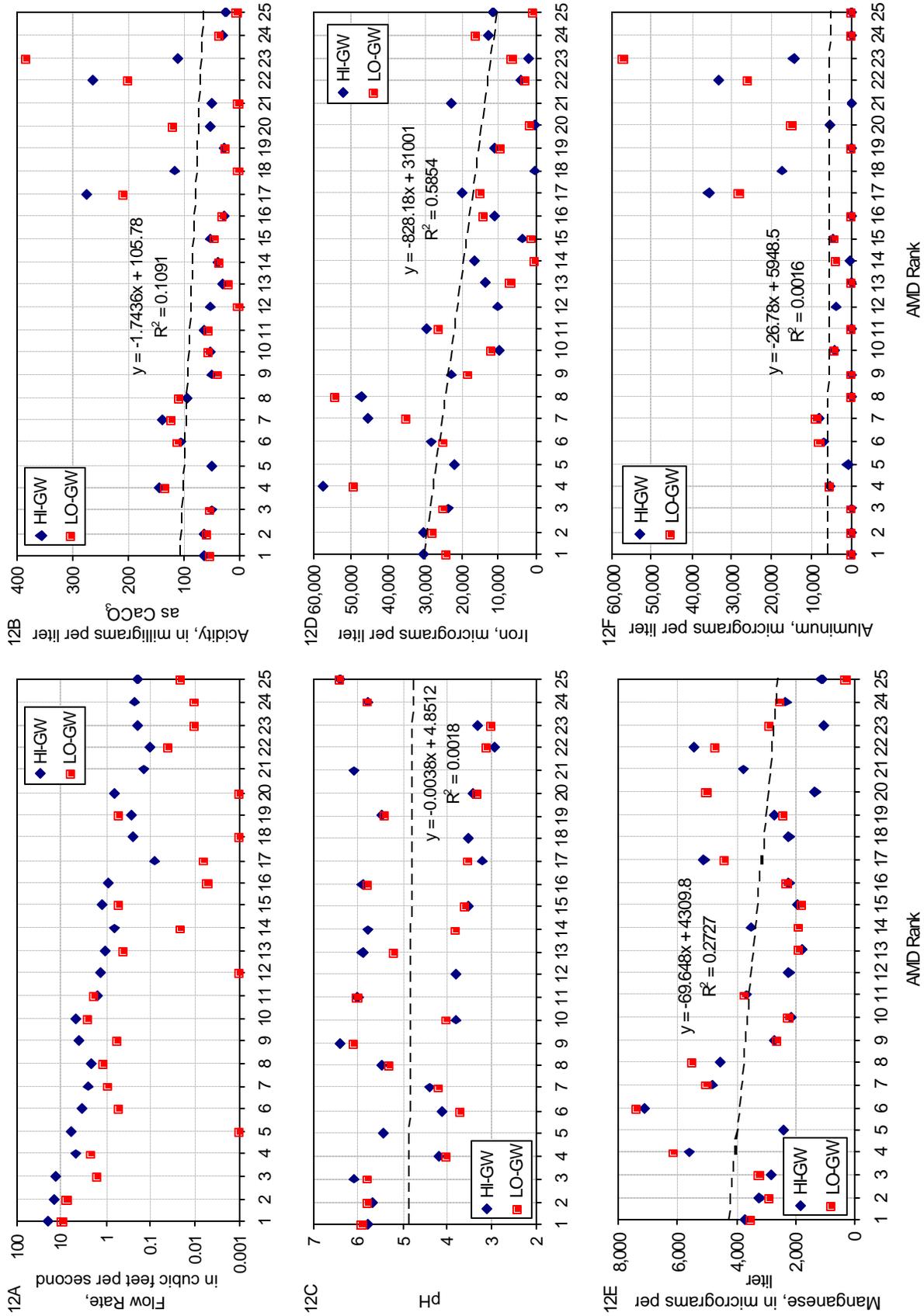


Figure 12. Relation between priority ranking on the basis of dissolved metals loading in March 2000 for top 25 abandoned mine discharge sites and (A) flow rate, (B) acidity, (C) pH, (D) iron, (E) manganese, and (F) aluminum concentrations for high base-flow (HI-GW) and low base-flow (LO-GW) AMD samples.

