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Scientific Investigations Report 2020–5031

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

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Conversion Factors

Inch/Pound to SI

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)
Acre	0.4047	hectare (ha)
square mile (mi^2)	259.0	hectare (ha)
	Volume	
cubic feet (ft^3/s)	7.48	gallon (gal)
gallon (gal)	0.13368	cubic feet (ft^3/s)
million gallons (Mgal)	3,785	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	1.85814	cubic foot per second (ft^3/s)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	megagram (Mg)
ton per day (ton/d)	0.9072	metric ton per day
ton per day (ton/d)	0.9072	megagram per day (Mg/d)
ton per day per square mile [(ton/d)/mi^2]	0.3503	megagram per day per square kilometer [(Mg/d)/km^2]
ton per year (ton/yr)	0.9072	metric ton per year

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

°C=(°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 1983 (NAD 83).

Elevation, as used in this report, refers to the distance above the vertical datum.

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

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L)

Abbreviations

ASTM	American Society for Testing and Materials
BMP	best management practice
BOL	Bureau of Laboratories
MRL	method reporting limit
NWQL	National Water Quality Laboratory
PaDEP	Pennsylvania Department of Environmental Protection
SSC	suspended-sediment concentration
USGS	U.S. Geological Survey
WRTDS	Weighted Regressions based on Time, Discharge, and Season
WY	water year

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Abstract

Big Spring Run is a 1.68-square mile watershed underlain by mostly carbonate rock in a mixed land-use setting (part agricultural and part developed) in Lancaster County, Pennsylvania. Big Spring Run is a subwatershed of Mill Creek, a tributary to the Conestoga River. These watersheds are known contributors of nutrient and sediment loads to the Chesapeake Bay and several stream reaches are on the Pennsylvania impaired waters list. Big Spring Run is listed as impaired and was selected by the Pennsylvania Department of Environmental Protection to evaluate a novel best management practice to restore natural aquatic ecosystems by removing legacy sediment. The study was designed to quantify sediment and nutrient contributions in pre- and postrestoration periods (water years 2009–11 and 2012–15, respectively) using an intensive monitoring approach at three surface-water sites within the watershed. Instrumentation at each site continuously measured (15-minute intervals) streamflow, water temperature, and turbidity. Water-quality samples were collected routinely (generally monthly and during selected storms); sampling frequency varied by site and constituent at the three monitoring sites.

Effects of legacy sediment removal and restoration on nutrient concentrations varied in surface water samples depending on the form (particulate, dissolved, organic, inorganic). For example, total phosphorus concentrations at the downstream site decreased from a median of 0.19 milligram per liter (mg/L) to 0.04 mg/L, pre- and postrestoration periods, respectively. Concentrations of orthophosphate, the dissolved form of phosphorus, were not significantly different pre- to postrestoration at the downstream site. Similarly, nitrate concentrations, the dominant form of nitrogen in Big Spring Run surface-water samples (92.3 percent of total nitrogen) were not significantly different in the pre- compared to the postrestoration periods.

Legacy sediment removal and restoration had significant effects on suspended-sediment concentrations and loads. Median suspended-sediment concentrations at the downstream site decreased from 556 mg/L prerestoration to 74 mg/L postrestoration even though streamflow hydrographs during the two periods were similar. In the postrestoration period, the mean annual suspended-sediment load conveyed to the restoration area from the upstream sites was 839 tons, whereas mean annual suspended-sediment load at the downstream site was reduced to 242 tons.

Streamflow during storms transports a large proportion of the suspended-sediment load; there were a total of 320 storms over the study period. In Big Spring Run, a single storm event can transport more than 25 percent of the annual suspended-sediment load. The greatest single-storm contribution to suspended-sediment load was 38 percent in water year 2015 at the downstream site. Although streamflow magnitudes during storms varied greatly over the study period, median streamflow was 17.5 cubic feet per second and median duration was about 3 hours and 24 minutes.

Results observed for this study using the newly proposed best management practice were compared with other best management practices intended to reduce sediment. For example, during a previous study, statistically significant reductions in suspended-sediment concentration were observed when streambank fencing was implemented in an adjacent watershed; however, suspended-sediment reductions were an order of magnitude less than the reductions observed in the current study. Median suspended-sediment concentration at the downstream site was reduced by 482 mg/L in the current study compared to only 30 to 46 mg/L as a result of streambank fencing.

Introduction

Identification and quantification of the relative contribution of nutrient and sediment sources from watersheds in the Chesapeake Bay are needed to assist resource managers in developing and implementing strategies to reduce nutrient and sediment loads to the bay. These reductions are necessary to meet nutrient and sediment allocation goals to help remove the Chesapeake Bay from the impaired waters list. Recognition of large amounts of historical sediment with relatively high nutrient concentrations that are stored along valley-bottom corridors, also known as legacy sediment (Walter and Merritts, 2008), has led the Commonwealth of Pennsylvania to evaluate a best management practice (BMP) that targets legacy sediment-impaired aquatic ecosystems for restoration (Hartranft and others, 2011). The valley morphology changes resulting from legacy sediment storage alter natural aquatic ecosystem functions and processes that maintain healthy water quality and habitat (Hartranft and others, 2011). Aquatic ecosystem restoration resulting from removal of legacy sediment is proposed to substantially reduce sediment and nutrient loads to streams. Sediment storage historically increased in valley bottoms and stream channels as a result of timbering, land clearing, deposition of sediment behind thousands of small mill dams, and marginal and ineffective soil retention methods. The proposed BMP involves legacy sediment removal to restore natural valley morphologies, biogeochemical processes, and biological components of natural aquatic ecosystems (Hartranft and others, 2011).

The landscape around Big Spring Run has been greatly altered since the arrival of European settlers in the early to mid-1700s; dark rich soils containing plant macrofossils characteristic of wetland vegetation indicate a wetland-dominated paleoenvironment (Merritts and others, 2010). Land-clearing activities led to migration of soil down the gentle slopes to the valley bottom. In addition, a grain mill dam about 8-feet (ft) high was built on the lower reach of Big Spring Run in the mid-1700s. The eroded sediment filled the valley bottom over time and the amount of stored sediment in the Big Spring Run corridor increased. At some point in time (between 1890 and early 1900), dam breaching caused stream incision into the legacy sediment.

Big Spring Run was selected by the Pennsylvania Department of Environmental Protection (PaDEP) to evaluate the proposed restoration BMP approach to determine the effects of legacy sediment removal on nutrients and sediment because of previous studies done in the basin and the historical evidence of a small mill dam. Galeone and others (2006) monitored surface water, nutrient and sediment loads, and groundwater quality from 1993–2001. Gutshall (2004) and Walter and Merritts (2008) determined that streambank erosion in the Big Spring Run headwaters during a 1.5-year period (2003–04) occurred at a rate of approximately 0.2 ton of sediment per linear foot of stream channel per year. Prior to restoration in October 2011, as much as 35 and 54 percent of the sediment originated from two tributaries upstream from the restoration area (U.S. Geological Survey [USGS] 015765185 and USGS 01576516, respectively), and as much as 70 percent originated within the sediment restoration area (Merritts and others, 2010). Additional studies by Franklin and Marshall College (Walter and others, 2007; Weitzman, 2008; Merritts and others, 2010, 2013) present information on nutrient and sediment sources and identify the large volume of legacy sediment in the valley bottom as a major contributor of nutrients and sediment in watersheds such as Big Spring, and that much of the sediment originates from streambank erosion.

Long-term BMP efficiency studies to assess and document sediment and nutrient reductions with components consisting of (1) identification of sources and loads, (2) prerestoration monitoring, (3) remediation, and (4) postrestoration monitoring are costly and rarely applied in management strategies in a quantifiable fashion. This study was designed to document changes in water quality (specifically, sediment transport) after restoration. An upstream-downstream approach was utilized to quantify the sediment mass transported into and out of the restoration area by comparing streamflow and surface-water-quality data in the pre- and postrestoration periods.

Purpose and Scope

This report presents the results of nutrient and sediment contributions from Big Spring Run prior to, during, and after the removal of legacy sediment and restoration of natural aquatic ecosystem forms and processes. Nutrient and sediment concentrations and loads were determined for a prerestoration period (water years 2009–11) and compared to nutrient and sediment concentrations and loads for a 4-year postrestoration period (water years 2012–15). Water year is defined as the 12-month period from October 1 through September 30 of the following year and is designated by the calendar year in which it ends. The comparison presented here documents the effects of removing legacy sediment in Big Spring Run.

Study Area

The 1.68-square mile (mi^2) Big Spring Run watershed is near the town of Willow Street, which is approximately 4 miles (mi) south and southeast of the city of Lancaster in Lancaster County, Pennsylvania. The study reach includes the main stem of Big Spring Run and an unnamed headwater tributary (fig. 1). Big Spring Run flows north and joins Mill Creek, which is a tributary to the Conestoga River. The Conestoga River and Mill Creek watersheds have been identified as important contributors of nutrient and sediment loads to Chesapeake Bay (Koerkle, 2000; Gellis and others, 2004). Many stream reaches in the Conestoga River and Mill Creek watersheds are impaired, including Big Spring Run, which is listed for aquatic life, construction, siltation, habitat modification, and unknown toxicity (Pennsylvania Department of Environmental Protection, 2014).

