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## PROJECT SPOTLIGHT

### Abandoned Mine Drainage in the Swatara Creek Basin: Streamwater Quality Trends Coinciding with the Return of Fish

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#### Introduction

Drainage from abandoned mines affects the water quality and ecology of streams and lakes in coal and metal mining regions worldwide (Nordstrom 2000). Mining in the Appalachian Coalfield of the eastern USA has transformed the local landscape and rendered many streams fishless because of "acidic" mine drainage (AMD) (Herlihy et al. 1990). In Pennsylvania, AMD from abandoned coal mines is the leading cause of nonpoint source (NPS) pollution, degrading approximately 8,800 km (5,500 mi) of streams (Pennsylvania Department of Environmental Protection 2004, 2007) and accounting for lost revenues of approximately $67 million annually because of recreational fishing losses (Pennsylvania Organization for Watersheds and Rivers 2002).

Effects of AMD are complex but can be categorized as acidity, metal toxicity, sedimentation, and salinization (Gray 1997). AMD is commonly acidic (pH < 4.5) and has elevated concentrations of sulfate ($SO_4$), iron (Fe), aluminum (Al), manganese (Mn), zinc (Zn), nickel (Ni), copper (Cu), lead (Pb), and other solutes that result from the oxidation of pyrite ($FeS_2$) and the subsequent dissolution of aluminosilicate, oxide, and carbonate minerals by acidic water (Blowes et al. 2003, Cravotta 2008, Nordstrom 2000). Low pH and elevated concentrations of dissolved metals in the water column and pore water of stream sediment can be stressful or toxic to fish and aquatic macroinvertebrates (Baker and Schofield 1982, Butler et al. 1973, Courtney and Clements 2002, Dsa et al. 2008).

## EDITOR'S NOTE

In this issue of *NWQEP NOTES*, we continue our series on National Nonpoint Source Monitoring Program (NMP) projects that have documented improvements in water quality due to the implementation of best management practices (BMPs).

In Pennsylvania, acidic mine drainage (AMD) from abandoned coal mines is the leading cause of nonpoint source pollution, adversely impacting water quality, aquatic ecology, as well as revenues from recreational fishing. Swatara Creek in eastern Pennsylvania has a history of AMD contamination, characterized by acidity and elevated levels of sulfate and dissolved metals, which can be harmful to fish and aquatic macroinvertebrates. Data from 1959-1986 indicate that fish were mostly absent in upper Swatara Creek.

The Swatara Creek project was accepted into the NMP in 1998. To neutralize the AMD and reduce the transport of dissolved metals, the project implemented innovative passive-treatment systems in the upper Swatara Creek Basin. These treatment systems were all aimed at adding alkalinity to the streams and included limestone-sand dosing, open limestone channels, anoxic and oxic limestone drains, limestone diversion wells, and aerobic wetlands. Effectiveness of the treatment systems was evaluated over the eleven-year project period using upstream/downstream and before/after monitoring designs.

The results indicate that the AMD treatment implemented during the 1990s helped to reduce acidity, reduce the transport of metals, and recover fish populations in Swatara Creek. During 1996-2006, as many as 25 species of fish were identified, including several taxa intolerant of pollution and low pH. Base flow data indicated increased pH (to near-neutral) and decreased concentrations of sulfate, dissolved iron, and dissolved aluminum.

The author notes that recovery of the aquatic ecology in Swatara Creek will be compromised by the presence of metals in the streambed sediment, which continue to be transported in suspended and dissolved form particularly during storm events. Several suggestions are offered for addressing the additional challenges of controlling pH and metals transport during stormflow conditions.

As always, please feel free to contact me with your ideas, suggestions, and possible contributions to this newsletter.

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The severity of metals toxicity tends to be greater under low-pH conditions than under near-neutral conditions. Accordingly, the U.S. Environmental Protection Agency (USEPA) (2002) recommends pH 6.5 to 9.0 for protection of freshwater aquatic life, and the Commonwealth of Pennsylvania (2002) stipulates that effluent discharged from active mines must have pH 6.0 to 9.0 *and* alkalinity greater than acidity. Near-neutral pH could result from dissolution of limestone and other calcareous bedrock by the AMD or from mixing of acidic AMD with neutral, carbonate-buffered surface water. At near-neutral pH, concentrations of dissolved Al and Fe are limited by the precipitation of hydrous oxide and hydroxysulfate minerals, and the transport of other toxic metals, such as dissolved Cu, Pb, Ni, and Zn is attenuated through adsorption to such minerals (Cravotta 2008). Nevertheless, even if concentrations of solutes in the water column are below toxicity thresholds, the accumulation of metal-rich solids within the streambed can degrade the benthic habitat and affect trophic structure and reproduction (Dsa et al. 2008, Havas and Rosseland 1995). Accordingly, strategies to treat the AMD before it discharges to streams commonly implement steps that increase pH and alkalinity, promote the oxidation of Fe and Mn, and facilitate the precipitation and settling of hydrous oxides of Fe, Mn, Al, and other metal-rich compounds (Johnson and Hallberg 2005, Skousen et al. 1998, Watzlaf et al. 2004).

Chemical conditions in streams may rebound quickly following neutralization of AMD; however, the recovery of aquatic invertebrates, zooplankton, and fish may take decades (Herricks 1977, Monteith et al. 2005, Youndt and Niemi 1990). Impediments to ecological recovery of acidified systems include impaired or unstable water quality, residual effects of degraded substrate or habitat, inadequate or inaccessible supply of organisms for recolonization, and community-level competition and dynamics (Herricks 1977, Nelson and Roline 1996, Yan et al. 2003).

Despite historical degradation from AMD, reproducing populations of brook trout (Salvelinus fontinalis) and other native fishes have been documented recently in several streams in the Anthracite Coalfield of eastern Pennsylvania that had been considered fishless in 1995 (Cravotta 2005, Cravotta and Kirby 2004, USEPA 1995). The recent appearance of fish coincides with improved water quality of the streams and associated AMD sources, characterized by near-neutral pH, increased alkalinity, and decreased concentrations of acidity and dissolved metals (e.g., Wood 1996, Raymond and Oh 2009).

This article discusses the hypothesis that AMD treatment has improved downstream water quality and promoted the return of fish and other aquatic life to the upper Swatara Creek and its major tributaries during the period 1996-2007. The discussion evaluates a unique combination of data from annual surveys of fish populations, and continuous records of streamflow, temperature, pH, and other chemical data for stream segments downstream from AMD sources during the study period.

## Description of Study Area

Swatara Creek drains an area of 1,472 km2 (568 $mi^2$) in the Ridge and Valley Physiographic Province of eastern Pennsylvania, flowing 115 km (71 mi) from its headwaters in the Southern Anthracite Coalfield of Schuylkill County to its mouth on the Susquehanna River at Middletown, Dauphin County. Approximately 75% of the 112-km2 (43 $mi^2$) area of the upper Swatara Creek Basin, upstream from the U.S. Geological Survey (USGS) streamflow gaging station at Ravine (Figure 1), is underlain by anthracite-bearing bedrock. During the late 1800s through the 1940s, extensive underground mines were developed to depths as great as 1,000 m (3,280 ft). Current land use in the upper area is classified as 87% forested, 5% agricultural, and 6% "barren, mined."

Prior to recent restoration efforts in the Swatara Creek Basin, surface water could drain to numerous abandoned underground mines through mine openings and subsidence pits. Further downstream, contaminated groundwater discharged from more than 40 AMD sources, degrading Swatara Creek and rendering the uppermost 20 km (12 mi) fishless for most of the 20$^{th}$ century (Growitz et al. 1985, Shoemaker 1932, Stuart et al. 1967). Because of low pH and metals contamination from the AMD, Pennsylvania included upper Swatara Creek on the state's 303(d) list of impaired waters in 1996 and designated the upper basin a "high priority watershed" for reducing NPS pollution (Pennsylvania Department of Environmental Protection 2007, 2008).

Various low-cost methods of treatment were implemented at or near the largest AMD sources (Figure 1B), including open limestone channels, anoxic and oxic limestone drains, limestone diversion wells, hydrated lime dosing, and aerobic wetlands (e.g., Arnold 1991, Ziemkiewicz et al. 2003, Skousen et al. 1998, Johnson and Hallberg 2005, Watzlaf et al. 2004). Specific details on most of the AMD treatments, installed during 1995-2001, and their water-quality effects are reported by Cravotta (2009). Additionally, surface reclamation of abandoned mine land (AML) areas ranging from 7.7 to 35 ha (19 – 86 ac) over a total area of 230 ha (568 ac) was implemented during this period (Pennsylvania Department of Environmental Protection 2004, Schuylkill Conservation District et al. 2006).

## Methods

The USGS collected hydrologic data at more than 80 locations in the upper Swatara Creek Basin during 1996-2007 (Szpir et al. 2007, U.S. Geological Survey variously dated). To evaluate the cumulative effects of AMD remediation and the transport of pollutants from the mined part of the upper Swatara Creek Basin to unmined areas downstream, in 1996 the USGS reestablished "continuous-record" stations for streamflow and water quality monitoring on Swatara Creek at Ravine near the outlet of the 112-km2 (43 $mi^2$) upper basin, on Swatara Creek at Newtown near the headwaters, and on Swatara Creek at Pine Grove approximately 6 km (3.7 mi) downstream from the mined area (Figure 1). These sites had been monitored previously by USGS and others. Additionally, continuous-record streamflow and water-quality gaging stations were established on Swatara Creek at Newtown upstream of limestone diversion wells and on Lorberry Creek at Mollystown (Figure 1). For this article, a subset of the monitoring data collected at primary streamflow gaging stations on Swatara Creek, Good Spring Creek, and Lorberry Creek were used.

The continuous-record stations were equipped with automatic stage recording, water quality monitoring, and/or water sampling devices. Stream stage was measured continuously with a pressure transducer, and the temperature, pH, and specific conductance (SC) were measured continuously with a multiparameter sonde. The stage and water quality values were recorded at 15- minute intervals. Streamflow was computed from stage-discharge ratings developed for each site. Instantaneous data for temperature, SC, pH, redox potential (Eh), and dissolved oxygen (DO) were measured using standard field methods when continuous-record data were retrieved at gaging stations or when water quality samples were collected. Fixed-interval grab samples, mostly at base flow conditions, were collected at 4-week or 6-week intervals from well-mixed zones in the stream. For Swatara Creek at Ravine, Swatara Creek at Newtown, and Lorberry Creek at Mollystown, numerous additional base flow and stormflow samples were collected using pumping samplers containing 24 bottles. Stormflow samples submitted for analysis were selected to cover rising, peak, and falling stages of the hydrograph. Stormflow samples of Swatara Creek at Ravine were analyzed for more than 60 events during the study.

Water samples were split into subsamples in the field or in the USGS Pennsylvania Water Science Center laboratory. Whole-water samples were analyzed for pH and "acid-neutralizing capacity" (alkalinity). Samples for "dissolved" (filtered, 0.45 mm membrane) and total recoverable (whole-water, HNO3 digestion), and hydrochloric acid (HCl) metal analysis were analyzed for major ions and trace metals by inductively coupled plasma atomic emission spectrometry (ICP-AES), ion chromatography (IC), colorimetry, and electrometric titration (Crock et al. 1999, Fishman and Friedman 1989, Hoffman et al. 1996). For quality assurance of chemical analyses, USGS standard reference water samples (SRWS) were submitted with each batch of samples.

Hardness, expressed in mg/L as CaCO3, was computed from the concentrations of dissolved calcium and magnesium in mg/L (2.5.CCa + 4.1.CMg). The net acidity was computed considering positive acidity contributions from protons and concentrations of dissolved iron, manganese, and aluminum, and negative contributions from alkalinity as described by Kirby and Cravotta (2005).

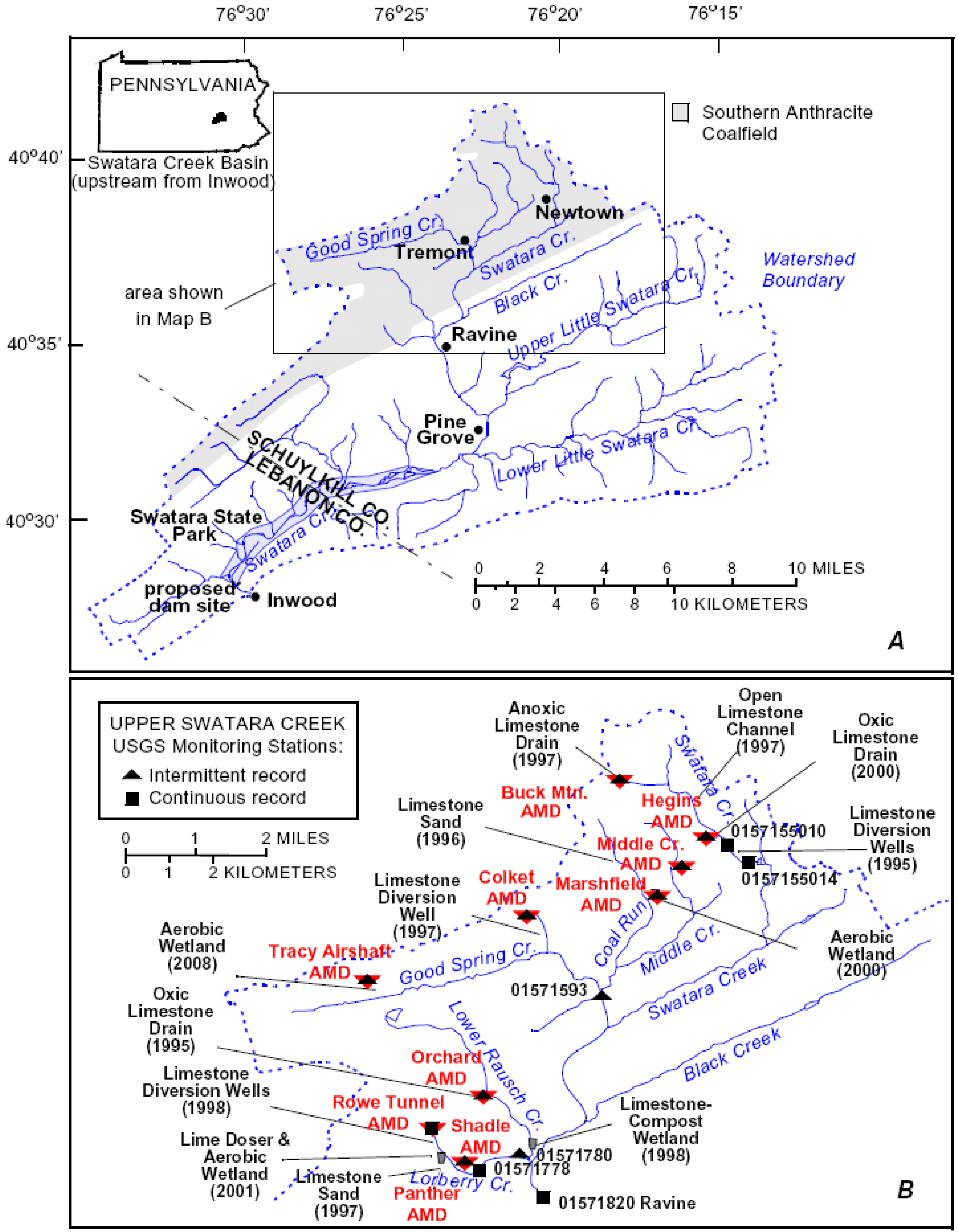


**Figure 1.** Municipalities, "acidic" mine drainage (AMD), AMD treatment with year of implementation in parentheses, and USGS monitoring stations in the Swatara Creek Basin upstream from the proposed dam for Swatara State Park Reservoir, Lebanon and Schuylkill Counties, Pennsylvania. USGS monitoring station numbers are indicated for sites with fish data.