Estimates of the metals loads and corresponding rankings of AMD priorities were similar on the basis of the metals in whole-water (total) and 0.45- μm filtered (dissolved) subsamples (fig. 13). Furthermore, the ranking sequence for the top AMD sources based on the high base-flow data generally matched that based on the low base-flow data (fig. 13). However, 4 of the top 20 AMD sources, SR55, SR5A, SR11, and SR8 (ranked 5, 12, 18, and 20, respectively) were not flowing in August 1999 (table 3, fig. 13). With the exception of SR11, the concentration of dissolved iron typically exceeded that of the other metals, indicating iron was the predominant source of acidity (fig. 13). Nevertheless, because the proportions of dissolved iron, manganese, and aluminum in the AMD varied from site to site, different rankings could result by weighting the metals with different factors such as dividing the concentration by regulatory standards.

The AMD priority ranking could have been developed using various other constituents or computational methods. Cherry and others (2001) and Herlihy and others (1990) used various biological and chemical constituents to assess AMD effects on a watershed scale. Williams and others (1996, 1999) used flow and chemical constituents including acidity, metals, and sulfate to develop a ranking scheme based primarily on contaminant loading; pH was used as a "tie-breaker." For the current assessment, rankings on the basis of sulfate were similar to those computed on the basis of dissolved metals (table 7). When "hot" acidity or net-alkalinity (alkalinity - computed acidity) loading was considered, the ranks for most AMD sources were similar to those based on their metals loading; however, ranks for various AMD sources with substantial alkalinity *and* metals loading shifted (table 7). For example, SR49 and SR21 had net-alkalinity rankings of 44 and 45 (shown as 43* in table 7) compared with their dissolved-metal rankings of 3 and 9, respectively. These rankings indicate that acidity loading from SR49 and SR21 is less than that from other top-ranked AMD sources; their treatment is likely to be more feasible than other large AMD sources. Another option would be a ranking of AMD sources based on the feasibility for their treatment or remediation. Ultimately, the feasibility of remediation of a particular discharge must consider the AMD quality and loading rates, if space is accessible for treatment, and if funding, construction permits, and other resources can be obtained for implementation. Comments were added to table 7 indicating possible remedial alternatives and other issues with respect to treatability for consideration by resource managers and land owners that may be involved in decisions to implement remediation. No attempt has been made in this study to evaluate the feasibility for remediation or treatment of the AMD sources.

Generally, to meet water-quality criteria for 0.3 mg/L dissolved iron, nearly all the AMD sources would require construction of some sort of settling basin or wetland to facilitate iron oxidation, hydrolysis, and deposition. Hence, to provide a basis for evaluating the feasibility of constructing a passive treatment at the sites, the minimum wetland size for each AMD source was computed using the data for maximum flow rate and maximum iron concentration for the August 1999 and March

2000 data and considering abandoned mine criteria of Hedin and others (1994) for an iron removal rate of 180 lb/acre/day (20 g/m²/day) (table 7). The computed wetland sizes ranged from 17.8 acres for SR19 to <0.1 acre for SR3, which were ranked 1 and 17, respectively. Many of the smaller AMD sources also were identified as requiring only small wetlands (<0.1 acre). Small wetland acreages were computed for sites with low flow rates and low concentrations of dissolved iron; however, many of these AMD sources, such as SR3, could have high concentrations of dissolved aluminum (table 7).

In the Shamokin Creek watershed, the primary water-quality concerns that result from AMD are low pH, high concentrations of aluminum and possibly other toxic metals, and thick iron-hydroxide coatings on streambeds. Low pH coupled with high concentrations of dissolved aluminum and other metals, such as nickel and zinc, can be toxic to many aquatic organisms (Burrows, 1977; Burton and Allan, 1986; Hyman and Watzlaf, 1997; Earle and Callaghan, 1998; U.S. Environmental Protection Agency, 2002a). Although dissolved iron is not acutely toxic at the concentrations documented in this watershed (<60 mg/L), thick accumulations of iron hydroxide effectively can eliminate the habitat of aquatic macroinvertebrates that serve as food sources for organisms at higher trophic levels. Manganese loading was incorporated in the AMD prioritization because manganese concentrations in streamwater and in effluent from active mines are regulated by Federal and State law (Commonwealth of Pennsylvania, 1998a, 1998b, 2001). Kleinmann and Watzlaf (1986) and Hyman and Watzlaf (1997) explained that the manganese regulation is in force not because of its toxicity, but rather because of the potentially flawed assumption that manganese concentration serves as a proxy for toxic trace metals.