The Big Spring Run watershed is underlain by Cambrian-Ordovician age carbonate and siliciclastic rocks covered by a variable layer of soil less than 5 ft thick. Approximately 90 percent of the watershed is underlain by limestone (Conestoga Formation); with the remaining area underlain by dolomite (Vintage Formation) and quartzite, schist, or phyllite (Antietam and Harpers Formations, undivided) (Berg and others, 1980; Galeone and others, 2006). The Conestoga

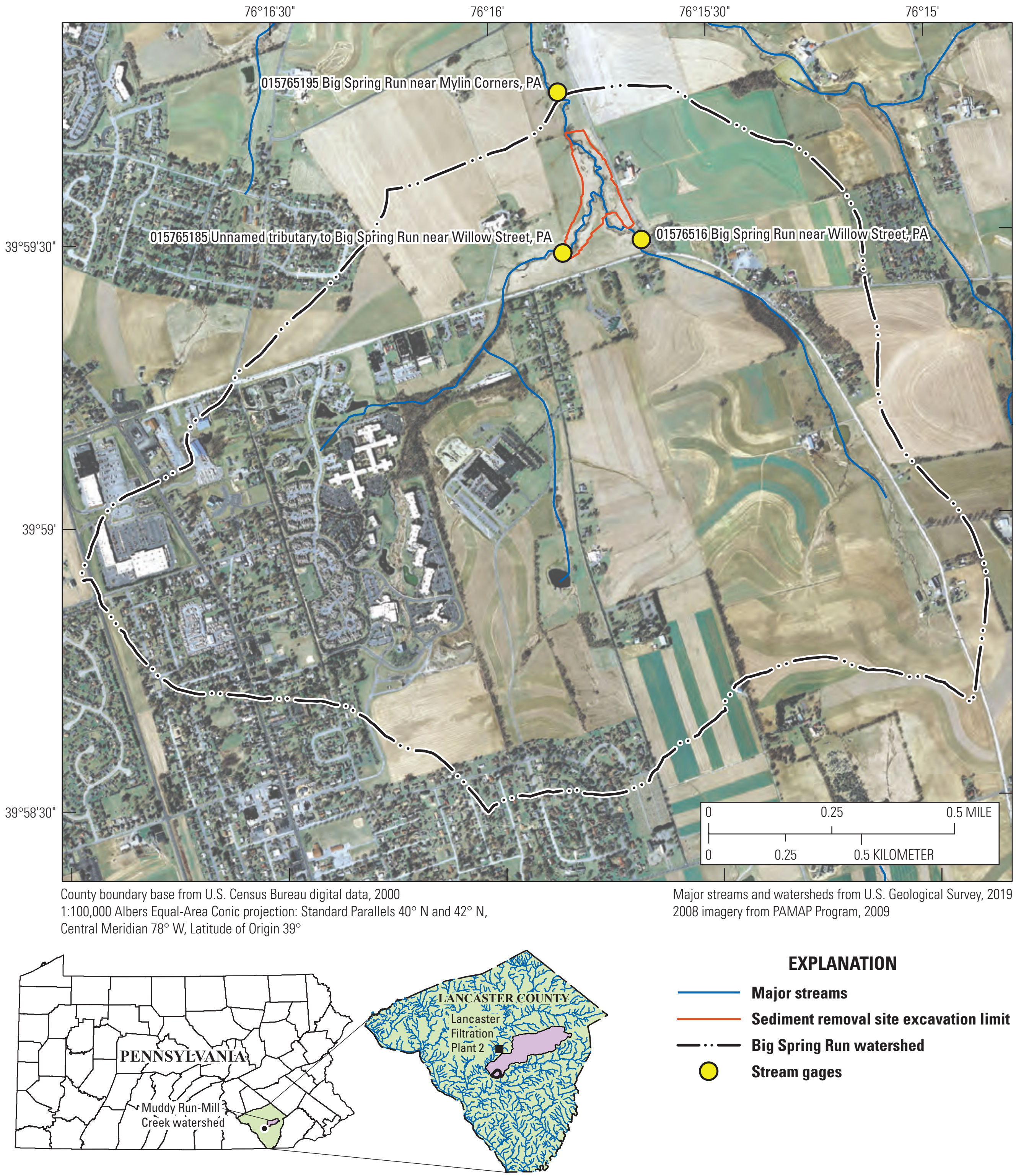


Figure 1. Location of Big Spring Run study area and vicinity, Lancaster County, Pennsylvania. Figure modified from Merritts and others (2013).

Formation has characteristics of karst, including sinkholes, surface depressions, springs, pinnacles, swales (Galeone and others, 2006), and typically higher recharge rates compared to nearby geologic formations (Gerhart and Lazorchick, 1988). The soils along the ridges and adjacent side slopes are predominantly classified as the Conestoga (fine-loamy), Penlaw (fine-silty), and Pequea (course-loamy) series. Along the middle and lower slopes, soils are classified as the Lehigh (fine-loamy) series and along the streams as the Clarksburg (fine-loamy) series (Custer, 1975).

Based on the 2011 National Land Cover Database (U.S. Geological Survey, 2014), land use in the Big Spring Run watershed is approximately

- 50 percent agricultural (pasture/hay and cultivated crops),
- 46 percent developed (open space, low, medium, and high intensity development, and barren land including rock/sand/clay), and
- 4 percent forested (deciduous and evergreen forests, shrub/scrub, and emergent herbaceous and woody wetlands).

From 2001 to 2011, land classified as developed increased by 10 percent and forested land increased by 1 percent, with agricultural lands decreasing by 11 percent (LaMotte, 2008; U.S. Geological Survey, 2014). The increase in developed land and decrease in agricultural land mostly occurred in the western part of the watershed near the town of Willow Street. The mean basin elevation is 409 ft above the North American Vertical Datum of 1988 (NAVD 88).

Limited local precipitation data were available within the study area; therefore, rainfall patterns were characterized using data from the Pennsylvania State Climatologist LCRP1 site (Lancaster Filtration Plant #2) operated by the Lancaster Water Company 4.1 mi to the northeast of the study area (fig. 1). The average yearly precipitation and temperature at the LCRP1 site are 41 inches and 60 °F, respectively (Pennsylvania State Climatologist, 2016). Daily precipitation data from the Pennsylvania State Climatologist (2016) from October 1, 2008, to September 30, 2015, used in data analysis described in this report are available in Langland (2019b). A summary of the rainfall data by water year is provided in table 1.

For this study, three U.S. Geological Survey streamgages were installed—two upstream of the restoration area (referred to hereafter as the east and west sites for USGS 01576516 and USGS 015765185, respectively) and one downstream of the restoration area (hereafter referred to as the downstream site for USGS 015765195) (fig. 1). Each streamgage was equipped with a transducer to measure water-level change, a water-quality sonde, satellite telemetry equipment, and automatic samplers. The locations of the three streamgages were based on the original restoration removal plans and were to have been placed directly upstream or downstream from the removal area. By the time of construction, increased costs necessitated changes to the original plan. The downstream site (USGS 015765195) is approximately 400 ft downstream and outside of the final sediment removal area. The upstream east and west site locations (USGS 01576516 and 015765185) were located approximately 130 and 175 ft, respectively, upstream and outside of the restoration area. In 2015, the west site (USGS 015765185) was moved approximately 195 ft downstream and inside the restoration area.

Table 1. Precipitation totals by water year at Lancaster Filtration Plant #2 (LCRP1) rain gage near Big Spring Run, Lancaster County, Pennsylvania. The end of the prerestoration period and beginning of the postrestoration period occurred between 2011 and 2012.

Water year[1]	Precipitation at LCRP1 (in inches)
2009	41.19
2010	39.95
2011	51.42
2012	37.67
2013	39.02
2014	55.4
2015	40.52
Average, prerestoration period	44.19
Average, postrestoration period	43.15

[1]Water year is defined as the 12-month period from October 1 through September 30 of the following year. The water year is designated by the calendar year in which it ends.

Methods

In this section, sample-collection and data-analysis methods for nutrient, streamflow, turbidity, and suspended-sediment concentration (SSC) data are described. The analytical and statistical methods for estimating missing continuous streamflow and turbidity records and additional modifications to the data are discussed, and statistical approaches to data analysis are described.

Nutrients

From water year (WY) 2009 through WY2011, nutrient samples were collected using a Teledyne ISCO® automated sampler that was programmed to collect a sample based on in-stream conditions. Nutrient samples were collected concurrently with suspended sediment samples. If the automated sampler was triggered while field personnel were on site, measurements of instream specific conductance, pH, dissolved oxygen, and temperature were made using a calibrated field meter as described in the USGS National Field Manual (U.S. Geological Survey, variously dated). The automated samplers were programmed to collect a sample every 15 minutes for the first 3 hours (12 samples) and then programmed to collect samples every 30 minutes for the next 6 hours (12 samples) for a total of 24 samples collected over a sampling event (total of 9 hours). The sampling event trigger for the automated sampler was when stream stage increased by 0.5 ft over a preset stage or when instream turbidity exceeded 100 Formazin nephelometric units (FNU). From WY2009 through WY2011, when the 24 samples were recovered from the automated sampler, bottles for nutrient analysis were selected from the rising limb, peak, and falling limb of the hydrograph. The samples were then processed according to the sample processing guidelines described in the USGS National Field Manual (U.S. Geological Survey, variously dated). Once processed, the samples were shipped on ice to the USGS National Water Quality Laboratory (NWQL, Lakewood, Colorado). Nutrient analysis at the NWQL included filtered nitrate, filtered ammonia, total nitrogen, filtered total nitrogen, total phosphorus, filtered total phosphorus, filtered nitrate plus nitrite, and filtered orthophosphate.