Fish were collected annually in Swatara Creek at Ravine and Newtown, Good Spring Creek at Tremont, and Lorberry Creek near Ravine (Figure 1) by electrofishing over a 150-m (492-ft) reach consisting of mixed riffle, run, and pool habitats (Barbour et al. 1999, USEPA 1993). Individual fish were identified to species and measured before releasing most specimens.

Streamflow and water-quality data were evaluated using various graphical and computational methods to indicate frequency distributions, correlations, and trends. To compare hydrologic conditions among sites during the study with the long-term record, streamflow duration records (probability plots) for the Ravine and Newtown streamflow gaging stations were displayed with records for stations on Swatara Creek at Pine Grove and Harper Tavern, which were 7.7 and 48.0 km (4.8 and 30 mi) downstream from Ravine, respectively. Daily mean streamflow values for these sites also were used with the PART hydrograph-analysis computer program (Rutledge 1998) to estimate annual mean streamflow and base-flow and surface-runoff contributions during the study. Interbasin variability during the study was indicated by the streamflow "yield," computed by dividing the annual streamflow by the estimated drainage area at the gaging station. In units of cm/yr, the streamflow yield can be compared with annual rainfall and used to indicate evapotranspiration (rainfall minus streamflow yield), recharge (base-flow yield), and other water-budget terms for the basin (Cravotta and Nantz 2008, Rutledge 1998). Hydrographs and time-series displays of water-quality data, such as boxplots and probability plots by time interval, were used to illustrate potential trends during the study. For graphical illustration, the instantaneous load (transport) was computed as the product of concentration and flow rate.

A multivariate approach was used to compute daily concentration and unbiased estimates of annual load at continuously gaged monitoring sites. This approach described by Langland et al. (2006) uses the log-linear 7-parameter "ESTIMATOR" regression model of Cohn et al. (1989) with daily mean streamflow and time parameters to estimate the continuous distribution of daily concentration values.

After determining the regression models on the basis of measured concentrations and streamflow, the daily mean streamflow values were used to estimate daily concentrations of hydrogen ion (pH), alkalinity, dissolved calcium, dissolved sulfate, dissolved and total iron, dissolved and total manganese, dissolved aluminum, and dissolved zinc for Swatara Creek at Ravine and Swatara Creek at Newtown. The daily concentration estimates for the 1997-2006 period were then multiplied by daily mean streamflow and integrated over time to indicate annual loads. Next, by dividing the annual load by the annual streamflow, the annual mean flow-weighted concentration was computed for each calendar year of the study. The flow-weighted concentration computed on this basis is considered an unbiased estimate of the mean concentration in a total volume of water flowing past a specific location in a specific time period (Langland et al. 2006). Flow-adjusted trend analysis was conducted to indicate changes in water quality that result from factors other than streamflow, such as changes in land use or other management practice (Helsel and Hirsch 2002).

## Results

### *Return of Fish Populations, 1996-2006*

During the 1990s, native fish populations returned to upper Swatara Creek. No fish had been found during ecological surveys of Swatara Creek at Ravine prior to 1990 (Bradford and Sickles 1950, Shoemaker 1932, Skelly & Loy, Inc. 1987). However, in 1996, six species, including blacknose dace (Rhinichthys atratulus), brook trout (Salvelinus fontinalis), and white sucker (Catostomus commersoni) were captured by electrofishing (Table 1). The colonizing fish were believed to have originated from wild stocks in unaffected or marginally affected tributaries and downstream reaches in the watershed. From 1996 to 2002, the number of fish species in Swatara Creek at Ravine increased annually to 25 species (Table 1, Figure 2). However, during high base flow conditions in 2003 and 2004, fewer fish were captured than preceding years (Figure 2). When the surveys were resumed in 2005 and 2006, base flow conditions were comparable to earlier survey conditions and large numbers of fish of various species were captured.

The number of fish species and total number of fish counted in Swatara Creek at Ravine were inversely related to the streamflow on the date of survey and, to a lesser extent, to the maximum streamflow during the week of the survey (Figure 2). High base flow conditions on the date of the survey increased water depth, turbidity, and velocity of transport of stunned fish resulting in reduced capture efficiency. Fish species that were relatively abundant during the higher streamflow conditions, notably rock bass (Ambloplites rupestris), were concentrated near large rocks and boulders along the stream bank and were more easily captured than other fish species at higher flows.

In 1996 and 2006, streamflow conditions of Swatara Creek at Ravine during the dates and weeks of fish surveys were similar (Figure 2). Despite similar survey conditions and methods, only 76 fish of 6 species were collected in 1996 compared to a total of 195 fish of 16 species in 2006. Comparing survey results for 1996 and 2006, increases in fish-species diversity also were apparent for Good Spring Creek at Tremont (5 species in 1996; 9 species in 2006) and Swatara Creek at Newtown (0 fish in 1996; 2 brook trout in 2006) (Figure 2).

As indicated by boxplots summarizing water-quality data for the sites where fish surveys were conducted (Figure 3), Swatara Creek at Ravine and Good Spring Creek at Tremont generally exhibited net-alkaline water quality with consistently near-neutral pH from 1996 to 2007. These two sites also had the largest streamflow and yielded the greatest numbers of fish

**Table 1.** Fish species identified during annual surveys of Swatara Creek at Ravine, Pa., 1996-2006.

| Taxa[a]: ORDER / Family / *Genus species* | Common Name | Minimum pH in PA[b] | Pollution Tolerance[c] | 7/96 | 10/97 | 9/98 | 9/99 | 10/00 | 10/01 | 10/02 | 10/03 | 10/04 | 10/05 | 10/06 | Other Records[d] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Number of Individuals | | | | | | | | | | | |
| CYPRINIFORMES | | | | | | | | | | | | | | | |
| Cyprinidae | | | | | | | | | | | | | | | |
| *Campostoma anomalum* | Central stoneroller | 6.0 | M | 0 | 0 | 0 | 2 | 35 | 67 | 69 | 5 | 1 | 231 | 6 | LG |
| *Cyprinella spiloptera* | Spotfin shiner | 6.4 | M | 0 | 0 | 3 | 3 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | |
| *Exoglossum maxillingua* | Cutlips minnow | 6.1 | I | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | G |
| *Luxilus cornutus* | Common shiner | 6.0 | M | 0 | 0 | 0 | 0 | 0 | 6 | 1 | 0 | 0 | 1 | 0 | G |
| *Nocomis micropogon* | River chub | 6.0 | I | 1 | 14 | 9 | 44 | 27 | 75 | 76 | 7 | 2 | 26 | 9 | G |
| *Notemigonus crysoleucas* | Golden shiner | 4.6 | T | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | |
| *Notropis amoenus* | Comely shiner | 6.5 | T | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | G |
| *Notropis hudsonius* | Spottail shiner | 6.4 | M | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 1 | 0 | 0 | |
| *Notropis rubellus* | Rosyface shiner | 6.0 | I | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | |
| *Pimephales notatus* | Bluntnose minnow | 5.6 | T | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | G |
| *Rhinichthys atratulus* | Blacknose dace | 5.6 | T | 22 | 47 | 162 | 6 | 46 | 26 | 99 | 6 | 2 | 108 | 22 | NLG |
| *Rhinichthys cataractae* | Longnose dace | 5.9 | I | 12 | 1 | 17 | 4 | 24 | 28 | 15 | 0 | 0 | 105 | 0 | LG |
| *Semotilus atromaculatus* | Creek chub | 5.2 | T | 0 | 7 | 22 | 1 | 7 | 2 | 32 | 0 | 0 | 8 | 2 | NLG |
| *Semolitus corporalis* | Fallfish | 6.1 | M | 0 | 66 | 54 | 30 | 20 | 121 | 49 | 1 | 1 | 235 | 22 | G |
| Catostomidae | | | | | | | | | | | | | | | |
| *Catostomus commersoni* | White sucker | 4.6 | T | 20 | 25 | 52 | 22 | 19 | 35 | 26 | 2 | 1 | 43 | 6 | G |
| *Hypentelium nigricans* | Northern hog sucker | 6.0 | I | 0 | 0 | 0 | 5 | 2 | 0 | 1 | 0 | 3 | 30 | 3 | |
| SILURIFORMES | | | | | | | | | | | | | | | |
| Ictaluridae | | | | | | | | | | | | | | | |
| *Ameiurus natalis* | Yellow bullhead | 6.5 | T | 0 | 1 | 1 | 0 | 1 | 2 | 1 | 2 | 0 | 2 | 0 | |
| *Ameiurus nebulosus* | Brown bullhead | 4.6 | T | 0 | 1 | 12 | 2 | 1 | 0 | 1 | 0 | 0 | 1 | 2 | G |
| *Noturus insignis* | Margined madtom | 5.9 | M | 0 | 0 | 2 | 9 | 3 | 9 | 2 | 1 | 0 | 6 | 0 | G |
| ESOCIFORMES | | | | | | | | | | | | | | | |
| Esocidae | | | | | | | | | | | | | | | |
| *Esox niger* | Chain pickerel | 4.6 | M | 0 | 0 | 0 | 2 | 0 | 1 | 4 | 0 | 0 | 0 | 0 | G |
| SALMONIFORMES | | | | | | | | | | | | | | | |
| Salmonidae | | | | | | | | | | | | | | | |
| *Oncorhynchus mykiss* | Rainbow trout | 6.5 | M | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | G |
| *Salmo trutta* | Brown trout | 5.9 | M | 2 | 0 | 1 | 2 | 1 | 2 | 3 | 0 | 0 | 1 | 0 | LG |
| *Salvelinus fontinalis* | Brook trout | 5.0 | M | 19 | 10 | 21 | 5 | 7 | 3 | 8 | 2 | 4 | 11 | 1 | NLG |
| SCORPAENIFORMES | | | | | | | | | | | | | | | |
| Cottidae | | | | | | | | | | | | | | | |
| *Cottus sp.* | Sculpin | 5.9 | M | 0 | 0 | 2 | 0 | 2 | 1 | 3 | 0 | 0 | 1 | 1 | |
| PERCIFORMES | | | | | | | | | | | | | | | |
| Centrarchidae | | | | | | | | | | | | | | | |
| *Ambloplites rupestris* | Rock bass | 6.0 | M | 0 | 0 | 0 | 6 | 5 | 20 | 66 | 109 | 31 | 15 | 110 | G |
| *Lepomis auritus* | Redbreast sunfish | 6.2 | M | 0 | 0 | 2 | 2 | 4 | 12 | 1 | 0 | 0 | 0 | 0 | G |
| *Lepomis cyanellus* | Green sunfish | 6.4 | T | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 0 | 5 | 0 | |
| *Lepomis gibbosus* | Pumpkinseed | 4.6 | M | 0 | 1 | 0 | 2 | 3 | 7 | 3 | 0 | 0 | 0 | 0 | G |
| *Lepomis macrochirus* | Bluegill | 6.5 | M | 0 | 0 | 2 | 1 | 1 | 0 | 6 | 0 | 1 | 0 | 2 | G |
| *Micropterus dolomieu* | Smallmouth bass | 6.0 | M | 0 | 7 | 0 | 52 | 4 | 12 | 12 | 5 | 0 | 17 | 3 | G |
| *Micropterus salmoides* | Largemouth bass | 4.7 | M | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | |
| Percidae | | | | | | | | | | | | | | | |
| *Etheostoma olmstedi* | Tessellated darter | 5.9 | M | 0 | 12 | 16 | 3 | 6 | 5 | 8 | 2 | 0 | 27 | 3 | |
| *Percina peltata* | Shield darter | 6.5 | I | 0 | 0 | 0 | 3 | 2 | 3 | 6 | 0 | 1 | 13 | 0 | |
| Total number of individuals collected: | | | | 76 | 195 | 379 | 206 | 227 | 443 | 495 | 142 | 48 | 890 | 195 | |
| Total number of species identified: | | | | 6 | 15 | 17 | 21 | 24 | 25 | 25 | 11 | 11 | 23 | 16 | |

[a] Names are consistent with the Pennsylvania species taxa list of Steiner (2000).
[b] Minimum pH of occurrence in freshwater in Pennsylvania as reported by Butler et al. (1973).
[c] Pollution tolerance: I (intolerant), M (moderate), T (tolerant), adapted from Barbour et al. (1999)
[d] Letter indicates fish species identified during 1996-2006 at other stations: N, Swatara Creek at Newtown; L, Lorberry Creek at Lorberry Junction; G, Good Spring Creek at Tremont.

compared to Lorberry Creek and Swatara Creek at Newtown (Figure 2). In contrast, the water quality for Lorberry Creek and Swatara Creek at Newtown frequently was acidic with corresponding values of pH ranging to 5.5 and less during the study (Figure 3).