An inherent assumption in the three-metal assessment used for this study is that "If the instream loadings of iron, manganese, and aluminum are decreased to acceptable levels by appropriate treatment or natural processes, other chemical, physical, and biological parameters will be within a range that should support normal aquatic populations." For pH, acidity, and alkalinity, this assumption should be valid because the AMD treatments appropriate for removal of iron, manganese, and aluminum also will increase the pH and alkalinity while decreasing acidity in receiving streams. Because trace-metal concentrations in streamwater and sediments tend to be controlled by their adsorption to precipitated Fe(III) and Mn(IV) hydroxides, trace-metal toxicity also can be reduced by treatments that effectively remove acidity and promote the formation of the metal hydroxides. Dissolved oxygen concentrations in flowing streams should be adequate to support warm-water fish populations once the chemical-oxygen demand associated with Fe(II) and Mn(II) loadings is reduced. Although SO_4^{2-} concentrations will be little affected by AMD treatment, the SO_4^{2-} concentrations in this watershed are not expected to negatively affect biological recovery.

Once streamwater chemistry improves, the remaining obstacle to ecosystem improvement could be lack of adequate aquatic habitat or stream substrate. Most stream substrates in

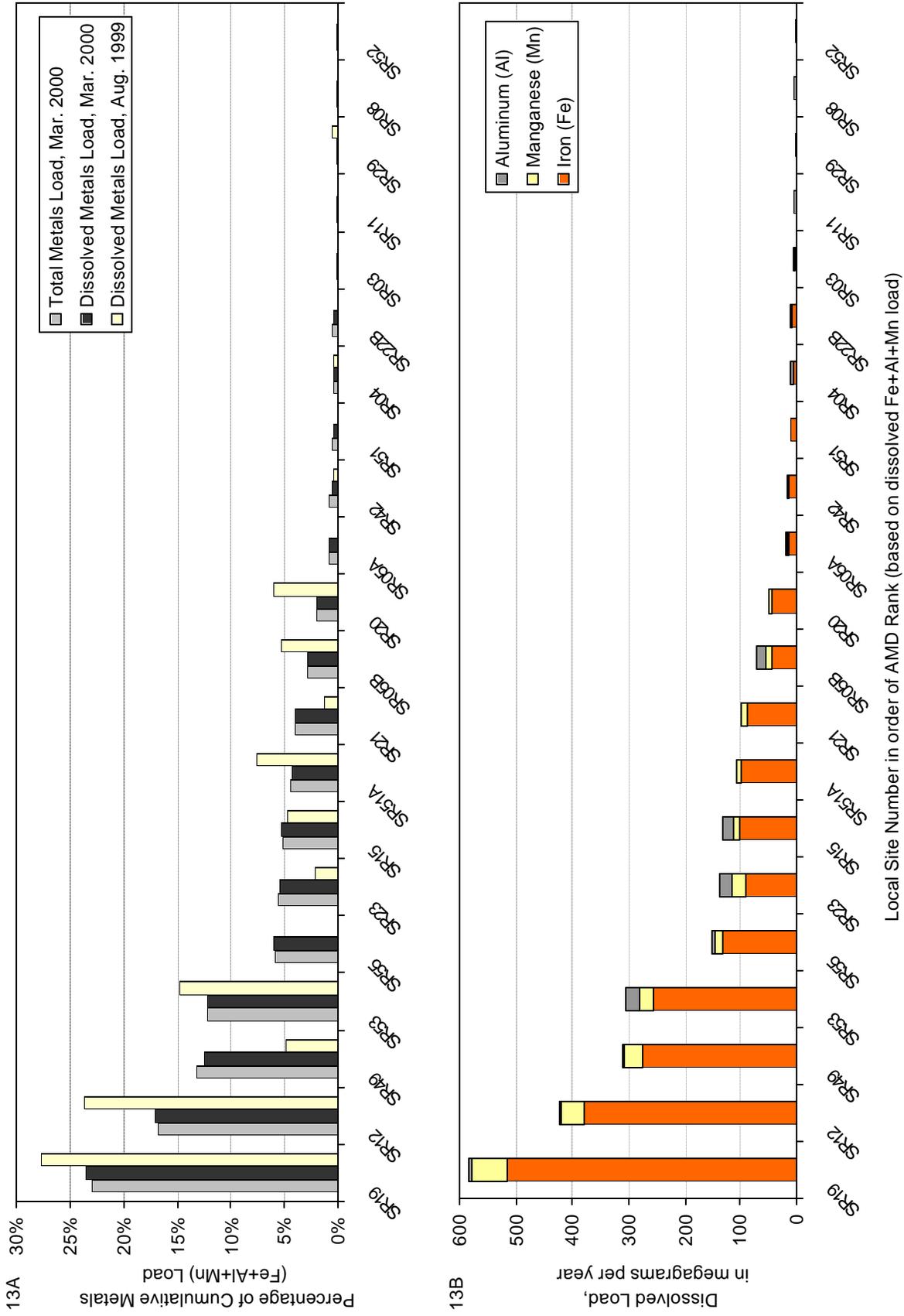


Figure 13. (A) Comparison of priority ranks for top 20 abandoned mine discharge (AMD) sites, Shamokin Creek Basin, Pa., on the basis of concentrations of iron, aluminum, and manganese in whole-water and filtered samples collected in March 2000 and filtered samples collected in August 1999. (B) Relative contributions of dissolved iron, manganese, and aluminum to the dissolved metals loading for top 20 AMD sites, March 2000.

the Shamokin Creek watershed are coated by relatively loose iron-hydroxide flocculents rather than “armored” by tightly bound iron-hydroxide cements. Much of the loose flocculent could be scoured away by fast-flowing water following treatment installation. Evidence of such scouring is observed downstream of the SR42 passive-treatment system in the Carbon Run subwatershed (Kirby, 2001) and in Swatara Creek (Cravotta and Bilger, 2001). At least two major remaining substrate or habitat problems will not be addressed by AMD treatment alone. First, during high-flow events, the erosion of coal and waste-rock particles from numerous mine roads and waste-rock piles into streams periodically will disturb stream habitats. Second, a few stream reaches (especially North Branch Shamokin Creek, Locust Creek, and Coal Run) are ephemeral (always dry except during high flow events) because water is lost to deep mine complexes. The three-metal dissolved load ranking for base-flow conditions does not address these problems.

A variety of restoration activities could be considered to mitigate the AMD contamination in the upper Shamokin Creek Basin. Because many of the AMD sources are extremely large or have insufficient land area for construction of active or passive-treatment systems, emphasis could be placed on the prevention of infiltration through mine spoil or into the underground mines. Ideally, flow rates and metals loading from AMD sources can be reduced by the restoration of streamflow. If surface reclamation or streamflow restoration is planned or completed, the design of any AMD treatment system should consider additional monitoring to document potential changes in flow and loading rates. The following examples of restoration activities were reported as strategies to meet TMDLs in the Shamokin Creek Basin (Pennsylvania Department of Environmental Protection, 2001a, 2001b).