From WY2012 through WY2015, nutrient samples were collected concurrently with SSC samples using a multiple-vertical channel-integrated sampling approach (a nonisokinetic equal width integrated sample) as described in the USGS National Field Manual (U.S. Geological Survey, variously dated). During sample collection, field properties (specific conductance, pH, dissolved oxygen, and temperature) were determined using a calibrated field meter as described in the USGS National Field Manual (U.S. Geological Survey, variously dated). Field properties were measured in each of three sections at each site and the median value was reported. After collection, samples were split using a 7-liter (L) polyethylene churn splitter and processed according to sample processing methods described in the USGS National Field Manual (U.S. Geological Survey, variously dated). Nutrient samples were analyzed by the Pennsylvania Department of Environmental Protection Bureau of Laboratories (PaDEP BOL) for filtered and unfiltered nitrate plus nitrite, filtered and unfiltered total phosphorus, filtered and unfiltered ammonia, filtered and unfiltered total nitrogen, and filtered and unfiltered orthophosphate.

All discrete nutrient, total suspended solids, and suspended-sediment concentration data are available in the companion data release (Langland, 2019b). Laboratory reporting standards vary between analytical laboratories and as a result, nomenclature is often different between laboratories. In our study, the terms “dissolved” and “filtered” and the terms “total” and “unfiltered” are used interchangeably throughout this report.

Streamflow

Three continuous streamflow streamgages were established on Big Spring Run (table 2). Two of the sites were upstream of the restoration area, the easternmost upstream tributary in the study area was USGS 01576516, and the westernmost upstream tributary in the study area was USGS 015765185. The third site, which was downstream of the restoration area, was USGS 015765195. Streamflow was measured at these three sites according to standard USGS protocols and methods (Turnipseed and Sauer, 2010). Briefly, every 15-minutes a stream stage (gage height) measurement was made with a pressure transducer. Periodic (every 4–6 weeks) instantaneous streamflow measurements were made adjacent to the stream stage sensor using a Sontek Flowtracker handheld Acoustic Doppler Velocimeter (ADV®). Over time, a relational rating was established between stream stage and instantaneous discharge so that instantaneous discharge could be predicted. Streamflow measured at 15-minute increments is described as continuous streamflow throughout this report. All streamflow data from this site are available in the companion data release (Langland, 2019b).

Table 2. Description of three U.S. Geological Survey surface-water monitoring sites, Big Spring Run, Lancaster County, Pennsylvania.

[USGS, U.S. Geological Survey; Pa., Pennsylvania; mi^2, square miles]

USGS site number	USGS site name	Local name	Latitude[1] (decimal degrees)	Longitude[1] (decimal degrees)	Drainage area (mi^2)
01576516	Big Spring Run above Tributary near Willow Street, Pa.	East site (east)	39.99154444	76.2609306	0.36
015765185	Unnamed Tributary to Big Spring Run near Willow Street, Pa.	West site (west)	39.99119167	76.26395278	1.05
015765195	Big Spring Run near Mylin Corners, Pa.	Downstream site	39.9959361	76.26403889	1.68

[1]Latitude/longitude coordinate datum is North American Datum of 1983 (NAD 83).

Turbidity

At each of the three USGS sites (east, west, downstream), a YSI or ANALITE turbidity probe and sonde were deployed according to standard USGS protocols (Wagner and others, 2006). Turbidity sondes were programmed to measure, record, and transmit data every 15 minutes. Turbidity measured in 15-minute increments is described as continuous turbidity data throughout this report. Throughout the 7-year course of data collection for this study, the make and model of turbidity probes used at each site was changed. The timing of these changes and specifications for each instrument is documented in table 3.

Sediment

Suspended-sediment samples were collected concurrently with nutrient samples as described in the Nutrients section. From WY2009 through WY2011, all SSC samples were analyzed at the USGS Pennsylvania Water Science Center (New Cumberland, Pennsylvania) using the American Society for Testing and Materials (ASTM) D3977-97: Test Method A-Evaporation (American Society for Testing and Materials, 2006). From WY2012 through WY2015, suspended sediment samples were analyzed by the USGS sediment laboratory in Louisville, Kentucky, using ASTM D3977-97: Test Method B-Filtration (American Society for Testing and Materials, 2006).

Data Management and Statistical Evaluation

This section describes the methods of data handling, including pairing continuous streamflow and turbidity datasets, censoring of data, regression models used to predict missing continuous data, and regression models used to predict continuous suspended-sediment concentration. In addition, methods used to analyze continuous streamflow, turbidity, sediment, and discrete nutrients and physical stream characteristics in the pre- and postrestoration periods are described. Note, all times in all datasets presented in this report and in the companion data releases (Langland, 2019a,b,c) are in Eastern Standard Time (Coordinated Universal Time minus 5 hours).

Data Handling

Raw continuous streamflow and turbidity data were retrieved internally from the USGS Aquarius Timeseries database for sites 01576516 (east), 015765185 (west), and 015765195 (downstream). Data were loaded into R-stats (R ver. 3.5.0) using R-studio (ver. 1.1.453). Data were handled with the R statistical computing software (combination of tidyr and base R packages; R Core Team, 2017). All continuous data values were paired with a date-time value from a complete time series from October 1, 2008, at 00:00:00 through September 30, 2015, at 23:45:00, creating a dataset of 245,280 datapoints for date-time, streamflow, and turbidity measurements.

Streamflow data were censored at the 10-year recurrence base-flow interval as determined using USGS Streamstats (ver. 4.2.1) available at https://streamstats.usgs.gov/ss/. Streamflow at the east site was censored at or below 0.29 cubic feet per second (ft^3/s), streamflow at the west site was censored at or below 0.63 ft^3/s, and streamflow at the downstream site was censored at or below 0.97 ft^3/s. All turbidity values below 0.1 FNU were censored, as variation below this range is outside of the operational limits of the sensors. Missing data from the data import and data censoring were indicated with NA values.

Discrete suspended sediment data were loaded into R using the USGS dataRetrieval package (De Cicco and others, 2018). Discrete samples were paired with the proper sites and appended to the 15-minute time point that fell closest to the date and time of the discrete sample collection.

Table 3. Description of turbidity sondes and sensors used at three sites on Big Spring Run, Lancaster County, Pennsylvania.

[LED, light emitting diode; USGS, U.S. Geological Survey; nm, nanometers]

USGS site number	Make and model	Light source	Range	Reported units	Date installed	Date removed
01576516 (East site)	ANALITE NEP395	Broad brand, 400–680 nm	1–1,500	Formazin nephelometric units	9/15/2008	8/30/2011
	YSI 6136	Near infrared LED, 780–900 nm	1–1,000	Formazin nephelometric units	8/30/2011	11/1/2017
015765185 (West site)	ANALITE NEP395	Broad brand, 400–680 nm	1–1,500	Formazin nephelometric units	9/30/2008	8/30/2011
	YSI 6136	Near infrared LED, 780–900 nm	1–1,000	Formazin nephelometric units	8/30/2011	11/1/2017
015765195 (Downstream site)	YSI 6026	Near infrared LED, 780–900 nm	1–1,000	Formazin nephelometric units	10/7/2008	8/30/2011
	YSI 6136	Near infrared LED, 780–900 nm	1–1,000	Formazin nephelometric units	10/7/2008	Current

Once regression models were computed to predict missing continuous streamflow and turbidity values, the surrogate regressions were computed to predict continuous SSC. Complete time-series record for streamflow and turbidity at each site using regression models to fill missing values was not possible. Rather, regressions were used to fill in as much data as possible at each site based on streamflow and turbidity at the other two adjacent study sites. If the two adjacent sites had gaps in streamflow or turbidity in their measured record, then a regression model could not be used to predict the missing data. Finally, all possible predicted and measured streamflow and turbidity data at each site was merged to create a blended time series. The methods used are covered in detail in Langland (2019a). Continuous suspended-sediment load was computed using base R and tidyr packages. Continuous SSC is the quantity of suspended sediment passing a point in a stream over a specific period of time. The regression model selected to predict continuous SSC was based on continuous turbidity. All continuous turbidity measurements were made (or missing/censored values predicted) at 15-minute intervals. When 15-minute SSC concentration data are converted to load and expressed as tons per day, suspended sediment load per day is computed with the following formula,

$$SSL_{day} = \sum_{1 \rightarrow 96} SSC_{Ci} \times Q_i \times k$$

where

SSL_{day} is the suspended-sediment load for the ith values, in tons per day;

SSC_{Ci} is suspended-sediment concentration for the ith value in milligrams per liter (mg/L);

Q is streamflow for the ith value in ft^3/s; and

k is a conversion factor equal to $\dfrac{0.0027 \text{ seconds} \times L \times \text{short tons}}{\text{day} \times ft^3 \times mg}$

The value for the constant k is derived from other common conversions (86,400 seconds/day × 28.32 L/ft^3 × 1.102 /10^9 tons/mg) (Norton and others, 2019). To convert the daily load to a 15-minute load, the SSL_{day} must be divided by 96 (the number of 15-minute intervals in 1 day):

$$SSL_{15\text{-minute}} = SSL_{day}/96$$

where

$SSL_{15\text{-minute}}$ is the suspended-sediment load, in tons, per 15-minute interval; and

96 is the number of 15-minute intervals in 1 day.

Daily, monthly, and annual suspended sediment loads were computed by summing all available continuous values. Annual suspended sediment loads were computed on the basis of water year, not calendar year. For the purposes of our report, missing values were treated as zero load, so the values presented here, although accurate for measured and predicted data, may underrepresent the total load at larger time intervals (days, months, years) with large proportions of missing values (table 4).