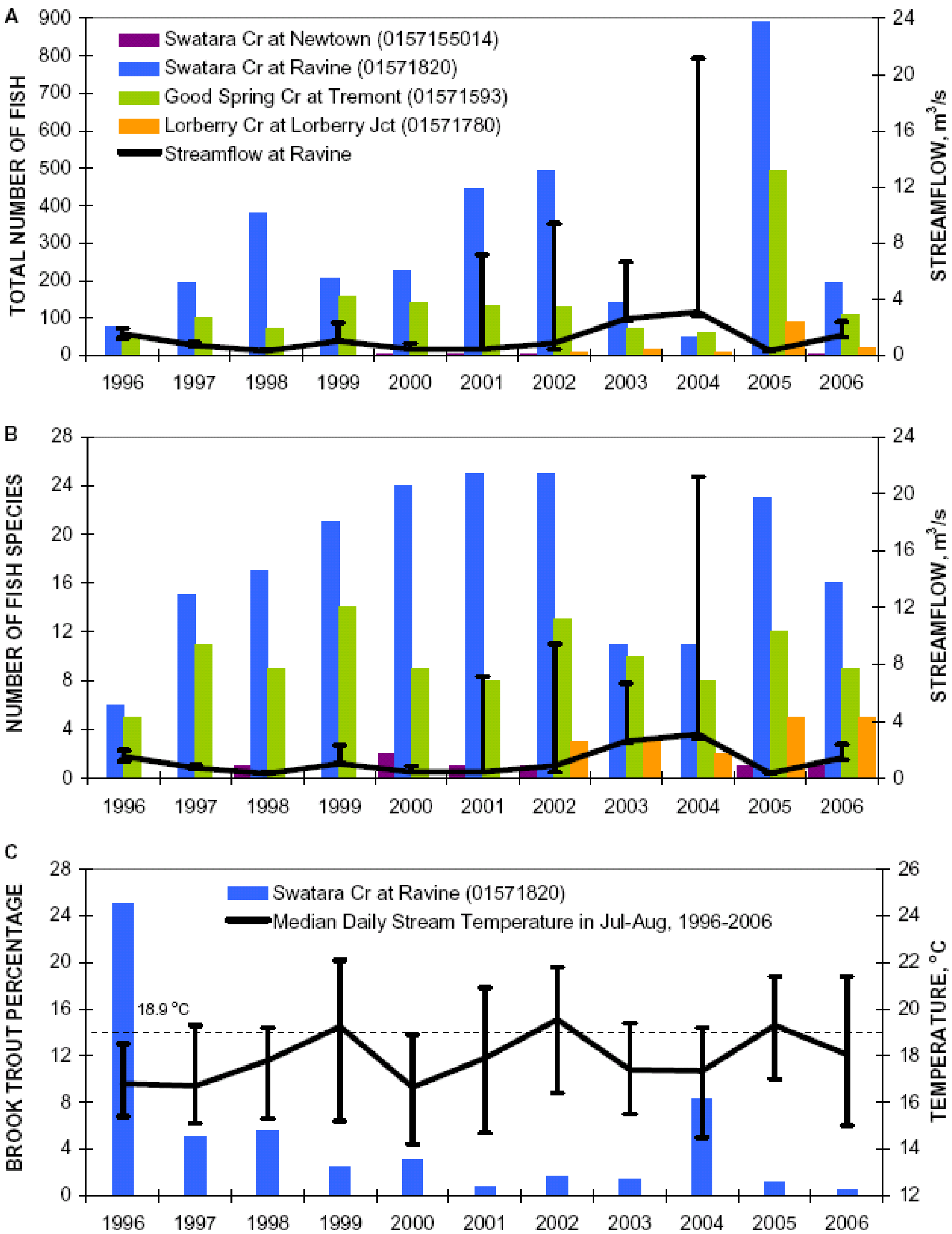


**Figure 2.** Annual electrofishing survey results at selected sites* in Swatara Creek Basin, 1996-2006: A, total number of fish at each site; B, number of fish species at each site; C, percentage of brook trout relative to total number of fish at Swatara Creek at Ravine. *Lorberry Creek was not surveyed before 2002. In A and B, solid black line indicates observed streamflow for Swatara Creek at Ravine during survey; vertical error bars indicate range of daily mean streamflow at Ravine during the week before the survey. In C, solid black line indicates daily mean temperature in July and August; vertical error bars indicate associated range of daily mean temperature; dashed horizontal line indicates maximum temperature permitted for "cold-water fishery" in July and August (Commonwealth of Pennsylvania 2002).

### *Streamwater Quality and Streamflow*

Temporal variability in streamflow is one of the most important factors affecting water quality. Although annual streamflow was within the normal range during 1996-1998 and 2005-2007, it was lower than normal in 1999-2001 and greater than normal in 2002-2004 (Figure 4A). Hydrograph separation indicated the total streamflow at Ravine during the study was composed of about 75% base flow and 25% storm runoff (Table 2). Generally the runoff associated with stormflow events lasted from hours to several days.

The upstream station on Swatara Creek at Newtown had lower annual mean streamflow yield than downstream gaging stations on Swatara Creek at Ravine, Pine Grove, and Harper Tavern (Table 2). This pattern is consistent with this upstream drainage area losing water to the underground mine that flows eastward to the Otto Colliery in the adjacent watershed. In contrast, large streamflow and base flow yields for Lorberry Creek (Table 2) are consistent with contributions by groundwater inflows from outside the delineated surface watershed. During the present study and historically, the Rowe Tunnel (that drains the Lincoln Mine pool extending beneath the Lorberry Creek and Lower Rausch Creek watersheds) discharge accounted for more than 60% of the annual streamflow of Lorberry Creek.

At Ravine, the continuously recorded pH ranged from 4.7 to 8.2 and SC ranged from 27 to 540 mS/cm during the study (Figures 4 and 6); pH and SC values generally decreased with increased streamflow (Figure 6). Minimum values of pH and SC were recorded for stormflow, implying that storm runoff that mixes with base flow is both acidic and dilute, as explained in more detail below.

One could hypothesize that with the implementation of limestone-based treatment systems at many of the AMD sources in the Swatara Creek Basin during the late 1990s (Figure 1), streamflow would not be affected, but pH, alkalinity, and calcium concentrations would increase at downstream sites. Frequency

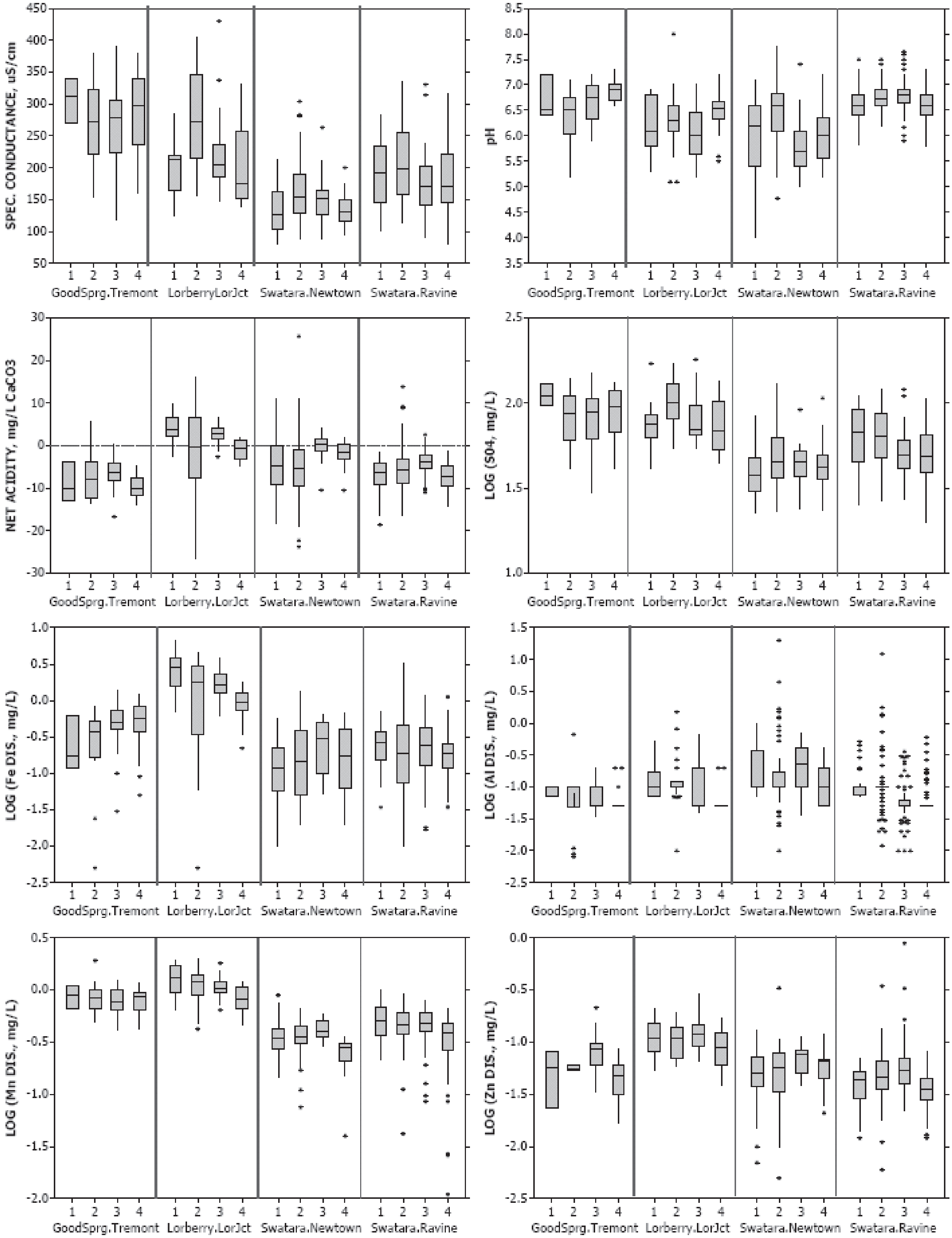


**Figure 3**. Boxplots summarizing hydrochemical characteristics of stream water at sites of annual fish surveys in Swatara Creek Basin, Pa., over 3-year intervals: (1) 1996-1998, (2) 1999-2001, (3) 2002- 2004, (4) 2005-2007. Shaded area of box indicates the "interquartile" range (IQR = 25th to 75th percentile); horizontal line inside the box indicates the median; vertical lines extend to extreme values within 1.5 times the IQR; symbols indicate outlier values.

distribution plots of streamflow, pH, SC, and temperature of Swatara Creek at Ravine for 3-year intervals during 1996-2007 (Figure 4) show that the streamflow distribution during 1996-1998 was comparable to the long-term distribution. However, during the 1996-1998 period, Swatara Creek had a greater frequency of low values of pH and SC and a smaller range in temperature compared to later periods (Figures 4 and 5). The decrease in the frequency of low values of pH and SC and the increase in the range of temperature after 1998 coincided with, and could result from, the implementation of AMD treatments. Limestone diversion wells, limestone drains, and limestone channels are sources of calcium and alkalinity that would tend to increase the pH and SC. Constructed wetlands and the diversion of streams from mines to surface channels would have little effect on dissolved solute concentrations but could affect water temperature. After 1998, maximum stream temperatures increased during summer months and decreased during winter months (Figure 5). This increased range in maximum temperature is consistent with increased thermal exchange with the ambient atmosphere that could result from the impoundment of AMD in wetlands and the restoration of streamflow at mine-infiltration sites. Evaporation of stream water during low-flow periods would tend to amplify these effects on temperature and SC.

During 1996-2007, stream water quality samples for chemical analysis were collected for a wide range of hydrologic conditions (Figure 7). The samples collected with automated sampling devices during storm events were identified as rising, peak, and falling "stormflow" samples on the basis of the hydrograph for Swatara Creek at Ravine on the date of sampling. Samples collected during relatively stable stream stage between storm events were characterized as normal, low, and high "base flow" samples.

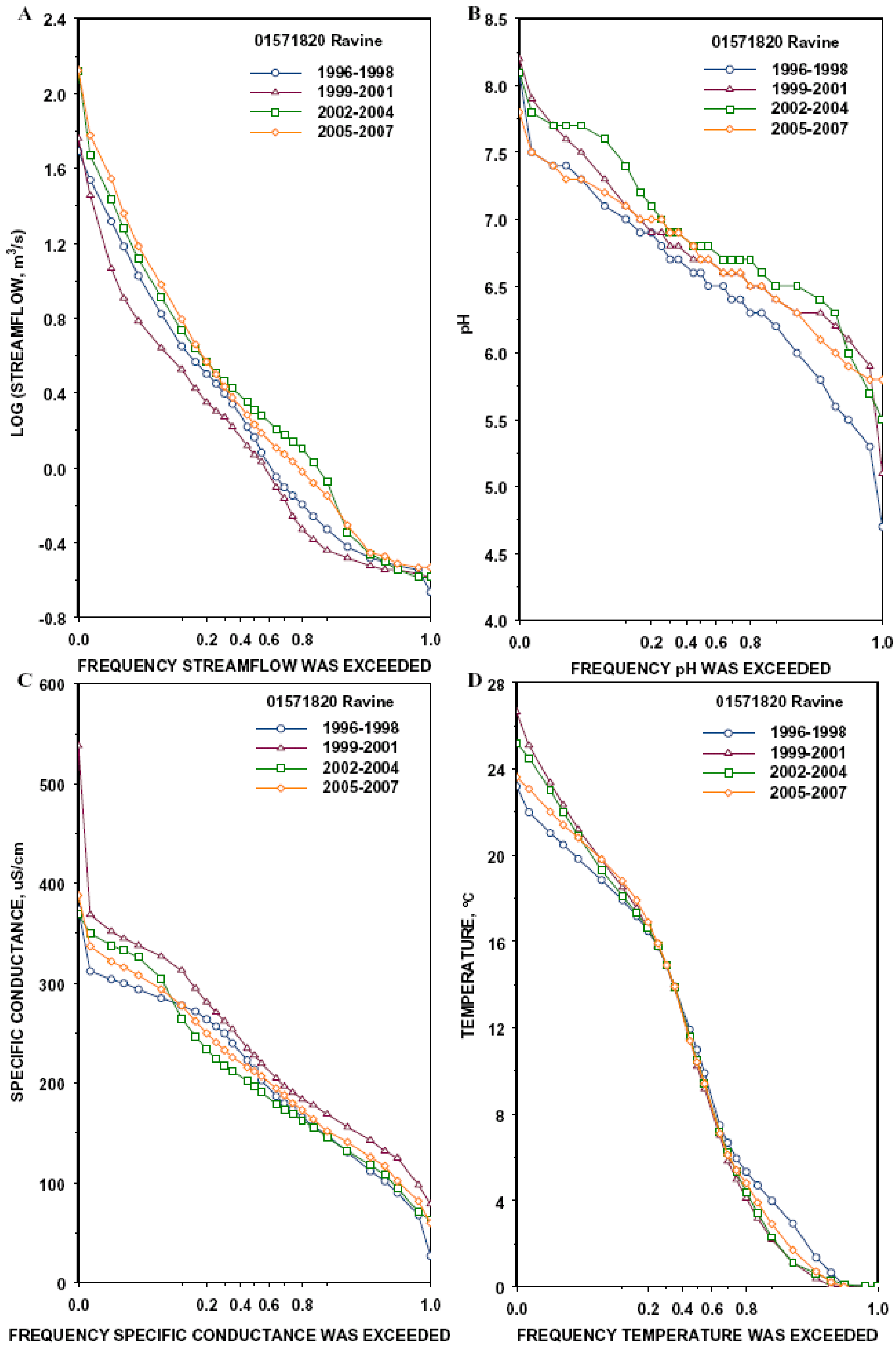


**Figure 4**. Probability plots of continuously measured (recorded at 15-minute intervals) data for Swatara Creek at Ravine, Pa., September 1996 through September 2007: A, streamflow; B, pH; C, specific conductance; D, temperature. The X-axis indicates the frequency that values were exceeded during 3- year intervals.