- Reclamation of abandoned surface mines, including removal of abandoned highwalls and spoil banks and filling abandoned surface-mine pits. Reclamation would eliminate surface-water accumulations that become contaminated with mine drainage because of contact with exposed acid-producing strata and greatly reduce the amount of surface runoff directed into the mine-pool systems by promoting surface drainage. The regrading of disturbed areas would provide a more natural flow pattern for runoff and prevent surface flows from percolating through abandoned refuse and entering underground mine pools and emerging as mine discharges.
- Removal, regrading and replanting of abandoned coal-refuse piles would reduce the amount of sediments, silt, and coal-waste runoff into surface streams and eliminate a source of AMD.
- Restoration of surface channels and flow of streams that now disappear into spoil banks and enter deep-mine pools. The reduction of recharge to the deep mines could lessen the volume of water discharged by AMD sources.
- Site-specific assessments to determine whether passive treatment is practical and which systems are best suited for specific discharges. Assessments should include discharge water quality and flow, topographical setting, construction

costs, and long-term operation and maintenance costs. The technology may not be available to passively treat many of these high-volume discharges.

Flow Considerations

The evaluation of contaminant loading rates and the use of these data for the development of TMDLs or design of treatment systems requires sufficient samples to characterize the average values and extremes in flow rates and quality at each of the AMD sources. The low and high base-flow data collected for this study were collected with the intent to bracket average conditions and indicate some of the variability in flow and chemistry (fig. 7). Average conditions generally are not known, however, because continuous records or data on the extremes for flow or chemistry for individual mine discharges in the watershed are not available. Considering the long-term streamflow data for Shamokin Creek at the USGS streamflow-gaging station near Shamokin (figs. 7 and 8), data collected for the high base-flow survey in March 2000 are likely to be consistent with long-term average flow conditions and presumably representative of current water quality. Thus, these data were considered useful for ranking of AMD remediation priorities. For the computation of wetland size (table 7), the maximum flow rate and maximum iron concentration documented for the low and high base-flow surveys were used to indicate a conservative estimate of wetland size. Nevertheless, specific, detailed treatment design at any AMD site would require additional data on the range of flow rates and corresponding variations in water quality. Furthermore, bench-scale testing of the feasible treatment alternatives such as that by Cravotta (2002, 2003), Cravotta and Watzlaf (2002), and Dietz and Dempsey (2002), probably would be required prior to selecting an alternative.