Continuous Data

Once the data were prepared as described above, six regression models were developed and compared for each site. For streamflow regression models, a subset of data was created for instances when all three sites had concurrently measured streamflow values (no missing values between the three sites) for the prerestoration period (WY2009–WY2011) and postrestoration period (WY2012–WY2015). A similar process was also used to subset the data for which all three sites had concurrently measured turbidity values from pre- and postrestoration periods. Regressions were then built in base R relating the variable of interest (either turbidity or streamflow) at one site with concurrent measures at one other site or both of the other sites. These regressions were computed both in linear and $\log_{10}$ space. Comparisons of the diagnostic statistics of the regression models were made for the six models (three linear models, three $\log_{10}$ models) at each location for two conditions (pre- and postrestoration periods) for both streamflow and turbidity. We expected that there would be large difference in the relation between streamflow and turbidity at the downstream site after restoration. Therefore, we built models for all sites to represent pre- and postrestoration conditions. To consistently analyze and select the best regression model for each site and constituent, the six regression models for streamflow and the six regression models for turbidity were evaluated using (1) summary statistics for all dependent and independent variables; (2) boxplots of all variables; (3) exploratory correlation plots of all variables; and (4) basic model statistics including the number of observations, the root mean square error, the adjusted coefficient of determination (adjusted R^2), the model standard percent error, the predicted residual error sum of squares statistic, and a bias correction factor for log normalized data. The input data that were used to create each regression model, a description of the model selection process, and an archive of each model are available in Langland (2019a). Output from the selected models that was used in subsequent analysis for this report is provided in Langland (2019b). The number of censored and missing continuous values for each site are reported in table 4.

Next, six regression models were developed and compared to relate streamflow and (or) turbidity to SSC. It should be noted, that although we did estimate as much of the missing turbidity and streamflow record as possible with the models described above, there were still some gaps in data that could not be filled. The datasets were used in a similar workflow to model the relation between streamflow and (or) turbidity and measured discrete SSC. Models were created only for data from the site where sediment was being predicted and were created for the prerestoration (WY2009–WY2011) and postrestoration (WY2012–WY2015) periods. The data subsets that were used to create all regression models, a description of the model selection process, and an archive of the models are available in Langland (2019a). The SSC output from the selected models that was used in all subsequent analysis for this report is provided in the companion data release (Langland, 2019b).

Table 4. Summary of missing and censored 15-minute unit-value data for streamflow and turbidity at three sites, Big Spring Run, Lancaster County, Pennsylvania, water years 2009–15.

[Streamflow is censored at and below the 10-year recurrence base-flow interval for each site. The 10-year recurrence base-flows for East Branch, West Branch, and Downstream are 0.29 cubic feet per second (ft^3/s), 0.63 ft^3/s, and 0.97 ft^3/s, respectively. Turbidity is censored at 0.1 Formazin nephelometric units (FNU) at all three sites. Only missing 15-minute unit-values for streamflow and turbidity above prescribed censoring levels are presented]

Water year[1]	01576516 East site				015765185 West site				015765195 Downstream site			
	Censored streamflow unit-values (percent)	Missing streamflow unit-values above censor level (percent)	Censored turbidity unit-values (percent)	Missing turbidity unit-values above censor level (percent)	Censored streamflow unit-values (percent)	Missing streamflow unit-values above censor level (percent)	Censored turbidity unit-values (percent)	Missing turbidity unit-values above censor level (percent)	Censored streamflow unit-values (percent)	Missing streamflow unit-values above censor level (percent)	Censored turbidity unit-values (percent)	Missing turbidity unit-values above censor level (percent)
2009	0.00	24	0.00	18	50	36	0	12	3	5	1	16
2010	6.19	0	0.00	5	42	20	0	18	13	6	0	16
2011	0.04	17	0.00	27	48	28	0	59	0	5	0	60
2012	0.01	0	0.00	14	48	2	0	31	4	16	0	47
2013	0.00	24	0.00	31	66	47	21	39	1	5	34	41
2014	7.63	0	1.72	3	43	0	16	3	3	0	2	15
2015	3.77	0	2.01	5	60	1	35	15	10	0	11	12
Prerestoration period (2009–11)	2.40	14	0.00	17	46.86	17	0.02	30	5.45	5	0.26	31
Postrestoration period (2012–15)	3.03	6	1.03	13	53.30	6	19.04	19	4.84	5	11.81	26
Study period (2009–15)	2.78	9	0.60	15	50.73	11	11.54	24	5.10	5	7.04	28

[1]Water year is defined as the 12-month period from October 1 through September 30 of the following year. The water year is designated by the calendar year in which it ends.

In computing daily, monthly, and annual summaries of data, there was still an issue with a significant number of missing data (table 4). We compared a summing method, where all data for each available period were summed, then averaged over that period, and the average values were substituted for missing values. The summing method is the more conservative method and biases the suspended-sediment load values low, when contrasted with the less conservative averaging method that biases the suspended-sediment load values high. All subsequent data evaluations presented in this report and the daily, monthly, and annual outputs presented in the companion data release (Langland, 2019b) are based on the summing method.

Flow-duration curves were used to define the storm event streamflow value. A flow-duration curve is a statistical cumulative frequency curve that shows the percent of time for which specific discharges are equaled or exceeded (exceedance frequency distribution) during a given period of time. In a single plot and related table, the flow characteristics of a stream throughout the range of observed discharges are combined without regard to the sequence in which those discharges were observed. If the period of observation is long enough, the curve can be used to evaluate the differences in the distribution of flows (Searcy, 1959). In this study, flow-duration curves were compiled using the methods of Granato (2009) for 3 years prior to restoration and 4 years after restoration.

The compiled flow-duration curves were used to compare streamflow distribution in the pre- and postrestoration periods at the downstream site. The flow-duration curve of the downstream site in the prerestoration period was used to assign a value for the 5-percent exceedance probability. The 5-percent exceedance probability corresponded to a streamflow of 7.84 ft^3/s. Any streamflow at the downstream site greater than or equal to 7.84 ft^3/s lasting at least 15 minutes was considered a storm event throughout the study area.

Statistical Tests of Discrete Data

All statistical comparisons between groups of data (nutrients and sediment) were conducted using the nonparametric Wilcoxon (Mann-Whitney) rank-sum test as described in Helsel and Hirsch (2002). This test can be conducted with no assumptions about the distribution of the data and rejecting the null hypothesis (p-value <0.05) indicates that the median (and other percentiles of the data) are different. All Wilcoxon tests were done in TIBCO® S-PLUS, version 8.1.

In many figures, data are presented as boxplots. A boxplot is a way to compare the statistical distribution of one set of data with another. The box consists of a median line, with the upper part of the box representing the 75th percentile of the data and the lower part of the box representing the 25th percentile of data. Upper and lower adjacent lines that extend from the box represent 1.5 times the interquartile range, that is 1.5 times the range of the median to the 75th percentile, and 1.5 times the median to the 25th percentile, respectively. The upper and lower detached "x" symbols represent any observation that is 1–2 times the 75th percentile and the 25th percentile, respectively. The upper and lower detached "o" values represent values that are greater than 2 times the 75th and 25th percentiles, respectively (Helsel and Hirsch, 2002).

Data Limitations

Throughout this 7-year study, there were several factors that could limit data interpretability. Here, we describe the sources of study uncertainty so that we can reliably interpret the data provided.

One factor that could affect interpretation of the data was the change of equipment used to measure turbidity in the pre- (WY2009–WY2011) and postrestoration (WY2012–WY2015) periods (table 3). The maximum value that could be accurately reported on the turbidity probes decreased between these periods at the east and west sites. However, at the downstream site, even though the sonde was changed from a YSI 6026 to a YSI 6136, the maximum detectable value stayed the same. The change of equipment at the east and west sites was unlikely to affect the predicted SSC at the downstream site, although it could have affected the predicted SSC values at both the east and west sites.

In the prerestoration period, suspended-sediment concentrations were measured at the USGS Pennsylvania Water Science Center laboratory, and in the postrestoration period they were measured at the USGS Kentucky sediment laboratory. Although the laboratories and methods used to quantify suspended sediment were different, both laboratories used one of the approved methods (ASTM D3977-97) for suspended-sediment analysis (Federal Interagency Sedimentation Project, 2007).

In the prerestoration period, discrete sediment and nutrient samples were collected using an automatic sampler. This sampler uses a tube to collect a single, discrete sample from the water column at a defined place in the channel. In the postrestoration period, discrete sediment and nutrient samples were collected using a USGS equal-width increment multiple-vertical method, which is a depth- and width-integrated sample. Many studies have shown that discrete samples tend to bias sediment values low when compared to integrated samples. If this bias was present in this study, we would expect that a comparison of pre- and postrestoration suspended-sediment concentrations at the downstream site would show lower concentrations in the prerestoration period and higher concentrations post restoration; however, this was the opposite of the treatment effect observed. Therefore, we do not consider this to be an important source of bias in this study.

Additionally, there was a change in sampling protocol concurrent with changes in sampling method. In the prerestoration period, storm samples were collected by automated samplers that could be triggered 24 hours a day to catch sampling events. However, in the postrestoration period when the switch to manual sampling was made, there was a bias toward sampling during daylight hours and the maximum number of storm sampling events was set at eight samples per year. Both of these factors could exclude the collection of samples from some storm events each year. It was noted in our data analysis that discrete suspended-sediment concentrations in the postrestoration period were lower than in the prerestoration period. However, both pre- and postrestoration sampling was conducted over a representative range of flows and the surrogate regression used to predict continuous suspended-sediment concentration from continuous turbidity was analyzed on all available turbidity measurements/predictions (24 hours a day, 7 days a week). Therefore, the pre- to postrestoration difference in sampling protocol should not influence the results of the study.