**Base flow.** Current and historical data from 1959 to 2007 for Swatara Creek at Ravine indicate progressive improvement in stream water quality over the period (Figure 8). Although streamflow at times of collection of historical (1959-1985) and current (1996-2007) base flow samples generally was comparable, sulfate decreased from a median of about 150 mg/L in 1959 to 75 mg/L in 2007; pH increased sharply from 3.5-4.4 (median ~4) to 4.6-7.0 (median ~6.5) after 1995 (Figure 8). Concentrations of dissolved iron and aluminum generally decreased with increased pH. The decrease in concentrations of sulfate and associated AMD contaminants in Swatara Creek over the past 50 years could result from a progressive decrease in contaminant loading from AMD sources after the initial flooding of the abandoned mines. Flooding of a mine can result in the (1) dissolution of accumulated pyrite-oxidation products, (2) reduction in the access of oxygen to the subsurface with a corresponding decrease in the pyrite oxidation rate, and (3) progressive dilution of initially acidic water by alkaline groundwater inflows. Such processes could account for gradual improvement in AMD and surface-water quality that has been ongoing for decades throughout the region, particularly in the Northern, Western, and Southern Anthracite Coalfields (e.g., Wood 1996). The associated increase in pH of Swatara Creek probably was caused by the onset of carbonate buffering that occurred when the rate of alkalinity production equaled or exceeded acid production (e.g., Cravotta et al. 1999). The implementation of limestone-based treatment systems during 1995-2001 would be expected to enhance the potential for carbonate buffering.

**Stormflow.** Storm-runoff events can occur year round in the study area and can have a dramatic effect on streamflow. Generally, monthly runoff as a fraction of total streamflow was greatest during the late summer and early fall, when seasonal low base flow typically was punctuated by large storms. Expressed as a percentage of monthly-total streamflow at Ravine, the annual mean base-flow and runoff fractions were 75% and 25%, respectively (Table 2). However, during typical low base flow conditions in late summer and early fall, a large percentage of the streamflow was "storm runoff" estimated with PART. Months with an exceptionally high fraction of stormflow during the study included October 1996 (47%), September 1999 (58%), September 2001 (46%), October 2003 (45%), September 2004 (70%), and October 2005 (52%). In conjunction with large storm events, runoff was estimated to contribute 70 to 99% of the daily mean streamflow during October 19-21, 1996; September 16-17, 1999; September 30-October 1, 1999; September 24-26, 2001; October 27-29, 2003; September 18-21, 2004; October 7-9, 2005; and September 2-4, 2006 (Figure 9).

Several examples of storm hydrographs during September and October 1996-2006 with associated stream chemistry are illustrated in Figure 7. Although each storm hydrograph is unique, owing to variations in storm duration, intensity, and runoff contribution, some features are consistent among the hydrographs. Specifically, as streamflow increased during storm

**Table 2.** Hydrograph-separation analysis[a] and components of the annual hydrologic budget for streamflow-gaging stations in the upper Swatara Creek Basin.

| US Geological Survey Station ID | Gage Location | Drainage Area km$^2$ | Time Period[b] | Mean Streamflow[c] | | Mean Base Flow[d] | | | Mean Runoff[e] | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | m$^3$/s | cm/yr | m$^3$/s | cm/yr | Index, % | m$^3$/s | cm/yr |
| 01573000 | Swatara Cr at Harper Tavern | 862.7 | 1920-2006 | 16.44 | 60.1 | 10.12 | 37.0 | 61.5 | 6.32 | 23.1 |
| 01573000 | Swatara Cr at Harper Tavern | 862.7 | 1997-2006 | 17.33 | 63.4 | 10.55 | 38.6 | 60.9 | 6.78 | 24.8 |
| 01572025 | Swatara Cr at Pine Grove | 297.0 | 1997-2006 | 6.13 | 65.1 | 4.27 | 45.4 | 69.7 | 1.86 | 19.8 |
| 01571820 | Swatara Cr at Ravine | 110.8 | 1997-2006 | 2.44 | 69.5 | 1.84 | 52.4 | 75.4 | 0.60 | 17.1 |
| 0157155014 | Swatara Cr at Newtown | 7.5 | 1997-2006 | 0.13 | 54.0 | 0.10 | 42.1 | 78.0 | 0.03 | 12.6 |
| 01573000 | Swatara Cr at Harper Tavern | 862.7 | 2000-2006 | 18.83 | 68.9 | 11.08 | 40.5 | 58.8 | 7.75 | 28.3 |
| 01572025 | Swatara Cr at Pine Grove | 297.0 | 2000-2006 | 6.58 | 69.9 | 4.48 | 47.6 | 68.1 | 2.1 | 22.3 |
| 01571820 | Swatara Cr at Ravine | 110.8 | 2000-2006 | 2.64 | 75.2 | 1.95 | 55.5 | 73.8 | 0.69 | 19.7 |
| 0157155014 | Swatara Cr at Newtown | 7.5 | 2000-2006 | 0.14 | 57.4 | 0.11 | 46.3 | 80.6 | 0.03 | 12.6 |
| 01571778 | Lorberry Cr at Lorberry Jct | 9.0 | 2000-2006 | 0.31 | 109.1 | 0.27 | 94.7 | 86.8 | 0.04 | 14.0 |

[a]Hydrograph separation was conducted using the "PART" computer program (Rutledge 1998) to divide annual streamflow into base flow (B) and runoff (R) contributions on the basis of daily mean streamflow values during time period indicated.
[b]Time period is the range of water years, from October of the prior calendar year through September of the calendar year.
[c] Streamflow expressed as centimeters per year by dividing streamflow in cubic meters per second by the drainage area in square kilometers and then multiplying by the factor 3,156.
[d] Base flow expressed as cubic meters per second, centimeters per year, and percent of total annual streamflow (base-flow index).
[e] Runoff expressed as cubic meters per second or centimeters per year was computed by subtracting the base flow from total streamflow.

events, the pH, SC, and sulfate concentration decreased, whereas the concentrations of suspended solids and total and dissolved iron increased (Figure 9). Other sampled hydrographs for all months of the year exhibited comparable patterns, except that storm events during 1996-1998 exhibited greater propensity for change in pH, with lower extremes (Figure 4B), than later years.

Creek could result from mixing of weakly acidic storm runoff having pH 4.0-4.5 and low dissolved solids with poorly buffered stream water having pH 6.0-6.5 and high sulfate. The storm runoff is derived from acidic rainfall with minor contributions from pyrite-oxidation products and carbonate minerals (e.g., Olyphant et al. 1991).

## Discussion

### *Correlations among streamflow, metals, and suspended solids*

The pH, SC, sulfate, and other chemical concentrations varied in response to changes in streamflow. Generally, base-flow samples had higher pH, SC, alkalinity, hardness, and concentrations of dissolved major ions and lower concentrations of total metals compared to stormflow (Figures 9 and 10).

As streamflow at Ravine increased during stormflow events, pH, SC, and concentrations of sulfate and manganese typically decreased, and concentrations of suspended solids, iron, aluminum, and other metals in whole-water samples typically increased (Figures 9 and 10). Similar trends for dissolved and suspended solids during stormflow on Swatara Creek in 1959 were reported by Stuart et al. (1967, Figure 9). However, the trends for pH, SC, and sulfate are inconsistent with the work of others who evaluated impacts of acid rain on small streams in unmined, forested watersheds of the Appalachian Mountains of northeastern USA. For example, Corbett and Lynch (1982) and DeWalle (1990) showed pH typically decreased while sulfate increased with streamflow in Appalachian headwater streams during storm events.

Cravotta (2000) demonstrated that the decreases in pH, SC, and concentrations of major ions during storm events for Swatara

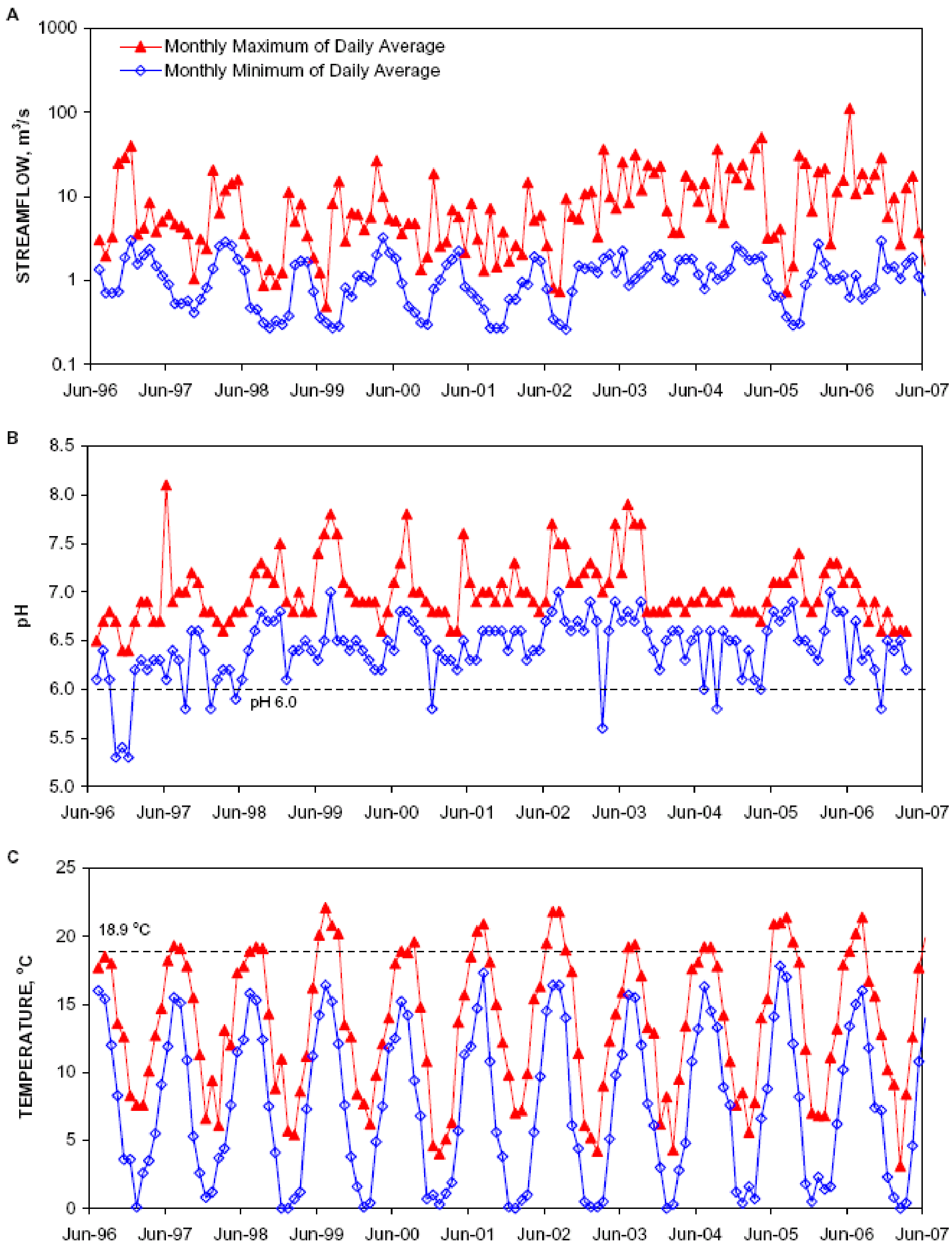


**Figure 5**. Time-series plots of the monthly range (maximum and minimum) of daily mean values for Swatara Creek at Ravine, Pa., June 1996 through June 2007: A, streamflow; B, pH; and C, temperature. In B and C, dashed horizontal lines indicate minimum pH and maximum temperature permitted for "cold-water fishery" in July and August, respectively (Commonwealth of Pennsylvania 2002).

Typically, the greatest changes in SC and pH occurred with the largest changes in streamflow (greatest dilution by storm runoff). The minimum SC typically occurred with peak streamflow, whereas the minimum pH lagged by several hours, generally occurring during the falling stage. In contrast, concentrations of suspended solids generally increased to peak values during the initial rising stage and decreased prior to peak stage. Although the concentration of total iron included contributions from suspended particles, peaks for total iron tended to be achieved after the peaks for suspended solids, possibly reflecting a time lag for iron-laden water and associated sediment from the upper, mined part of the watershed to reach Ravine. Generally, concentrations of suspended solids and total iron and other metals at a given streamflow during a storm event were greater during the rising stage than the falling stage (Figure 9). This "hysteresis" effect can be explained as resulting from the accumulation of metal-rich sediments (FeIII, MnIII-IV, and Al oxyhydroxides and clay minerals) within the streambed during base flow conditions, scour and transport of the streambed deposits during rising stormflow stage, and dilution during falling stages. Small storm events can scour metal-rich sediments from the streambed with little dilution of the concentrations, resulting in concentrations of total metals and suspended solids that are comparable to or greater than those of large storms. Stormflow hysteresis patterns indicated for Swatara Creek and other streams can be affected by preceding conditions, with large peak concentrations following relatively stable base flow and diminished peak concentrations during succeeding storms of the same magnitude (Bowes et al. 2005, Caruso et al. 2008).