Although cost estimates were not determined for the remedial alternatives, the flow and water-quality data collected for this study can be used to estimate and compare the relative sizes and costs (capital and annual maintenance) for different active-treatment and passive-treatment alternatives. The flow, acidity, alkalinity, and metals concentration data are critical data for such computations because they determine the quantities of neutralizing agents, the overall size of the treatment system, and the quantities of sludge that may require disposal. Given the estimated size and cost for a treatment system, its feasibility can be evaluated based on analysis with a computer program such as AMDTreat (U.S. Office of Surface Mining Reclamation and Enforcement, 2002). The comparison of alternatives becomes complicated, however, considering different assumptions about capital and long-term maintenance costs, replacement frequency, inflation rates, and interest growth. For example, data collected in March 2000 for SR19 were used with AMDTreat version 3.1 and default settings for unit costs (U.S. Office of Surface Mining Reclamation and Enforcement, 2002). Active treatment of SR19 with caustic soda or pebble quick lime was estimated to have a capital cost of approximately \$300,000 and annual maintenance cost of approximately \$200,000. Alterna-

tively, a passive system, such as an ALD coupled with aerobic ponds and assuming 20 g/m²/day iron loading rate (Hedin and others, 1994), is estimated to have a capital cost of approximately \$3,100,000 and negligible annual maintenance costs. For a design life of 20 years, annual inflation rate of 3 percent, and annual interest growth rate of 2.5 percent, AMDTreat indicates the net present cost for treatment of SR19 would be approximately \$3,400,000 for the active systems compared to \$3,100,000 for the passive system. If inflation remained at 3 percent and the interest growth rate were 8 percent or more, the net present costs for the active treatments would be less than that for passive treatment. This example illustrates “high capital, but low maintenance cost” for passive treatment compared to active treatment of large discharges and how these costs are considered in future planning. Nevertheless, land for installation of a passive system may not be available, and the best treatment alternative may not have been considered. Any treatment design would require additional site-specific data.

Summary

Shamokin Creek is a tributary of the Susquehanna River in east-central Pennsylvania. Contaminated runoff and discharges from abandoned anthracite mines in the upper 54 mi² (140 km²) basin degrade the aquatic ecosystem and water quality of Shamokin Creek to its mouth and along many of its tributaries within the upper basin. In order to assess the effects of AMD sources and to identify possible remedial alternatives, the USGS, in cooperation with the PaDEP, BU, and NCCD began a study in 1999. Data on the flow rate and quality of water were collected at all known AMD sites and at selected stream sites within the Shamokin Creek Basin during low base-flow conditions in August 1999 and then repeated during high base-flow conditions in March 2000. The basin-wide synoptic monitoring of flow and water quality during stable base-flow conditions was performed to (1) identify site-specific characteristics including temporal variability associated with seasonal changes in base flow, (2) indicate spatial variability and relative effects of the AMD throughout the basin, and (3) avoid complications in data collection and interpretation associated with rainfall or other short-term weather events. Additionally, during October 1999, 2000, and 2001, data on the diversity and biomass of fish species were collected at a subset of the sampled stream sites, and streamflow of Shamokin Creek below Shamokin was recorded continuously.

The results of this assessment indicate the streamwater in Shamokin Creek as it exits the mining region upstream of SC15 has near-neutral pH. However, this streamwater has elevated concentrations of dissolved iron and acidity compared to alkalinity. Repeated sampling of Shamokin Creek below Shamokin and at Sunbury during 1999 to 2001 indicates the acidity loading and neutralization were not consistent. The pH below Shamokin ranged from 6.2 to 6.5 but at Sunbury ranged from 4.2 to 6.6; lowest and highest values were in August and Octo-

ber 1999, respectively. The acidic character of most AMD sources and tributaries within the upper Shamokin Creek Basin will require the addition of alkalinity to buffer the acid load. Furthermore, the reduction of metals loading will require the installation of dedicated wetland areas or settling basins.