The nutrient laboratories used to analyze water samples in the pre- and postrestoration periods were also different. The average method reporting limit (MRL) for the USGS NWQL nutrient method was 0.04 mg/L (used in the prerestoration period), whereas the average reporting limit for the PaDEP BOL nutrient method was 0.008 mg/L (used in the postrestoration period), a difference of 168 percent. Although there is a large percent difference between the MRLs, the values observed in this study for all nutrients, except nitrite and ammonium, were more than 10 times the reporting limits discussed here. This indicates that the difference in laboratory reporting methods caused little, if any, bias in our analysis of nutrient data between the pre- and postrestoration periods.

From WY2009 to WY2015 the west site (USGS 015765185) was located approximately 175 ft outside of the restoration area. In the spring of 2015, the west site was moved 190 ft downstream, to about 15 ft inside of the restoration area as a result of the landowner installing a new sediment management practice upstream of, and adjacent to, the original site. The sediment management upstream of the west site could have affected the pre- to postrestoration outcome at the west site at that time. We hypothesize that this move had minimal impact on streamflow and turbidity measurements, but a change in location could induce positive or negative bias into the analysis of data from the west site in the pre- and postrestoration periods.

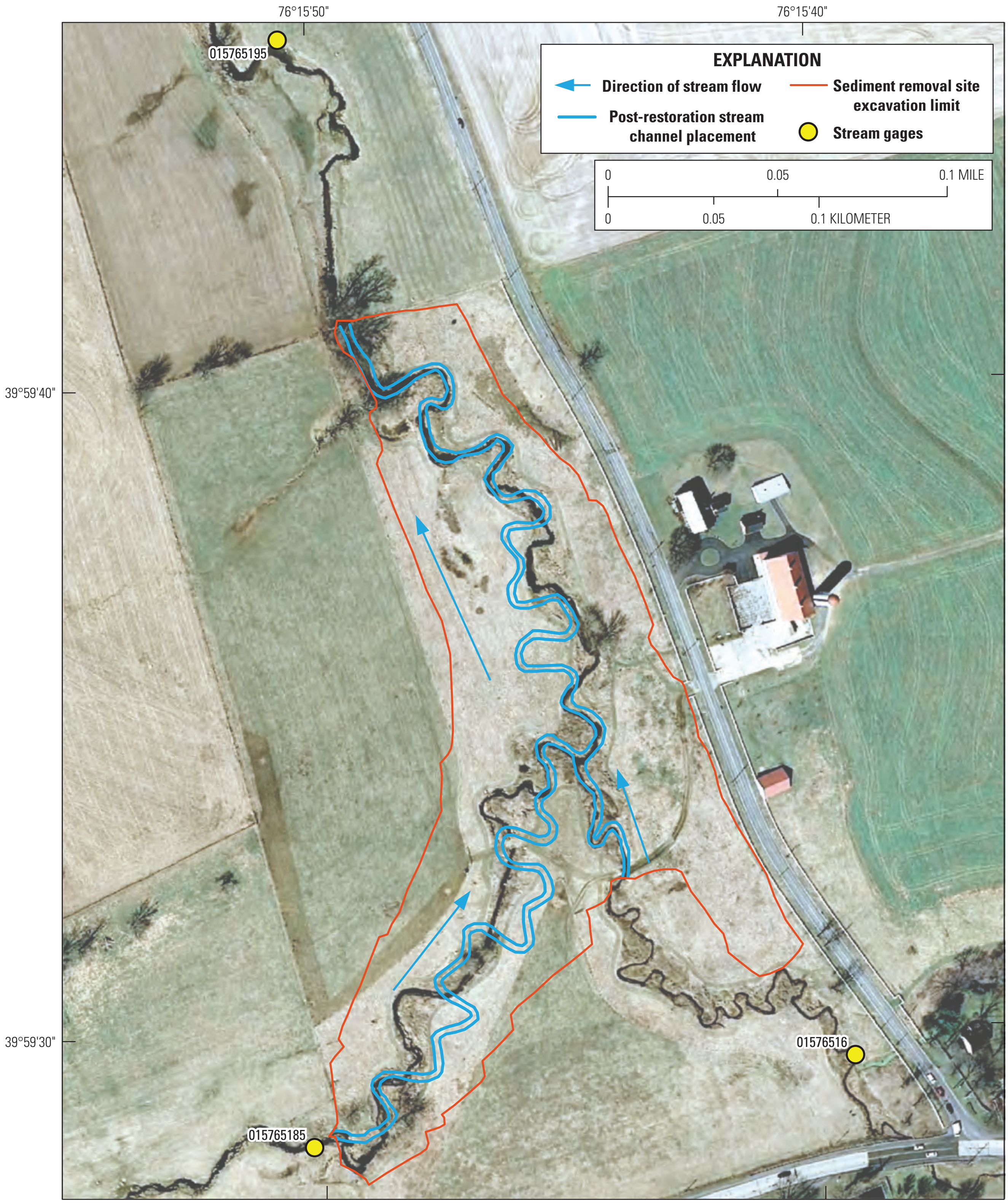
Quality Control Samples

During WY2014, there were two field-blank samples and four field-replicate samples collected for nutrients analysis. All field blanks and field replicates were collected at the downstream site. The two blank samples were negative for all nutrients (filtered and unfiltered nitrate plus nitrite, filtered and unfiltered total phosphorus, filtered and unfiltered ammonia, filtered and unfiltered total nitrogen, filtered and unfiltered orthophosphate, and total suspended solids). Although the number of blanks was limited, and no blanks were run at the NWQL, the two field blanks that were collected demonstrated that the sampling methodology used during the postrestoration period did not create any bias near the reporting level for any nutrients. These results lend confidence in any value at or near the method reporting level for samples in the postrestoration period.

The replicate data, which is only available for the PaDEP BOL from the postrestoration period, indicates that the field variability, expressed as percent difference, for the nutrients analyzed were as follows: filtered nitrate plus nitrite, 0.9 percent; unfiltered nitrate plus nitrite, 1.5 percent; filtered total phosphorus, 16.4 percent; unfiltered total phosphorus, 10 percent; filtered ammonia, 0.0 percent; unfiltered ammonia, 4.5 percent; filtered total nitrogen, 0.8 percent; unfiltered total nitrogen, 3.2 percent; filtered orthophosphate, 3.3 percent; and unfiltered orthophosphate, 4.0 percent. All nutrients had low field variability (less than 5 percent difference between field replicates) except filtered and unfiltered total phosphorus, which had a 10–16 percent different between field replicates. This higher variability is likely because total phosphorus has a higher affinity for the sediment in the water column; thus, any variation in sample splitting from the churn would be seen most prominently in total phosphorus data. We did observe a decrease in median phosphorus concentration from 0.19 mg/L in the prerestoration period to 0.04 mg/L in the postrestoration period. This decrease represents a difference of 160 percent, nearly 10 times greater than the variability owing to field sampling (16.4 percent), indicating that observed variability as a result of sampling was not a source of bias in our interpretations of the current study's data.

Effects of Legacy Sediment Removal

Changes in nutrient concentration and sediment transport occurred as a result of the restoration. From September 2011 through mid-December 2011, approximately 21,704 cubic yards (22,955 tons) of streambank and floodplain sediment was removed from the restoration area in the Big Spring Run watershed (fig. 2; Merritts and others, 2013). The stored sediment was moved offsite in 2012. In some regions of the restoration area, stream sinuosity was increased, and off-stream features were designed to restore 4.7 acres of a stream and wetlands complex that could affect the timing and delivery of water and sediment downstream. Sediment removal restored a potential maximum increase in storage of approximately 13.3 acre-ft (converted from cubic yards removed; Michael Rahnis, Franklin and Marshall College, written commun., 2016) or 4.3 million gallons (Mgal) of water. Total nitrogen and total phosphorus in the removed legacy sediment had concentrations of 2.9 and 1.5 pounds per ton, respectively (Merritts and others, 2013); that equates to about 63,670 pounds of total nitrogen and 26,346 pounds of total phosphorous permanently removed from the restoration area.



2008 imagery base from PAMAP Program, 2009
1:100,000 Albers Equal-Area Conic projection: Standard Parallels 40° N and 42° N,
Central Meridian 78° W, Latitude of Origin 39°

Figure 2. Aerial photograph in the prerestoration period at Big Spring Run, Lancaster County, Pennsylvania. Parallel blue lines represent the final stream channel placement (postrestoration) and red boundary line represents sediment removal site excavation limit (Michael Rahnis, Franklin and Marshall College, written commun., November 16, 2008).

Nutrients

Nutrient samples were collected over a wide range of streamflows (fig. 3), providing good representation of nutrient concentrations during baseflow and storms especially at the downstream site. Nitrogen and phosphorus can be present in many forms (particulate, dissolved, organic, inorganic) that are acted upon by various physical and chemical processes. Phosphorus more readily adsorbs to sediment particles than nitrogen, allowing for removal of phosphorous from the water column as sediment settles. Important processes for nitrogen reduction are plant uptake and denitrification, which involves mediation by microbes under anaerobic conditions to convert oxidized forms like nitrate to nitrogen gas.

Excavation of legacy sediment from the restoration area allowed water that was channelized before restoration to access the floodplain during storms, which decreased streamflow velocities and promoted deposition in the floodplain (Merritts and others, 2013). As a result, suspended-sediment concentrations at the downstream site decreased significantly after upstream banks were pared back and legacy sediments were removed (p-value < 0.0001; fig. 4*A*). Phosphorus adsorbed onto those sediment particles was also removed from the water column. Total phosphorus concentrations at the downstream site decreased from a median concentration of 0.19 mg/L to 0.04 mg/L (p-value = 0.0036; fig. 4*B*) during the pre- to postrestoration period even though streamflow hydrographs during the two periods were similar. Orthophosphate, also called dissolved inorganic phosphate, is a dissolved form of phosphorus available to aquatic plants and is more likely to be removed by plant uptake rather than sediment deposition. Orthophosphate at the downstream site was not significantly different in the postrestoration period (p-value = 0.4584; fig. 4*C*).