Because of the hysteresis effect, streamflow and metals concentrations in Swatara Creek at Ravine were poorly correlated (iron and aluminum) or uncorrelated (manganese, nickel, zinc) (Figure 11). However, concentrations of total metals were strongly correlated with the concentration of suspended solids (Cravotta and Bilger 2001). The correlations between concentrations of suspended solids and total metals are consistent with suspended solids that contained approximately 10% iron, 5% aluminum, and lesser amounts of manganese and trace metals, which were the reported concentrations in fine streambed sediments in the study area (Cravotta and Bilger 2001).

## Water Quality Trends

Continuous-record data for streamflow, pH, SC, and temperature for Swatara Creek at Ravine during the entire study could be evaluated directly to indicate temporal differences (e.g., Figures 4 and 5). However, the interpretation of trends in concentrations and loads of chemicals collected at different time intervals was complicated by the effects of changing streamflow on the pH and chemical concentrations (Figures 6, 7, and 10). Thus, continuous streamflow data were used to estimate daily loads and annual flow-weighted concentration (FWC) values for the study period. The use of these estimates could help to remove sampling bias and facilitate the interpretation of water-quality trends that resulted from factors other than changes in streamflow.

The FWC values for different chemicals exhibited temporal variations not correlated with streamflow (Figure 12). For Swatara Creek at Ravine, the FWC values for hydrogen ion, alkalinity, and dissolved iron had similar trends, decreasing from high

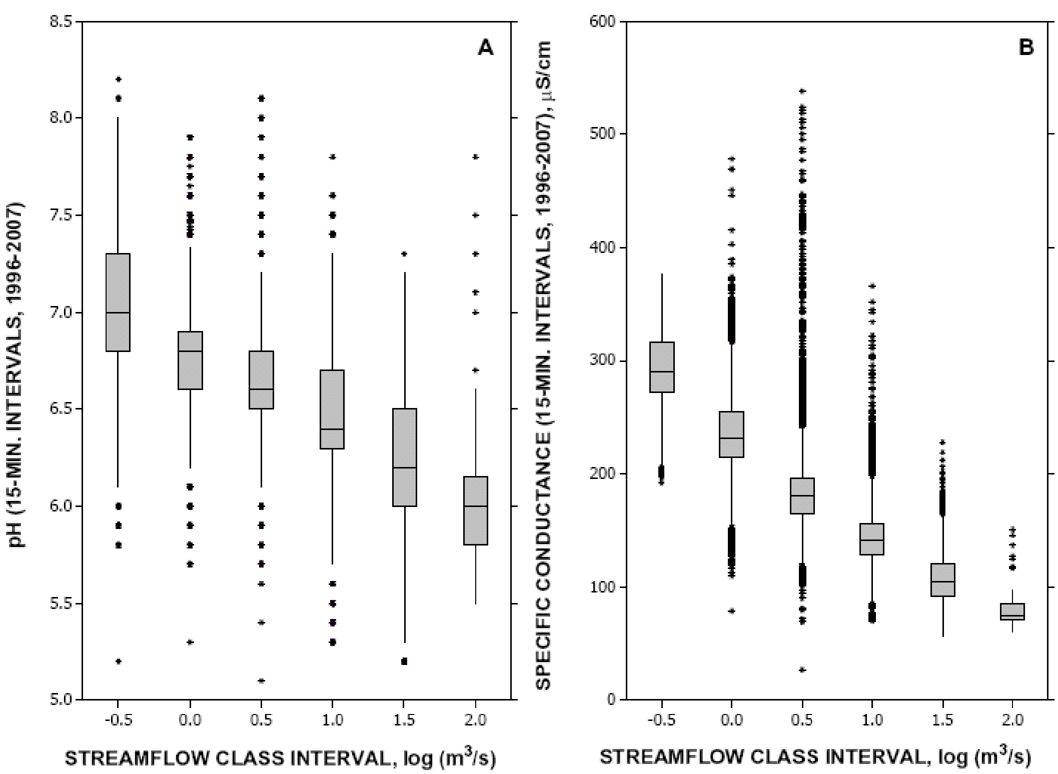


**Figure 6.** Boxplots showing continuously measured (recorded at 15-minute intervals) pH and specific conductance as a function of streamflow for Swatara Creek at Ravine, Pa., September 1996 through September 2007. Each streamflow class interval on the x-axis, where numbers are logged values of streamflow in cubic meters per second, includes values within 0.25 of the listed value (e.g. 1.0 is 0.75 to 1.25). Shaded area of box indicates the "interquartile" range (IQR = 25th to 75th percentile); horizontal line inside the box indicates the median; vertical lines extend to extreme values within 1.5 times the IQR; symbols indicate outlier values.

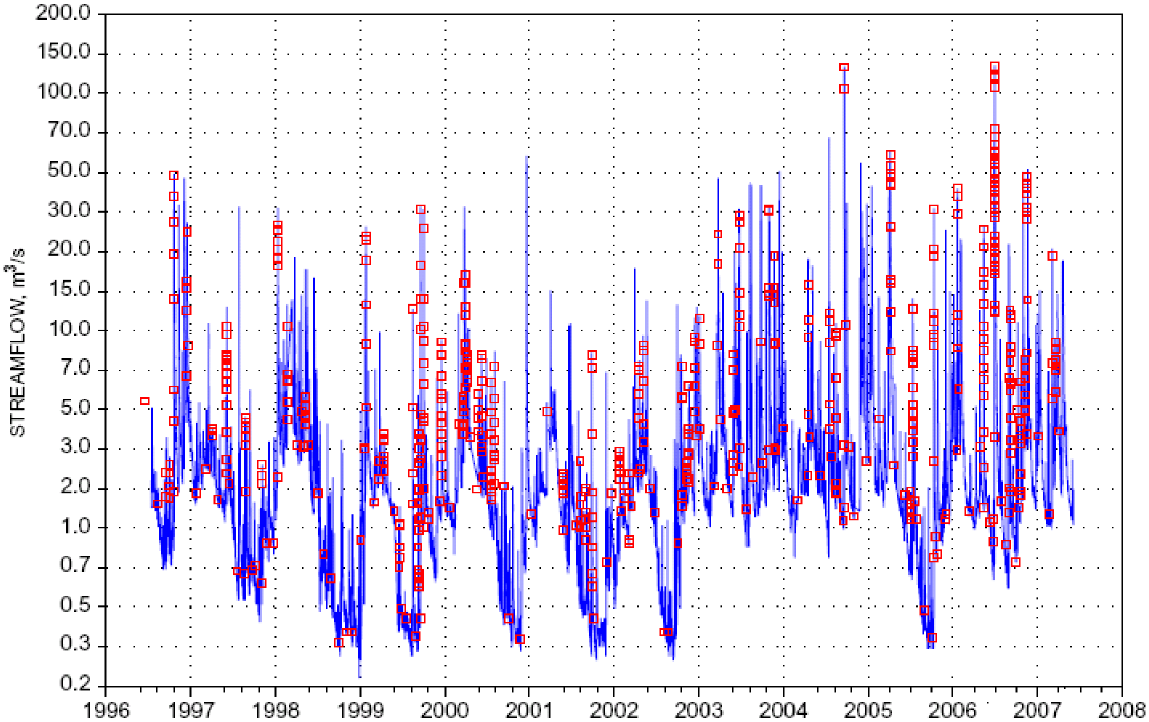


**Figure 7**. Streamflow hydrograph (recorded at 15-minute intervals) for Swatara Creek at Ravine, Pa., June 1996 through June 2007. Square symbols indicate instantaneous streamflow when water-quality samples were collected.

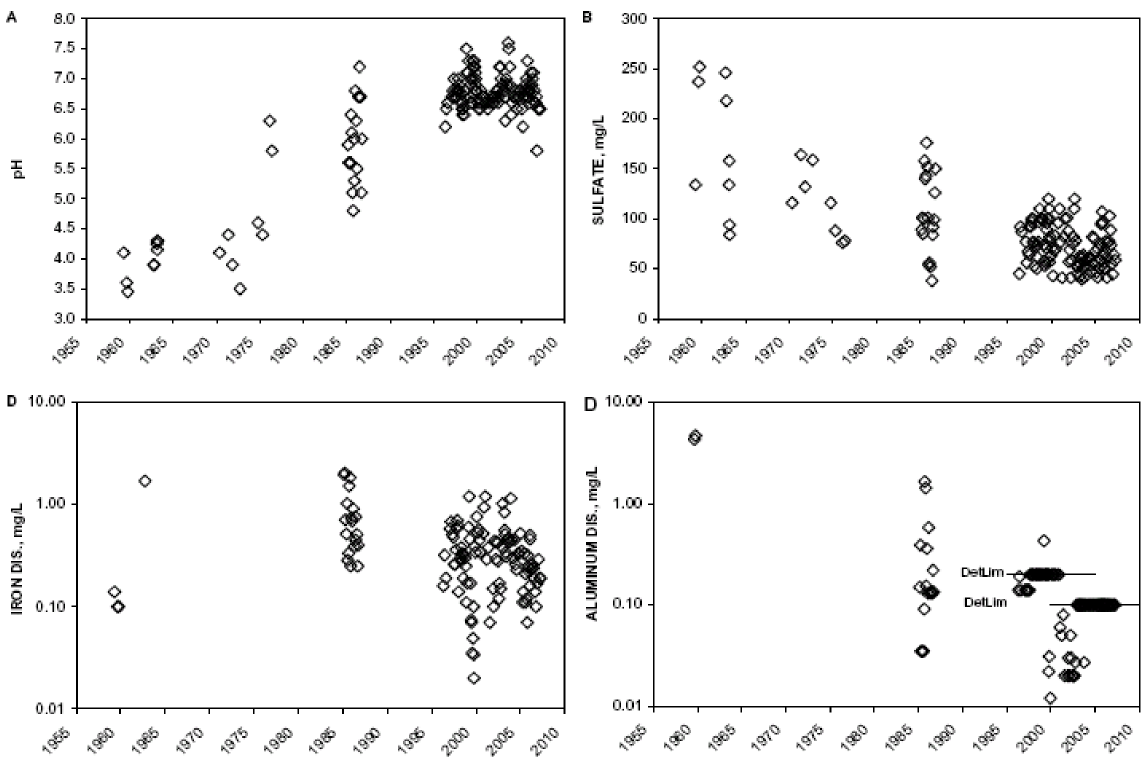


**Figure 8**. Long-term water-quality data for base flow of Swatara Creek at Ravine, 1959 - 2007: A, pH; B, dissolved sulfate; C, dissolved iron; D, dissolved aluminum. Data from McCarren et al. (1964), Stuart et al. (1967), Skelly & Loy, Inc. (1987), Fishel (1988), and U.S. Geological Survey (variously dated). Aluminum concentrations below detection are shown at detection limit (DetLim), indicated by horizontal line segments.

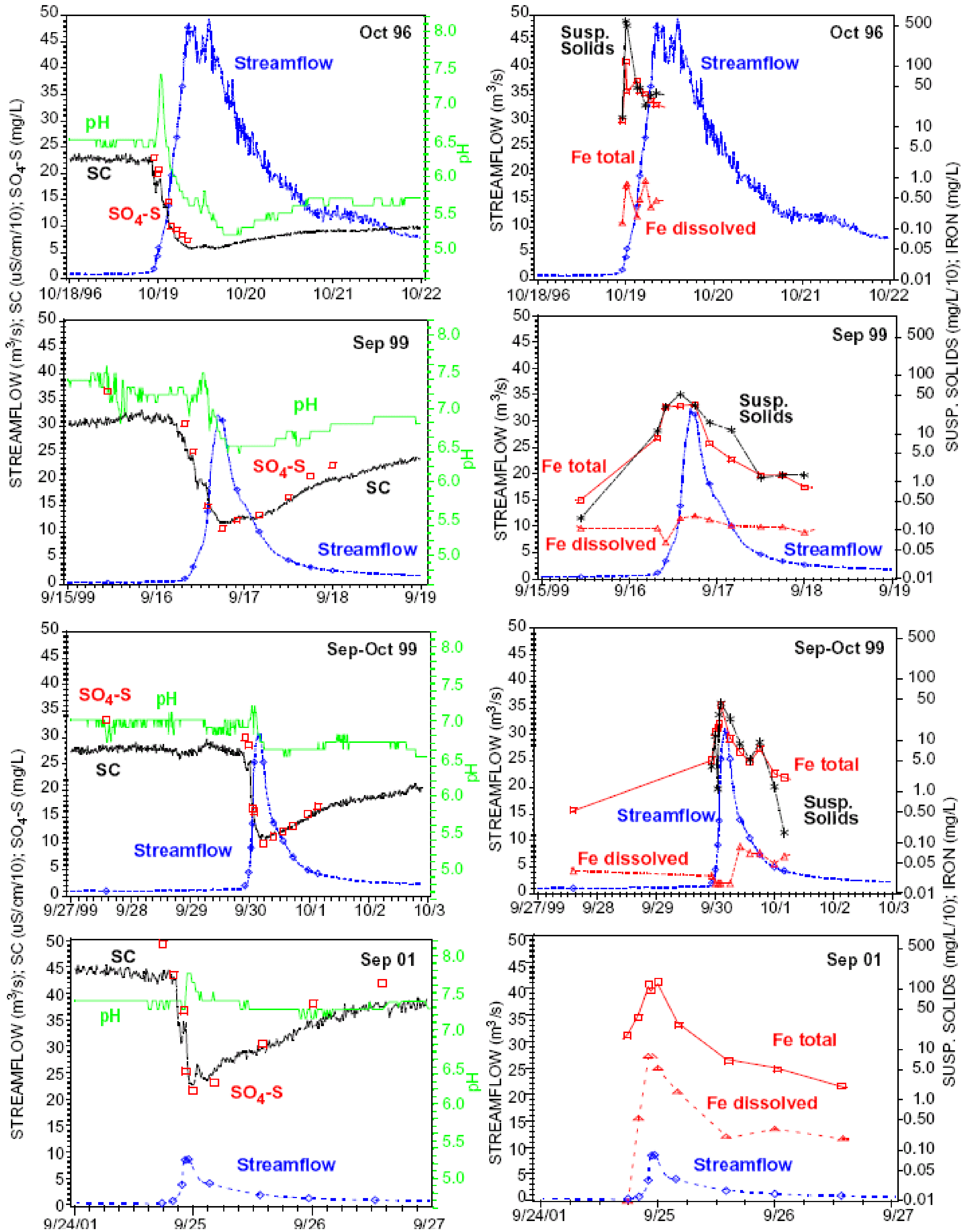


**Figure 9**. Hydrographs and associated water-quality data for selected stormflow events, Swatara Creek at Ravine, Pa. October 19-21, 1996; September 16-17, 1999; September 30-October 1, 1999; September 24-26, 2001; October 27-29, 2003; September 18-21, 2004; October 7-9, 2005; and September 2-4, 2006. Values shown for SC and suspended solids (divided by 10) and concentration of $SO_4$ (divided by 3) as sulfur.