The quantity and quality of water in Shamokin Creek to its mouth at Sunbury and in tributaries in the upper Shamokin Creek Basin above the city of Shamokin are affected by leakage to abandoned underground mines and by metal-contaminated discharges from tunnels, slopes, shafts, and unreclaimed spoil associated with abandoned mines in the Western Middle Anthracite Field. Low base-flow samples collected in August 1999 and high base-flow samples collected in March 2000 provided information on the current water-quality characteristics and the relative differences among AMD sources and stream sampling sites. Because as much as one-fourth of the known AMD sources were not flowing during August 1999, the data for March 2000 were used as the primary basis for characterizing aquatic quality at each site and distinguishing AMD priorities. Generally, concentrations of sulfate, iron, manganese, and aluminum for a particular AMD site were similar or greater during high base-flow than low base-flow conditions. Greater concentrations of these constituents at high base-flow than at low base-flow conditions indicate that recharge during the winter 1999 and spring 2000 was effective mobilizing pyrite oxidation products and was not effective as a diluting agent.

Although pH of approximately half the AMD sources was near neutral (pH 6 to 7), the majority of AMD sources was acidic, with negative values of net alkalinity, indicating that pH ultimately could decline to values less than 4.5 after complete oxidation and hydrolysis of dissolved metals. The predominant source of acidity in most streamwater samples was dissolved iron. Some streamwater and AMD samples, mainly in the North Branch Shamokin Creek and Locust Creek subbasins, had low pH and elevated concentrations of aluminum. Most of the streamwater and associated AMD sources exceeded water-quality criteria for the protection of freshwater aquatic life. In October 1999, no fish were found in Shamokin Creek above Shamokin, Quaker Run, and North Branch Shamokin Creek. Although a few fish were found in Carbon Run and Shamokin Creek below Shamokin, these fish populations were diminished compared to similar size streams in unmined areas. Fish tissue had elevated concentrations of metals, notably zinc.

The concentrations of dissolved metals provided a consistent basis for evaluation of acidity and contaminant loading and were similar to concentrations of total metals in AMD water samples. The computed, cumulative metals loading from AMD sources upstream of stream-monitoring sites generally exceeded the measured load at the stream site. The difference between the computed and measured loads indicates that metals accumulate in upstream segments. This accumulation of metals in the stream degrades the aquatic habitat and indicates that a greater quantity of metal would need to be removed at the AMD source to achieve similar load reduction at a downstream location.

44 Effects of Abandoned Coal-Mine Drainage on Streamflow and Water Quality in the Shamokin Creek Basin

Flow and concentration data for the high base-flow samples collected in March 2000 were used to determine priority ranks of the AMD sources on the basis of loads of dissolved iron, manganese, and aluminum. The AMD source with the highest loading was assigned a rank of 1, with successively higher ranks assigned to AMD sources in descending order of dissolved metal loading. The top 15 AMD sources on the basis of dissolved metals loading in March 2000 accounted for more than 98 percent of the dissolved metals loading to Shamokin Creek. When sampled in March 2000, these AMD sources had flow rates ranging from 0.7 to 19 ft³/s (1,138 to 32,285 L/min) and pH from 3.5 to 6.1. Only 1 of the top 15 AMD sources was net alkaline (alkalinity > acidity); the others were net acidic and will require additional alkalinity to facilitate metals removal and maintain near-neutral pH. Dissolved iron ranged from 10 to 57 mg/L. Dissolved manganese ranged from 1.9 to 7.4 mg/L. Dissolved aluminum exceeded 3.9 mg/L at seven of the sites but was less than 0.2 mg/L at seven others. The estimated aluminum concentration at SR55 was approximately 0.9 mg/L.

Alkalinity can be acquired by the dissolution of limestone and (or) bacterial sulfate reduction within various passive-treatment systems including anoxic or oxic limestone drains, limestone-lined channels, or compost wetlands. Subsequently, the gradual oxidation and consequent precipitation of iron and manganese can be accommodated within settling ponds or aerobic wetlands. For example, AMD at SR42 (ranked 13) currently is treated by a vertical-flow wetland system that consists of layered compost and limestone beds in the first cell followed by two oxidation/settling ponds. Additionally, at SR48, a series of three oxidation/settling ponds was constructed in 2001-2003 by the SCRA. These ponds divert all of a stream (essentially a mine discharge) at low flow and successfully remove most of the iron (the only constituent of concern) in this high-pH alkaline discharge. Assuming an iron removal rate of 180 lb/acre/day (20 g/m²/day), a minimum area of 0.7 to 17.8 acres (590 to 71,670 m²) would be needed for constructed wetlands at the other priority AMD sites. Considering this requirement, the proximity of many discharges to streams, roads, or railroads, and the limited availability or access to land at the discharge location, the implementation of passive treatment would not be feasible at most of the top 15 and many lower priority AMD sites. The reduction of infiltration and removal of culm waste and (or) the relocation of the discharge to nearby areas could decrease the AMD quantities and facilitate treatment at some of the priority AMD sites.