The decrease in suspended-sediment concentration demonstrated in figure 4*A* did not result in a corresponding decrease in nitrogen concentrations (fig. 4*D*). Nitrate is the dominant form of nitrogen in Big Spring Run (92.3 percent of total nitrogen), but it does not readily adsorb onto suspended-sediment particles like phosphorus does. The primary means of nitrogen removal are uptake by plants or denitrification and, over the timeframe of this study, neither of these processes seemed to be effective at producing a significant change in nitrate concentration (p-value = 0.1151; fig. 4*D*). As a result of legacy sediment removal, the plant community in the restoration area shifted from dominance by nonnative species preferring upland settings to native wetland species (Merritts and others, 2013). These species are more suited for nutrient uptake, thus nitrate concentrations in Big Spring Run may decline over time as the plant community matures.

Streamflow

Streamflow during storms transports a large proportion of the sediment load; in Big Spring Run a single storm event can transport more than 25 percent of the annual sediment load. For the purposes of this report, a storm is defined as streamflow with an exceedance probability of 5 percent or less and a duration of at least 15 minutes. All storms were defined on the basis of streamflow at the downstream site in the prerestoration data. By using these criteria, storms that move relatively small amounts of sediment, but cumulatively shape channel morphology over time (Rosgen, 1996) are included along with large storms that occur infrequently but can be responsible for transporting large percentages (greater than 25 percent) of the annual sediment load.

For the downstream site, any streamflow greater than 7.84 ft^3/s (5-percent exceedance probability) lasting at least 15 minutes was considered a storm. A total of 320 storms occurred over the study period, resulting in streamflows that ranged in magnitude from 7.95 ft^3/s to 417 ft^3/s, with durations from 15 minutes to more than 43 hours. Although streamflow magnitudes during storms varied greatly over the study period, the median streamflow was 17.5 ft^3/s and the median duration was about 3 hours and 24 minutes (table 5).

The effect of the restoration can be observed in photographs (fig. 5). In the restoration area, streambanks were pared back by excavation, allowing water that would otherwise be confined to the channel (fig. 5*A*) access to the floodplain. As water exits the channel and spreads out onto the floodplain (fig. 5*B–D*), velocity decreases along with the ability to sheer sediment particles and transport them downstream. Within a few hours of the peak streamflow, water recedes (fig. 5*E*,*F*) and eventually returns to the baseflow condition depicted in figure 5*A*. Although the floodplain of the restoration area temporarily stores stormwater, measurable attenuation of streamflow peaks was not observed downstream. Exceedance probabilities in the pre- and postrestoration periods at the downstream site were nearly identical (fig. 6), indicating any streamflow attenuation resulting from legacy sediment removal was not apparent in the streamflow record at the downstream site. Selected streamflow hydrographs upstream of restoration were also compared to hydrographs at the downstream site. Hydrograph shape was identical indicating no detectable attenuation of storm runoff, however, the timing of hydrograph rise and peak differed because of the upstream to downstream positions of the sites on the landscape. Attenuation of streamflow peaks may not have been observed because the area of restoration was small relative to the area draining to the downstream site; however, water velocities were likely lower in the restoration area, which provided for sediment removal from the water column.

Turbidity

Increases and decreases in turbidity are strongly related to changes in streamflow in most non-point source-dominated watersheds, such as Big Spring Run. The turbidity-streamflow relation is affected by streamflow velocity; high streamflow velocities are needed to entrain, suspend, and transport

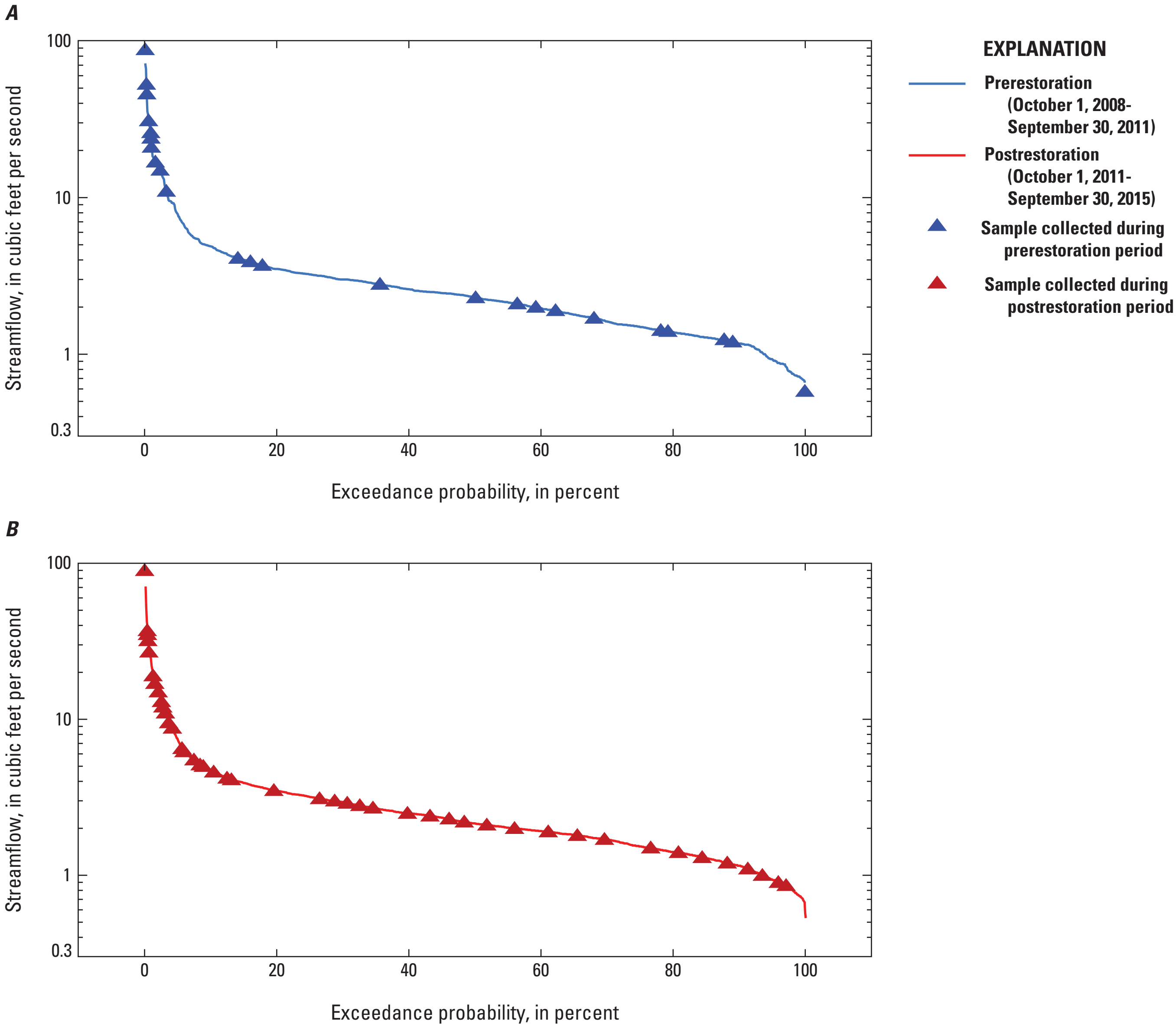


Figure 3. Sample collection and streamflow conditions for downstream site 015765195 during the *A*, prerestoration period (water years 2009–11) and *B,* postrestoration period (water years 2012–15).