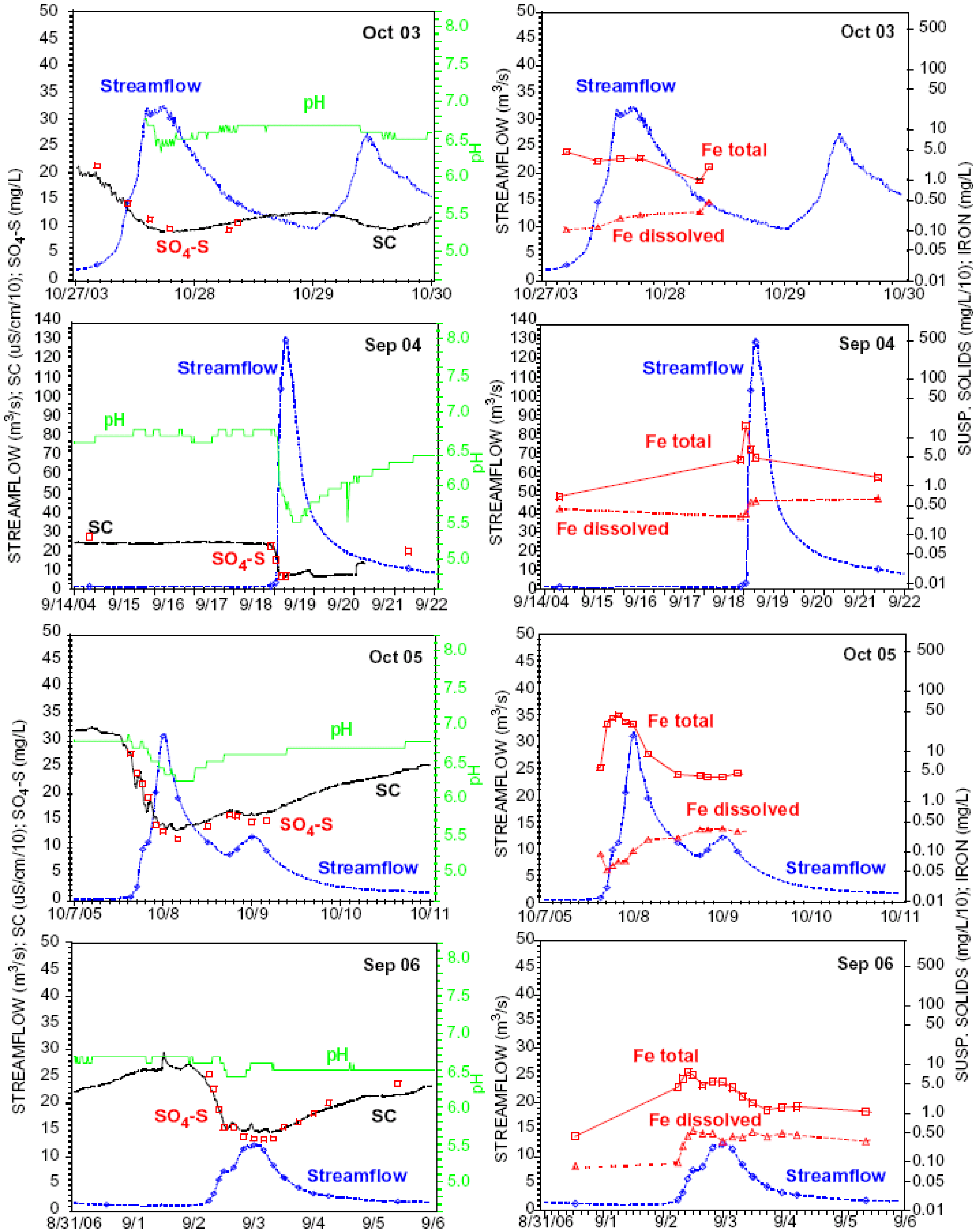


**Figure 9**. (Continued)

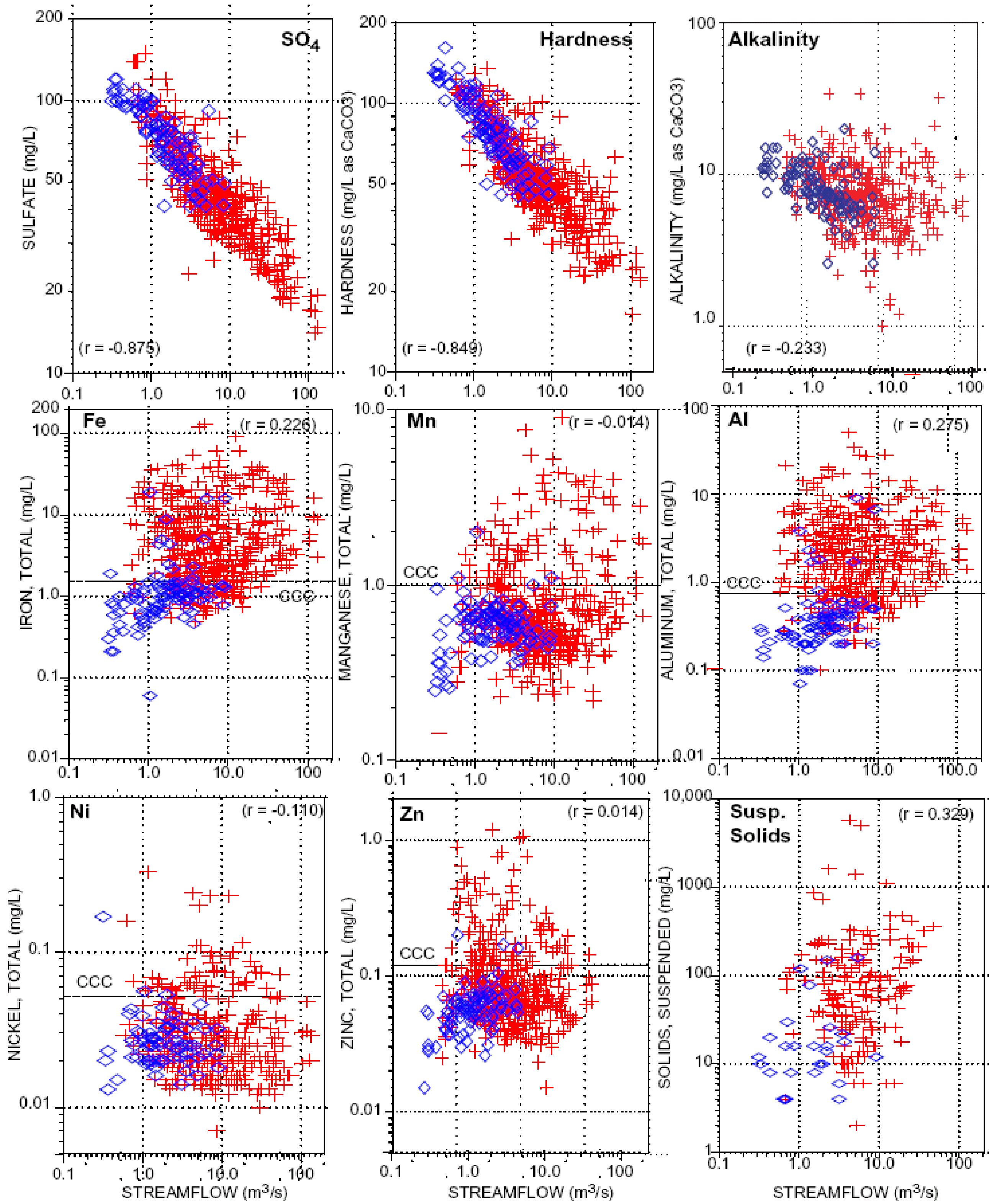


**Figure 10.** Relations between streamflow and concentrations of water-quality constituents in base flow (open diamond symbol) and stormflow (cross symbol) samples, Swatara Creek at Ravine, Pa. Hardness was computed from dissolved Ca and Mg in milligrams per liter ($2.5 \cdot C_{Ca} + 4.1 \cdot C_{Mg}$). Spearman rank correlation coefficient, r; values > 0.138 or < -0.138 are significant (p<0.001). Dashed horizontal lines, except for Mn, indicate criteria continuous concentration (CCC) values for protection of freshwater aquatic organisms (U.S. Environmental Protection Agency 2002); dashed lines for Mn indicate PaDEP standard for daily mean concentration (Commonwealth of Pennsylvania 2002).

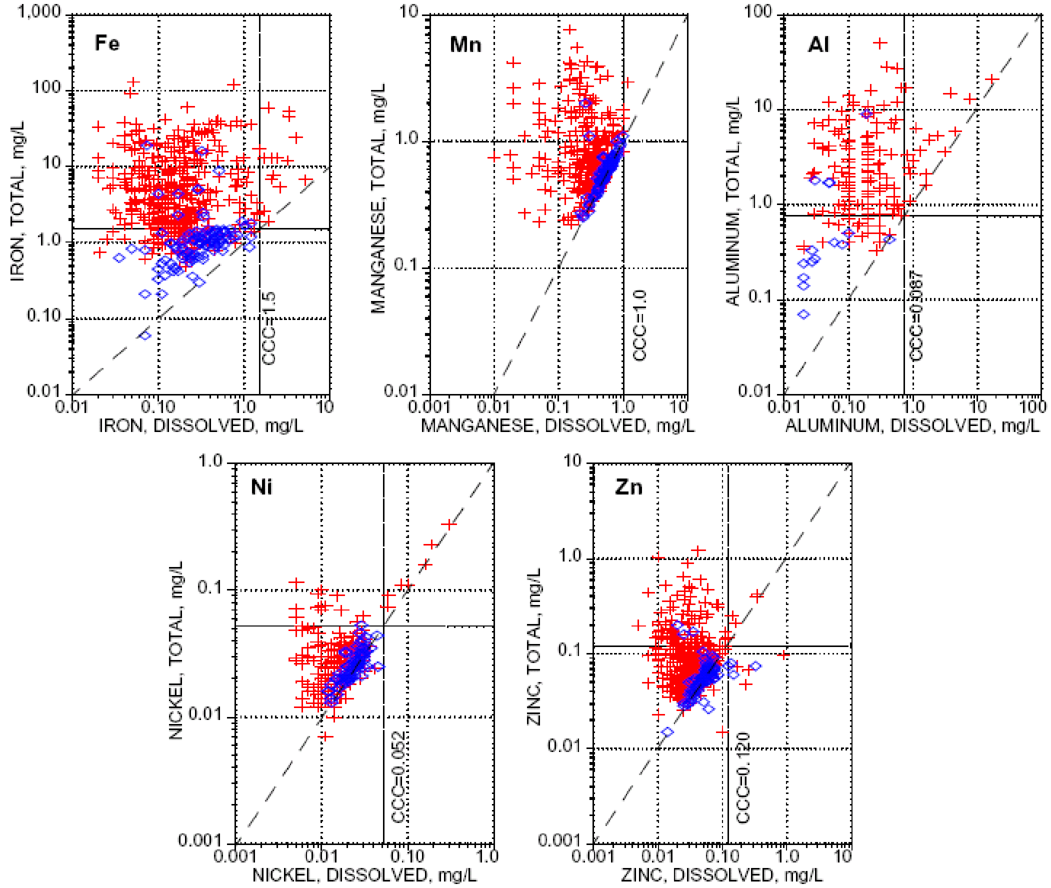


**Figure 11.** Relatins among concentrations of dissolved and total metals in stream water sampled during base-flow and stormflow conditions, Swatara Creek at Ravine, Pa. Values farther to right of diagonal line indicate decreasing fraction of dissolved ions (<0.45 mm) contributing to total concentration. Data plotted only if total and dissolved concentration above limit of detection. Dotted horizontal and vertical lines, except for manganese, indicate criteria continuous concentration (CCC) values for protection of freshwater aquatic organisms (U.S. Environmental Protection Agency 2002); dotted lines for manganese indicate PaDEP standard for daily mean concentration (Commonwealth of Pennsylvania 2002).

values during 1997-1998 to minimum values in 2001-2003 and then increasing during 2003-2006. In contrast, FWC values for manganese and, to a lesser extent, sulfate exhibited possible downward trends, whereas those for dissolved aluminum were more erratic.

For Swatara Creek at Newtown, FWC estimates were computed for the sites upstream and downstream of limestone diversion wells using the streamflow record from the downstream site (Figure 13). During 1997-2003, the FWC values for hydrogen ion and metals were lower and those for alkalinity were higher at the downstream site compared to the upstream site. These differences in water quality between the two sites were expected because of the continuous addition of alkalinity and pulverized limestone to the stream by the diversion wells. However, the diversion wells were damaged by storms associated with Hurricane Ivan in September 2004 and were not operated continuously thereafter. After 2004, the FWC values for hydrogen ion increased and those for alkalinity decreased at the downstream site, while differences between the FWC values at the two sites became smaller for dissolved iron and manganese.