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Appendix A.

COMPUTATION OF WATER QUALITY FOR THE RICHARD'S SHAFT DISCHARGE (SR55) USING AN INVERSE MIXING MODEL WITH UPSTREAM AND DOWNSTREAM DATA

The discharge from the Richard's Shaft Mine Drift near Atlas (SR55) emerges in a ponded area between sampled sites on North Branch Shamokin Creek (SC3B and SC3D) and could not be sampled directly. Therefore, its composition is not directly known. Its volume is known by difference in flow rates of SC3B (upstream) and SC3D (downstream). Its composition can be computed using the flow rates and compositions of the upstream and downstream samples. Then, given its volume and composition, we can compare the metal loading rates at SR55 with other AMD sources in the watershed and estimate the cost of its treatment considering various remedial alternatives.

For a mixture of two end-member solutions, conservation of mass of water and one or more elements in solution can be described as

$$Q_1 = Q_2 + Q_3 \quad (B1)$$

$$C_{i,1}Q_1 = C_{i,2}Q_2 + C_{i,3}Q_3 \quad (B2)$$

$$L_{i,1} = L_{i,2} + L_{i,3} \quad (B3)$$

where Q_n is the volumetric flow rate of solution n , $C_{i,n}$ is the concentration of solute element i in solution n , and $L_{i,n}$ is the load or mass of the solute computed as product of the concentration and flow rate, $L_{i,n} = C_{i,n} \cdot Q_n$. To apply these equations for the computation of SR55 water quality,

- Solution 1 = Base flow in N. Br. Shamokin at SC3D downstream from SR55 and SC3B,
- Solution 2 = Base flow in N. Br. Shamokin at SC3B, upstream of SR55, and
- Solution 3 = Discharge water from Richard's Shaft Mine Drift near Atlas at SR55.

The concentration of a conservative solute in solution 3, $C_{i,3}$, can be computed by dividing equation B2 by Q_1 resulting in

$$C_{i,1} = (C_{i,2} \cdot Q_2) / Q_1 + (C_{i,3} \cdot Q_3) / Q_1. \quad (B4)$$

Substituting proportions of end member solutions in the mixture, $f_2 = Q_2 / Q_1$ and $f_3 = Q_3 / Q_1$, and rearranging as

$$C_{i,1} = C_{i,2} \cdot f_2 + C_{i,3} \cdot f_3 \quad (B5)$$

$$C_{i,3} = (C_{i,1} - C_{i,2} \cdot f_2) / f_3. \quad (B6)$$

An inverse mixing model with PHREEQCI (Parkhurst and Appelo, 1999) that involved mixing and mineral dissolution and precipitation reactions was used to compute the composition of solution 3 on the basis of equation B6. The model involves five steps for the computations, described below, ultimately assuming equilibrium control of Fe and Al concentrations by goethite and amorphous aluminum hydroxide ($Al(OH)_3$ am), respectively.

- Step 1: Adjust $C_{i,2}$ by diluting with pure water ($C_{i,2} \cdot f_2 = C_{i,2}^*$).
- Step 2: Compute mole transfers to create $C_{i,1}$ from $C_{i,2}^*$ ($C_{i,1} = C_{i,2}^* + P_{i,d} - P_{i,p}$), where $P_{i,d}$ is the number of moles of phase containing element i that dissolves, increasing concentration of the solute; $P_{i,p}$ is the number of moles of phase that precipitates or exsolves, decreasing concentration of the solute.
- Step 3: Add computed mole transfers for dissolved phases, adjusted for mixing $C_{i,2}$ and $C_{i,3}$, in 1 liter pure water ($C_{i,3}^* = P_{i,d} / f_3$).
- Step 4: Allow precipitation of nonconservative solutes (Fe, Al) if saturated with respect to selected phases and to indicate the corresponding equilibrium solute concentrations and pH of solution ($C_{i,3} = C_{i,3}^* - P_{i,p}$). Different equilibrium concentrations and pH can result for different controlling phases, for example ferrihydrite vs. schwertmannite or amorphous aluminum hydroxide vs. basaluminite.
- Step 5: Compare results of measured mixture, solution 1, with that computed by mixing the known and computed end members, solutions 2 and 3, respectively.

A sample PHREEQCI program to compute the composition of solution 3 (SR55) in accordance with the above steps follows below. This program used the thermodynamic data base of WATEQ4F (Ball and Nordstrom, 1991).