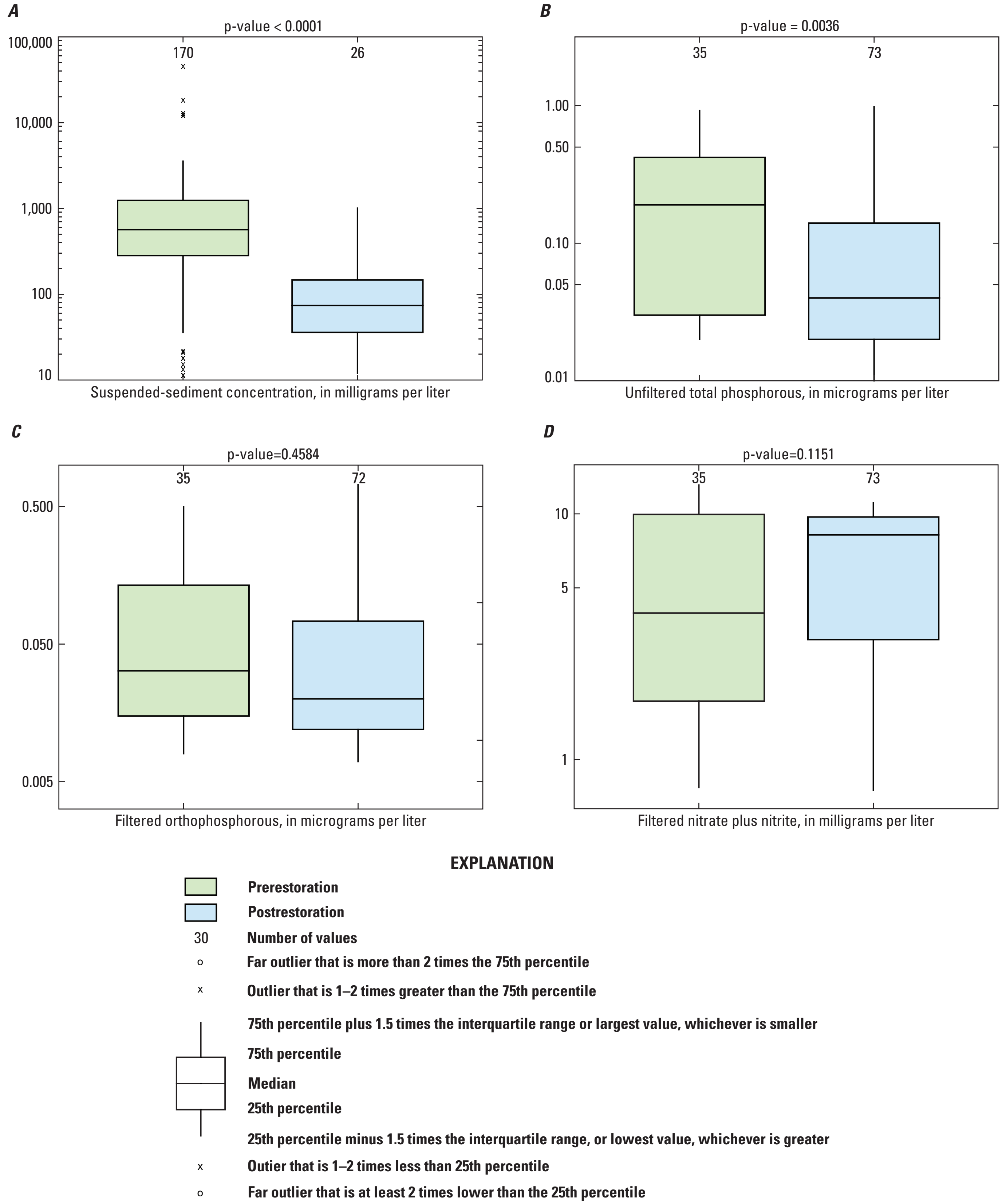


Figure 4. Comparison of pre- and postrestoration nutrient and suspended-sediment concentrations in Big Spring Run, Lancaster County, Pennsylvania. Data for unfiltered total phosphorous and for filtered orthophosphorous were censored at 0.02 and 0.008 micrograms per liter, respectively.

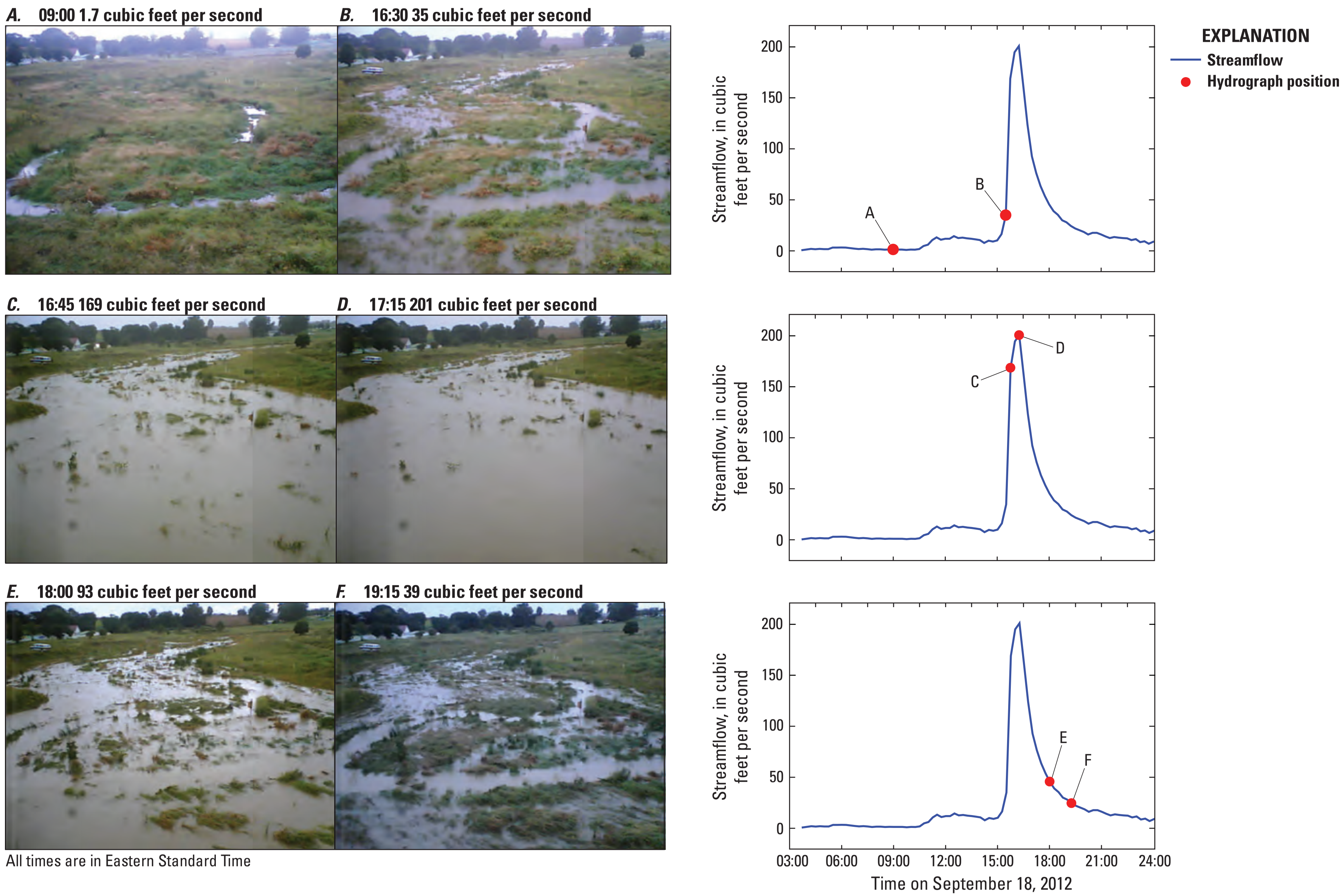


Figure 5. Time sequence for a storm at Big Spring Run, Lancaster County, Pennsylvania, September 18, 2012. Photographs are from a webcam operated by Telemonitor, Inc., approximately 150 yards upstream from downstream site 015765195, looking upstream and to the south-southwest. Hydrograph position at the time of the picture is presented on the right. All times are Eastern Standard Time.

Table 5. Streamflow statistics for storms at Big Spring Run near Mylin Corners, Pennsylvania, water years 2009–15.

[For Big Spring Run near Mylin Corners, Pennsylvania (015765195), a storm is defined as streamflow exceeding 7.84 cubic feet per second with a duration of at least 15 minutes. Streamflow of 7.84 cubic feet per second has an exceedance probability of 5 percent. ft^3/s, cubic feet per second; hrs:min:sec, hours minutes seconds]

Water year[1]/ Period of record	Number of storms	Median peak streamflow (ft^3/s)	Median duration (hrs:min:sec)	Date and time of storm with largest streamflow (hrs:min:sec)	Largest streamflow (ft^3/s)	Date and time of storm with longest duration (hrs:min:sec)	Longest duration (hrs:min:sec)
2009	53	13.5	2:47:04	8/28/09 22:30	223	12/11/08 23:00	20:34:22
2010	41	18.5	3:49:27	6/3/10 20:30	289	10/17/09 8:15	38:46:58
2011	53	18.8	3:01:41	9/7/11 20:00	417	9/7/11 20:00	43:17:30
2012	62	11.3	1:49:19	9/18/12 16:15	201	12/7/11 22:30	18:02:10
2013	32	24.8	3:52:41	1/31/13 0:30	222	10/29/12 18:00	38:22:11
2014	40	20.4	5:20:14	10/11/13 8:37	261	4/30/14 13:30	38:25:11
2015	39	18.7	3:24:01	10/15/14 13:35	221	3/10/15 22:15	17:32:31
Period of record	320	17.5	3:23:53	9/7/11 20:00	417	9/7/11 20:00	43:17:30

[1]Water year is defined as the 12-month period from October 1 through September 30 of the following year. The water year is designated by the calendar year in which it ends.