Flow-adjusted trends, which are identical for concentration and load of the particular chemical, were expressed as percent change between the 1997 start time and 2006 end time (period of continuous streamflow record). Flow-adjusted trends for Swatara Creek at Ravine (Figure 14) indicated significant decreases in hydrogen ion, dissolved and total manganese, total iron, and dissolved aluminum; no change in alkalinity, sulfate, or dissolved iron; and increases in calcium. The lack of trend in sulfate could indicate that the AMD contaminant loading rate was unchanged during the study. The decrease in hydrogen ion and increase in calcium could result from the dissolution of limestone in various AMD treatment systems. Although generated by limestone dissolution, the lack of trend in alkalinity could indicate alkalinity was consumed during neutralization reactions that buffered the pH to be near neutral. Combined with decreases in iron, manganese, and aluminum, these flow-adjusted trends support the hypothesis that AMD treatment has

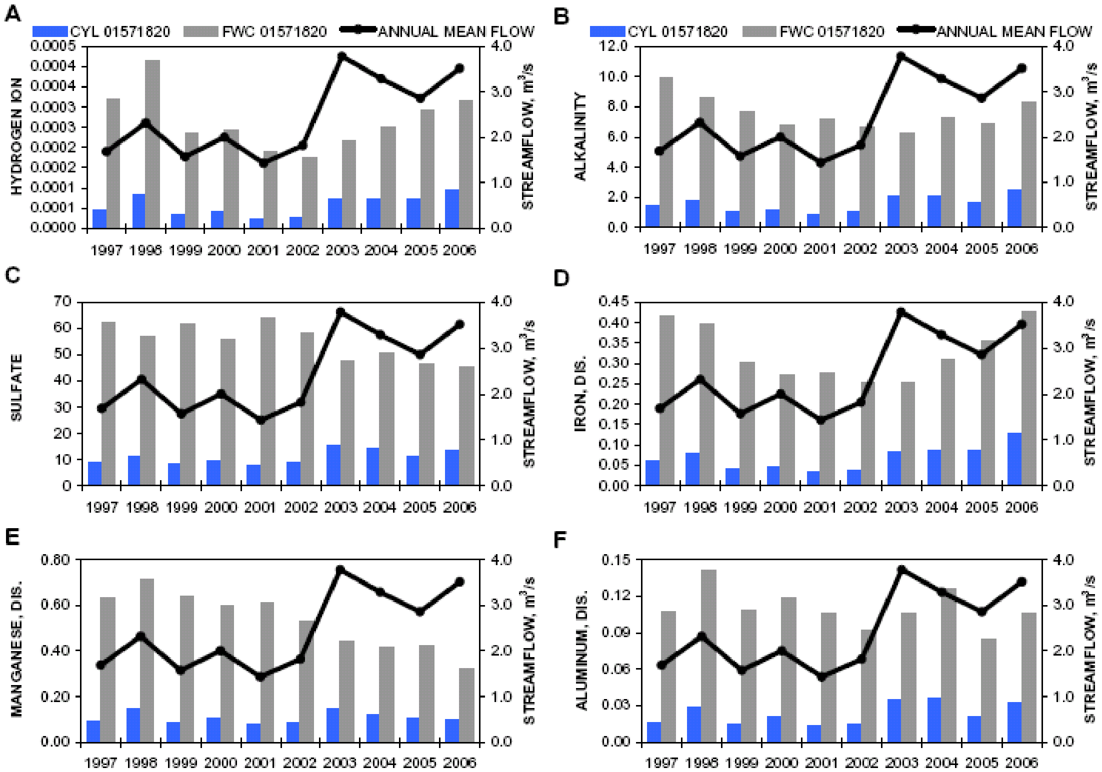


**Figure 12.** Annual mean streamflow for Swatara Creek at Ravine (01571820; black line) and corresponding loading by calendar year (CYL; left bar, units Mg/day) and flow-weighted concentration (FWC; right bar, units mg/L) of chemicals associated with mine effluent, 1997-2006: A, hydrogen ion; B, alkalinity; C, sulfate; D, dissolved iron; E, dissolved manganese; F, dissolved aluminum.

increased pH and decreased the transport of dissolved metals during the study.

## Ecological Ramifications

The increase in fish populations of Swatara Creek and its tributaries during the late 1990s coincided with the implementation of limestone-based treatment systems at many of the AMD sources (Figure 1). Possible effects of such treatments include increased concentrations of calcium and alkalinity with associated buffering of pH to be near neutral, which could benefit fish and other aquatic organisms that are intolerant of low pH and sensitive to toxic metals. Because of solubility and adsorption, the concentrations of dissolved metals would tend to decrease with increased pH (e.g., Cravotta 2008), plus added calcium may be important in regulating toxic effects of metals (Holt and Yan 2003, U.S. Environmental Protection Agency 2002, Yan et al. 2003). Flow-adjusted trends for Swatara Creek at Ravine indicating decreases in hydrogen ion and metals and increases in calcium during the 1997-2006 time period (Figure 14) and consistently near-neutral pH during 1999-2007 (Figures 4B, 5B, and 9) imply that the AMD treatments installed during 1995-2001 have helped to improve downstream water quality.

To maintain its designated use as a cold-water fishery, Swatara Creek and other such streams in Pennsylvania must have DO concentrations greater than 5.0 mg/L at all times and temperatures less than 18.9 °C during July and August (warmest months) (Commonwealth of Pennsylvania 2002). The minimum DO concentration at Ravine was 8.7 mg/L during July 1997. However, the streamwater temperature occasionally exceeded 18.9 °C during low-flow conditions in summer (Figures 2C and 5C), and concentrations of metals periodically exceeded water-quality criteria for protection of aquatic organisms (Figures 10 and 11). Although elevated temperatures can produce faster rates of iron oxidation and associated metals removal in AMD treatment systems (e.g., Cravotta 2007, Watzlaf et al. 2004), the prolonged exposure of stream water or AMD to ambient air temperatures or sunlight can produce temperature extremes that are not suitable for brook trout and other cold-water species.

The overall fish-community structure in Swatara Creek at Ravine could be characterized as transitional between cold-water and warm-water classifications. Although species abundance varied from year to year, the majority of the species collected during 1996-2006 was considered to have moderate tolerance to low pH and pollution (Table 1). Nevertheless, several of the fish taxa were intolerant of pollution and low pH, such as river chub (Nocomis micropogon), longnose dace (Rhinichthys cataractae), northern hog sucker (Hypentelium nigricans), and shield darter (Percina peltata) (Table 1). As the maximum stream temperature during summer months increased (Figures 2C and 5C), competition between cold-water and warm-water species could have been a factor affecting species abundance. For example, at Ravine during 1997- 1998, cold-water and cool-water species predominated, including blacknose dace, creek chub (Semotilus atromaculatus), fallfish (Semolitus corporalis), white sucker, brook trout, and tessellated darter (Etheostoma olmstedi) (Table 1). In 1999, cool-water species including smallmouth bass (Micropterus dolomieu), river chub (Nocomis micropogon), and fallfish were dominant, with substantially fewer blacknose dace, tessellated darter, and brook trout. Likewise, when rock bass, a warm-water species, were abundant in 2003 and 2006, numbers of brook trout were greatly diminished, possibly reflecting variations in streamflow during the survey in addition to the variations in maximum stream temperature (Figure 2). The range expansion of smallmouth bass and associated warm-water fish could be an important factor affecting food-web structure and the recovery of trout and associated cold-water fish in acid-stressed systems.

Base flow during the study met Commonwealth of Pennsylvania (2002) chemical water-quality standards; however, stormflow commonly *did not* meet standards for pH (6.0 to 9.0) or concentrations of total iron (1.5 mg/L daily mean), dissolved iron (0.3 mg/L maximum), and total manganese (1.0 mg/L maximum) (Figures 10 and 11). Furthermore, although concentrations of "dissolved" metals in filtered samples generally met USEPA criteria continuous concentration (CCC) limits for protection of freshwater aquatic organisms, the concentrations of "total recoverable" metals in unfiltered stormflow samples (Figures 10 and 11) commonly exceeded CCC values for iron (1.0 mg/L) and aluminum (0.087 mg/L) and occasionally exceeded CCC values for nickel (0.052 mg/L) and zinc (0.120 mg/L) (U.S. Environmental Protection Agency 2002). The CCC limits indicate potential for adverse effects resulting from long-term (30-day) exposure. Although storm conditions lasting only hours to days accounted for most exceedances of water-quality criteria, impounding the storm water could prolong exposure.

Metal-rich suspended solids and streambed sediments represent a potential source of dissolved metals. Solid forms of the metals could be ingested by aquatic organisms with subsequent uptake of dissolved species within the gut. Dissolved metals also could be derived by recrystallization of metastable solid phases to more stable phases, by dissolution or desorption , and/or by reductive dissolution of FeIII and MnIII-IV oxides. These processes could be promoted by decreases in pH and/or redox potential in the streambed or water column.

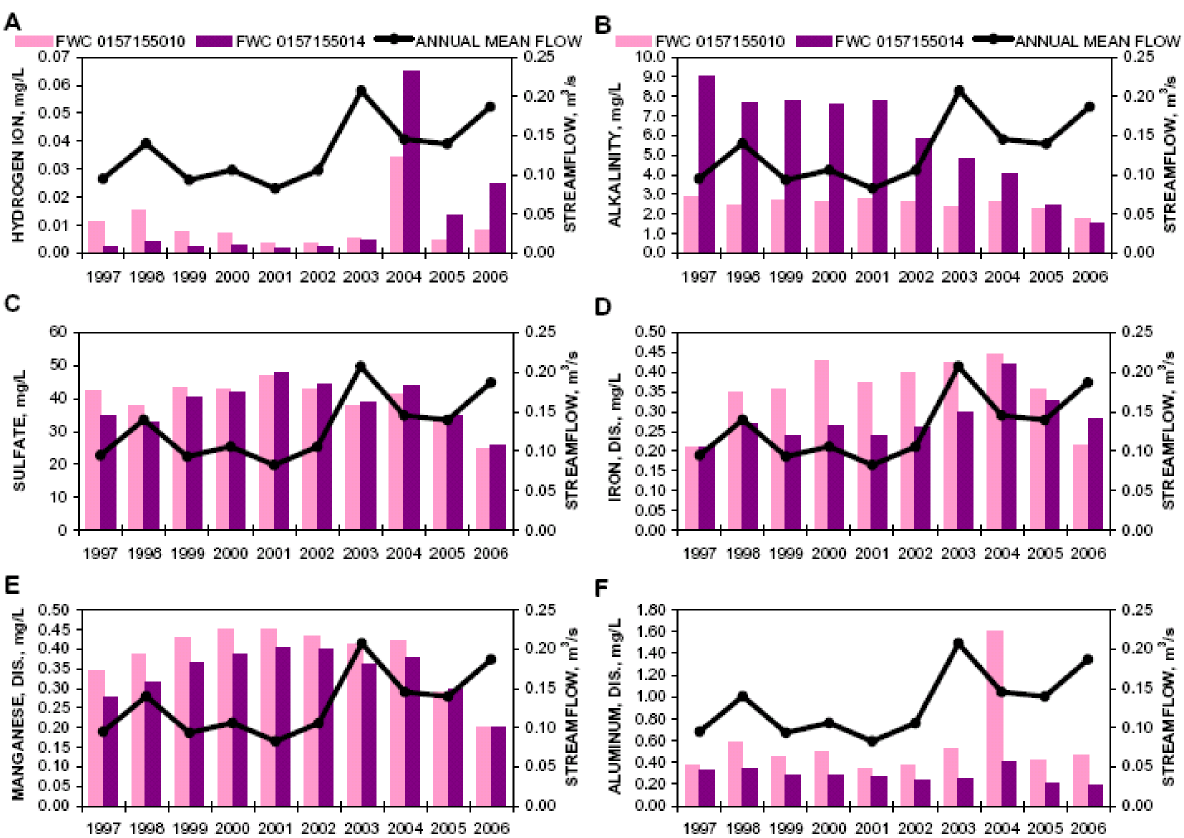


**Figure 13.** Annual mean streamflow for Swatara Creek at Newtown (0157155014; black bar) and corresponding flow-weighted concentration (FWC) of chemicals upstream (0157155010; left bar) and downstream (0157155014; right bar) of diversion wells, 1997-2006: A, hydrogen ion; B, alkalinity; C, sulfate; D, dissolved iron; E, dissolved manganese; F, dissolved aluminum.

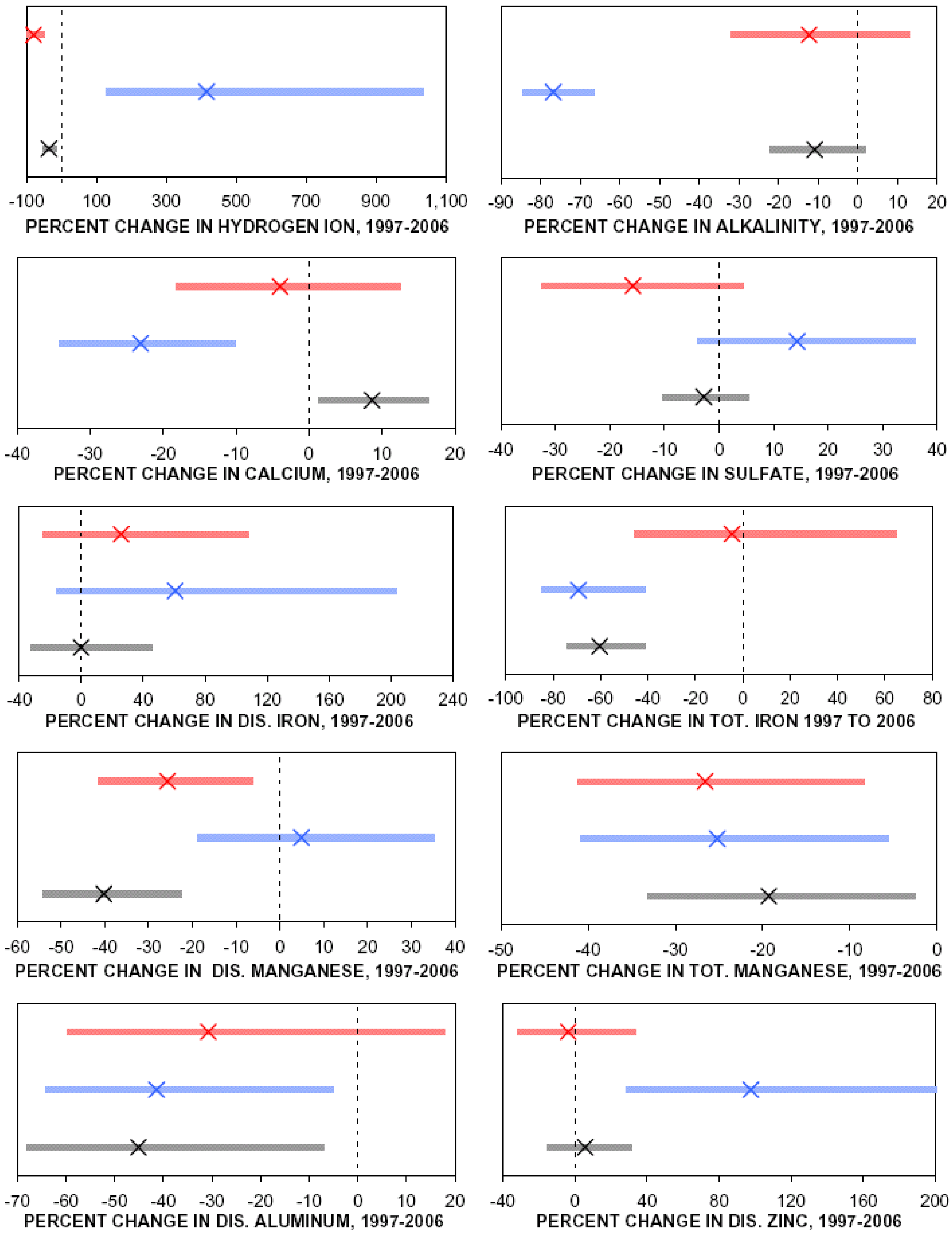


**Figure 14.** Estimated flow-adjusted trend (X) and confidence interval (CI) bar for chemicals in Swatara Creek at Ravine (01571820; lower black bar) and Swatara Creek at Newtown downstream (0157155014; middle blue bar) and upstream from diversion wells (0157155010; upper red bar), 1997-2006. If the CI is completely negative or completely positive, the trend is significant.