References Cited

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Example PHREEQC Program

```

DATABASE C:\Program Files\USGS\Phreeqc Interactive 2.8\wateq4f.dat
SELECTED_OUTPUT
  -file                SR55calAl(OH)3.sel
  -reset               false
  -simulation          false
  -solution            true
  -ph                  true
  -reaction            false
  -totals              Ca Mg Alkalinity S(6) Fe Al Mn
  -user_punch          true
USER_PUNCH
  -headings Ca.mg Mg.mg Alk.mg SO4.mg Fe.ug Al.ug Mn.ug
10 PUNCH TOT("Ca")*1000*40.08
20 PUNCH TOT("Mg")*1000*24.305
30 PUNCH ALK*1000*50
40 PUNCH TOT("S(6)")*1000*96.0
50 PUNCH TOT("Fe")*1000000*55.8
60 PUNCH TOT("Al")*1000000*27.0
70 PUNCH TOT("Mn")*1000000*54.9
END
PHASES
Schwert(1.75)
  Fe8O8(OH)4.5(SO4)1.75 + 20.5H+ = 8 Fe+3 + 1.75 SO4-2 + 12.5H2O
  log_k      18
# Bigham and others (1996, Geochimica et Cosmochimica Acta, 60:2111-2121)
SOLUTION 1 SC3D_3/16/00_1215
  temp      9.7
  pH        5.2
  pe        4
  redox     pe
  units     mg/l
  density   1
  Ca        19
  Mg        18.7
  K         1.3
  Alkalinity 10
  S(6)     153 charge
  Al       1510 ug/l
  Fe       10600 ug/l
  Mn       2240 ug/l
  -water   1 # kg
SOLUTION 2 SC3B_3/16/00_1245
  temp      10.5
  pH        3.9
  pe        4
  redox     pe
  units     mg/l
  density   1
  Ca        13.9

```

50 Example PHREEQC Program

```
Mg          15.6
K           1.3
Alkalinity  0
S(6)       127 charge
Al         3400 ug/l
Fe         430 ug/l
Mn         2100 ug/l
-water     1 # kg
SOLUTION 3 PURE_WATER
temp       10
pH         7
pe         4
redox      pe
units      mmol/kgw
density    1
-water     1 # kg
END
USE solution 3
USE solution 2
MIX 1
  2      0.53
  3      0.47
SAVE SOLUTION 4
END
INVERSE_MODELING 1
-solutions      4      1
-uncertainty    0.05   0.05
-phases
  O2(g)          dis
  CO2(g)         dis
  Melanterite    dis
  Calcite        dis
  Dolomite       dis
  Epsomite       dis
  Al(OH)3(a)
  AlumK
  Basaluminite
  Pyrolusite
  Goethite
#   Fe(OH)3(a)
#   Schwert(1.75)
-balances
  Mn            0.02   0.02
-tolerance      1e-010
-mineral_water  true
SAVE solution 5
END
USE SOLUTION 3
REACTION 1
  O2(g)         2.318e-005
  CO2(g)        3.182e-003
```

```
Melanterite      3.195e-004
  Calcite        2.903e-004
  Epsomite      4.292e-004
#   Al(OH)3(a)   -2.645e-005
  AlumK         1.563e-005
  Pyrolusite    2.052e-005
#   Goethite    -1.337e-004
2.128 moles in 1 steps
# Moles based on proportion mixed below, 2.128 = 1/0.47
EQUILIBRIUM_PHASES 1
#   Gypsum 0 0
#   Gibbsite 0 0
  Al(OH)3(a) 0 0
#   Fe(OH)3(a) 0 0
  Goethite
#   Basaluminite 0 0
#   Schwert(1.75) 0 0
SAVE SOLUTION 3
END
USE solution 3
USE solution 2
MIX 1
  2   0.53
  3   0.47
EQUILIBRIUM_PHASES 1
#   Gypsum 0 0
#   Gibbsite 0 0
  Al(OH)3(a) 0 0
#   Fe(OH)3(a) 0 0
  Goethite
#   Basaluminite 0 0
#   Schwert(1.75) 0 0
```

Appendix B.

Hydrological data for abandoned mine drainage and associated stream monitoring sites in the Shamokin Creek Basin, August 1999 to October 2001 (CD rom, only)

Appendix C.

Digital reproductions of out-of-print reports (CD rom, only)

Gannett Fleming Corddry and Carpenter, Inc., 1972, Operation Scarlift project no. SL-113: Mine drainage abatement measures for the Shamokin Creek Watershed: Gannett Fleming Corddry and Carpenter, Inc. Engineers, Harrisburg, Pennsylvania.

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