Twenty-four of the 33 fish species identified in Swatara Creek at Ravine during the study had been previously reported for Pennsylvania streams with pH 4.6 to 6.4 (Table 1). A subset of these fish was found in Good Spring Creek at Tremont, Lorberry Creek at Lorberry Junction, and Swatara Creek at Newtown (Table 1). According to Earle and Callaghan (1998), only 18 species of fish native to Pennsylvania have been found in Pennsylvania streams having pH <6; the majority of these species now can be found in Swatara Creek.

Concentrations of dissolved sulfate, iron, and manganese were greater for Lorberry Creek and Good Spring Creek than Swatara Creek at Ravine or Swatara Creek at Newtown (Figure 3). Although Good Spring Creek and Lorberry Creek had fewer fish than Swatara Creek at Ravine, these sites had more fish than Swatara Creek at Newtown (Figure 2). Such differences in fish numbers and species diversity probably reflect smaller streamflows and limited habitat at the upstream sites. Sections of the surveyed reach at Newtown flowed intermittently during the study. Generally, greater species diversity and larger populations would be expected for larger aquatic habitats. Although fish surveys were not conducted prior to 2002 for Lorberry Creek, potential downward trends in acidity and dissolved metals concentrations for Lorberry Creek during the study (Figure 3) could explain the appearance of blacknose dace, creek chub, and brook trout in this tributary. These species, which are moderately tolerant of low pH and pollution (Table 1), were among the first species found in Swatara Creek at Ravine during 1996, indicating early stages of its ecological recovery. Similarly tolerant fish species have been identified as early colonists in other systems recovering from acidification (e.g., Cravotta 2005, Mills et al. 2000, Short et al. 1990).

Cravotta and Bilger (2001) presented results for macroinvertebrate surveys on Swatara Creek at Ravine conducted during 1996-2000. Although 11 benthic macroinvertebrate taxa (family level), including 3 genera of Ephemeroptera (mayflies) were found, a few relatively pollution- tolerant taxa dominated, particularly Hydropsyche and Chironomidae. The lack of taxa richness and trophic imbalance in Swatara Creek is consistent with the identified toxic effect levels for metals in the streambed sediments (Cravotta and Bilger 2001) and implies that metals in the aquatic environment that are stressful to macroinvertebrates may not be severely limiting to fish. Because native fish populations had returned, but the macroinvertebrate community continued to indicate water-quality impairment in 2007, Swatara Creek was characterized as "partially meeting designated uses" and was not removed from the proposed 2008 Pennsylvania 303(d) list of impaired waters (Pennsylvania Department of Environmental Protection 2007).

## Summary and Conclusions

Streams affected by "acidic" mine drainage (AMD) in the northeastern USA commonly have diminished fish populations because of aquatic habitat degradation associated with low pH and/or elevated concentrations of iron, aluminum, and other metals from the AMD. Nevertheless, as impacts from AMD become less severe through natural attenuation and/or watershed-restoration activities, fish populations may rebound. For example, upper Swatara Creek, which drains the Southern Anthracite Coalfield in eastern Pennsylvania, had been contaminated by AMD for most of the 20th century. Because of progressive improvement in water quality and the recovery of native fish populations described in this paper, upper Swatara Creek recently was characterized by the Pennsylvania Department of Environmental Protection (2008) as "partially meeting designated uses" and by the USEPA (2007) as a "nonpoint source success story."

More than four decades of intermittent monitoring of base flow of Swatara Creek immediately downstream from the mined area indicated median sulfate concentration decreased from about 150 mg/L in 1959 to 50 mg/L in 2007; pH increased from acidic to near-neutral values. These long-term trends probably resulted from a decrease in pyrite oxidation and the onset of carbonate buffering, partly because of flooding the mines during the early period and the dissolution of limestone in treatment systems during the later period. As a consequence of the improved water quality, fish populations in Swatara Creek rebounded from nonexistent during 1959-90 to as many as 25 species during 1996-2006, including several taxa that are intolerant of low pH and pollution.

The AMD treatments with limestone that were implemented during 1995-2001 in the upper part of the Swatara Creek watershed added alkalinity, needed to maintain near-neutral pH, and calcium, important to aquatic organisms for regulating toxic effects of dissolved metals. The treatments not only reduced the influence of AMD but also mitigated extreme fluctuations in pH of Swatara Creek immediately downstream of the mined area that were associated with episodic acidification during storm runoff events. During 1996-1998, pH values approaching 5.0 were frequently recorded during stormflow events; however, during 1999-2007, after treatments were implemented in the upper watershed, such low-pH excursions were rarely recorded.

Despite near-neutral, aerobic, cool-water conditions in Swatara Creek that support a diverse fish population, untreated AMD and metal-rich streambed sediments in this and other mining-affected watersheds represent a substantial, long-term source of metals that are likely to impair water quality and complicate aquatic ecological recovery into the future. Although the transport of dissolved iron, aluminum, and most trace metals typically is attenuated at near-neutral pH, substantial transport of suspended and dissolved metals persists in Swatara Creek, especially during stormflow conditions. Iron, aluminum, and, to a lesser extent, manganese, nickel, and zinc, are transported as suspended particles resulting from scour and transport of metal-enriched streambed deposits. Total iron, manganese, aluminum, and associated trace metals commonly increase in concentration at the onset of stormflow conditions; peak metal concentrations typically are achieved prior to peak discharge. The metal content of the suspended solids is relatively constant over the range of streamflow conditions, implying a relatively uniform source of material such as streambed deposits.

On the basis of combined methods using fixed-interval base flow and automated stormflow sampling, total concentrations and loads of suspended sediment and metals were shown to be greatest and pH lowest during stormflow conditions in Swatara Creek. In general, temporal variations in water quality of low-order streams such as the northern part of Swatara Creek are difficult to characterize by routine monitoring at fixed-time intervals. This routine works well to characterize base-flow conditions and to establish potential long-term trends but is not appropriate to characterize rapidly changing conditions in response to streamflow. Automated samplers and continuous water quality and streamflow monitoring methods, as used in this study, generally will indicate extremes that can be important with respect to biological or regulatory thresholds, and can indicate significant relations between streamflow, water chemistry, and transport of sediment and associated chemicals. Water quality regulations established to achieve in-stream water-quality standards or to maintain designated uses of the water body (water supply, fishing, etc.), such as Total Maximum Daily Loads (TMDLs), require baseline characterization of pollutant loads in order to determine required reductions in loading from various contaminant sources (Caruso 2005, Pennsylvania Department of Environmental Protection 1999, 2002). Data that do not adequately represent stormflow conditions will underestimate the transport of sediment and associated metals and will not be useful to establish the data distribution.

Generally, to maintain stream pH in water bodies affected by AMD and subject to acidification during storms, limestone diversion wells or other dosing systems could be constructed to begin or increase alkalinity production as the stream stage rises, and underground limestone drains and/or limestone-filled basins could be constructed at AMD sites to enhance the buffering capacity of base flow. Nevertheless, as the limestone in treatment systems is consumed, supplemental buffering capacity would be needed to maintain near-neutral pH. Furthermore, neutralization and pH buffering alone will not remedy the problem of metals transport. Solid forms of the metals, as particulate and particle coatings, can be ingested and accumulated by aquatic organisms and can be remobilized by reductive dissolution of FeIII and MnIII-IV oxides in buried sediment. Additional measures such as wetlands and holding basins for stormwater could be warranted to prevent metals transport to the stream. However, impounding water in wetlands and shallow ponds could increase warming of the water during summer, potentially leading to temperatures that are not favorable to fish. If the restoration of fish and other aquatic organisms is a goal of reclamation, strategies for AMD treatment should be considered that minimize the potential for excessive warming of the water while removing toxic metals.

## For More Information

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# INFORMATION

## New Report: Decentralized Stormwater Controls for Urban Retrofit and CSO Reduction

A new WERF research report, Decentralized Stormwater Controls for Urban Retrofit and Combined Sewer Overflow Reduction: Phase 2 (stock no. 03SW3a), evaluates strategies for incorporating decentralized controls into an infrastructure management system. Case studies and design templates provide alternatives for adoption of decentralized controls. The research team, led by Neil Weinstein of the Low Impact Development Center, evaluates economic methods for assessing environmental costs and benefits and provides guidance for modeling decentralized controls with commonly used stormwater models. To obtain a copy of the report, visit http://www.werf.org/AM/Template.cfm?Section=Search&Template=/CustomSource/Research/ResearchProfile.cfm&ReportId=03-SW-3a&ID=03-SW-3a.

## New BMP and LID Whole Life Cost Tools

In partnership with U.S. EPA, WERF has developed a new suite of cost tools to address vegetative roofs, rainwater catchment systems, and bioretention facilities. These tools provide a framework to facilitate cost estimation for capital costs, operation and maintenance costs, and life-cycle net present value. The tools can serve as a format for cost reporting for past, current and future projects, and also provide users with planning-level cost estimates.

These new tools complement an existing suite of BMP whole life cost models for retention ponds, extended detention basins, swales, and permeable pavement developed under a previous WERF project. To access the complete set of tools and accompanying user's guide, visit http://www.werf.org/bmpcost.

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# MEETINGS

## Conference Presentations

**17th National Nonpoint Source Monitoring Workshop: Reducing Nutrients and Documenting Results: September 14-17'09, New Orleans, LA.** See Highlight on Page 27.

## Call for Abstracts

**StormCon '10: The North American Surface Water Quality Conference & Exposition, August 1 - 5, 2010, San Antonio, TX**. Visit conference website at http://www.StormCon.com

## Meeting Announcements — 2009-2010

### November

**AWRA 2009 Annual Water Resources Conference: November 9-12, 2009, Seattle, WA.** Visit conference website at http://www.awra.org/meetings/Seattle2009/

### December

**2009 NWEC: Northwest Environmental Conference and Tradeshow: December 7-8, 2009, Portland, OR.** Visit conference website at http://www.nwec.org/2009/

**Science to Solutions: Reducing Nutrient Export to the Gulf of Mexico.** Sponsored by the U.S. Department of Agriculture, U.S. Geological Survey and U.S. Environmental Protection Agency. Visit conference website at http://www.swcs.org/en/conferences/

### March 2010

**Urban River Restoration 2010. March 7-10, 2010. Boston, MA.** Visit conference website at http://www.wef.org/UrbanRiver/

### April 2010

**7th National Monitoring Conference-Monitoring From the Summit to the Sea: April 25-29, 2010, Denver, CO.** Visit conference website at http://acwi.gov/monitoring/conference/2010/index.html.

### July 2010

**Soil & Water Conservation Society 2010 Annual Conference. July 18-21, St. Louis, Missouri.** Visit conference website at http://www.swcs.org/en/conferences/

### August 2010

**2010 Watershed Management Conference: "Innovations in Watershed Management Under Land Use and Climate Change"** August 23-27, 2010. Madison, WI. http://content.asce.org/conferences/watershedmanagement2010/

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## 17th National Nonpoint Source Monitoring Workshop:

### Reducing Nutrients and Documenting Results

Sept. 14-17, 2009 – New Orleans, Louisiana
http://www.tetratech-ffx.com/nps_monitoring/

The Annual Nonpoint Source (NPS) Monitoring Workshop was an important forum for sharing information and improving communication about controlling and monitoring NPS pollution issues and projects. The focus of the 17th National Workshop was on nutrients and lessons learned that can be factored into State Nutrient Reduction Strategies.

Specific topics of interest highlighted at the 17th annual workshop included:

- Hypoxia
- CSREES-CEAP Synthesis and Preliminary Lessons
- National Monitoring Program (NMP): Long-Term Monitoring Projects Documenting Water Quality Improvements from Best Management Practices
- Monitoring Methods
- Upper Mississippi River Evaluation and Assessment
- Source Identification/Assessment
- Nutrient Issues in Louisiana
- Watershed/Field Scale Monitoring
- BMP Performance
- Watershed Restoration
- Lessons Learned from NPS Monitoring
- Water Quality Trading

**Mini Workshops were conducted on:**

- Nonpoint Source Monitoring Workshop Social Indicators
- Agricultural Nutrient Management Tools
- Analysis of Imperfect Data
- Introduction to the Watershed Central Web Site and the Watershed Central Wiki
- Urban Tools: Approaches Towards Effective Stormwater BMP Targeting

Production of NWQEP NOTES is funded through U.S. Environmental Protection Agency (EPA). Project Officer: Tom Davenport, Office of Wetlands, Oceans, and Watersheds, EPA. 77 W. Jackson St., Chicago, IL 60604. Website: http://www.epa.gov/OWOW/NPS

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