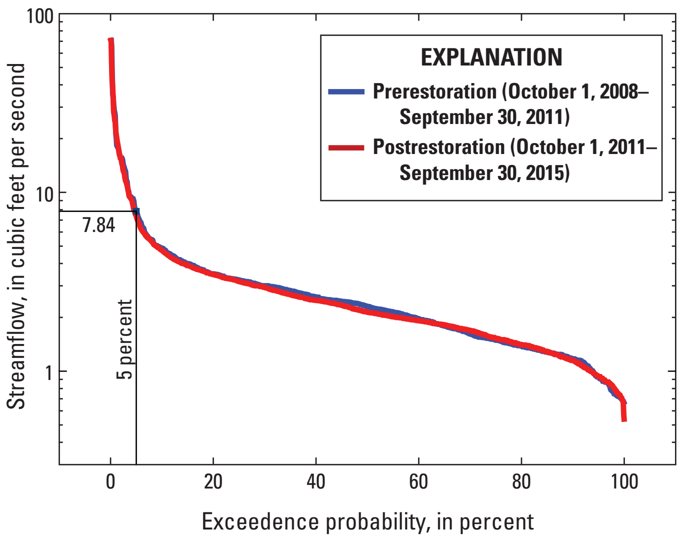
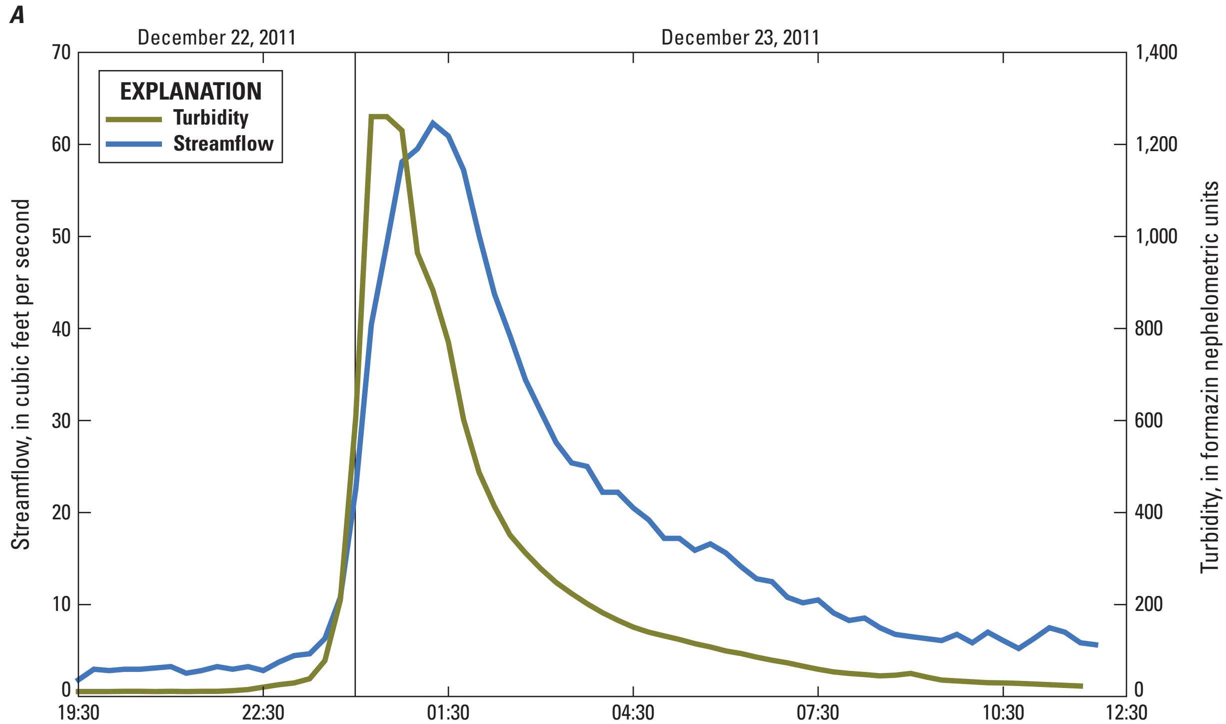


Figure 6. Exceedance probability of streamflow for site 015765195, Big Spring Run, Lancaster County, Pennsylvania. For the purposes of this report, a storm is defined as streamflow with a probability of exceedance of 5 percent or less and a duration of at least 15 minutes.

sediment in the water column. Examining graphs of turbidity and streamflow over time can provide an improved understanding of in-stream processes affecting sediment. A typical turbidity-streamflow response, in this case for a storm that occurred from December 22 to December 23, 2011, at the downstream site (USGS 015765195) is shown in figure 7*A*.

Peak turbidity may occur before or after storm peaks, depending on the sediment source and velocity of water acting on the stream bed and banks. This results in a time-shifted relation between turbidity and streamflow where equivalent instantaneous flows on the rising and falling limb of a storm hydrograph are characterized by dramatically different turbidity values (fig. 7*B*). This phenomenon is referred to as hysteresis and can influence the results of the daily suspended-sediment load derived from continuous measurements of turbidity, as shown for the same December 2011 storm at the downstream site (USGS 015765195) (fig. 7*B*). For a given streamflow of about 22 ft^3/s on the rising limb of the hydrograph, the turbidity is approximately 600 FNU, whereas on the falling limb of the hydrograph for the same streamflow of 22 ft^3/s, the turbidity is approximately 200 FNU.

The hysteresis shape and duration are a function of streamflow velocity (travel time) and the sediment sources in the basin. Analysis of the streamflow-turbidity shape can provide information on sediment sources in small watersheds (Oxley, 1974; Klein, 1984; Landers and Sturm, 2013). Sediment originating from the stream channel typically causes higher turbidity values as streamflow increases, and sediment originating from more distant basin sources may cause higher turbidity values as streamflow decreases because of the timing of the tributary inflows (Asselman, 1999). The hydrographs for storms producing flows greater than 7.84 ft^3/s



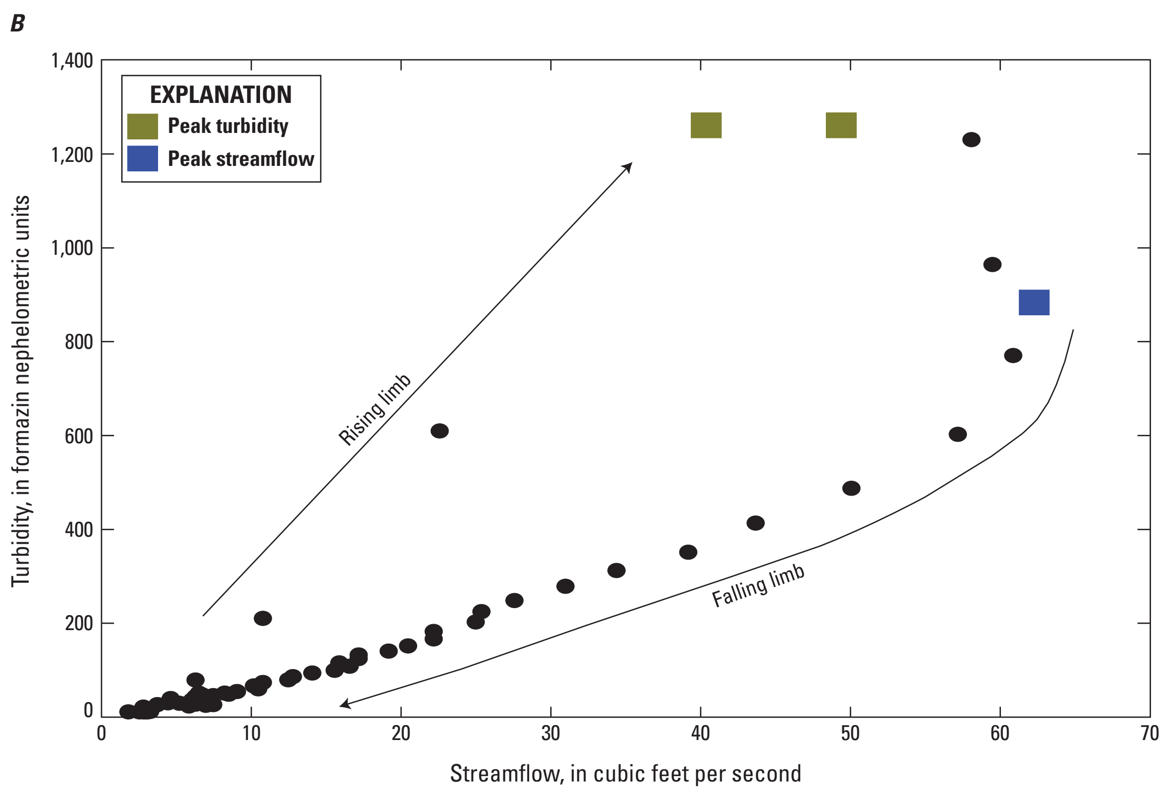


Figure 7. Turbidity in relation to streamflow at site 015765195, Big Spring Run, Lancaster County, Pennsylvania, during a storm event from December 22 to 23, 2011.

(5-percent exceedance probability) at the downstream site (USGS 015765195) suggest that suspended sediment is predominately from the stream channel in the Big Spring Run watershed. Merritts and others (2013) have estimated that streambanks in the Big Spring Run study area supply 30–65 percent of the overall load.

Decreases in average turbidity observed in the postrestoration period likely are due to surface water being reconnected to the floodplain, resulting in increased storage of sediment in the restoration area and a reduction in sediments originating from within the restoration area.

Continuous measurements of turbidity were used to provide a continuous time series of suspended-sediment concentrations and loads in the pre- and postrestoration periods in the Big Spring Run watershed. Continuous turbidity measurements have been shown to provide reliable estimates of suspended-sediment concentration with a quantifiable uncertainty (Gray and others, 2000). A simple linear regression model relating turbidity to suspended-sediment concentration is often sufficient for reliable computations of suspended-sediment concentration (Rasmussen and others, 2009). A linear relation between turbidity and sediment concentration can be difficult because of site-specific interferences such as water clarity, presence of organics and biota, and sediment particle size. In the current study, regression models were used to predict missing values to create a more complete record of continuous suspended-sediment concentrations over the 7-year study period for each of the three sites (Langland, 2019b).

Suspended Sediment

The model input data and regressions used to predict the continuous suspended-sediment record at each site in the pre- and postrestoration periods are presented in figure 8; additional regression diagnostics are presented in Langland (2019a).

Streambanks erode primarily by (1) freeze-thaw, where the soils expand upon freezing and loosen upon thawing; (2) fluvial erosion, where streambank and bed sediments are entrained and eroded by water; and (3) mass wasting, where part of the streambank slumps into the stream (fig. 9). Sediment concentrations at the three sites in Big Spring Run were greatly affected by mass wasting especially during the prerestoration period (2009–11). When streambanks were excavated and pared back during restoration, mass wasting decreased and the restoration area changed from a sediment source to a sediment sink, an area where sediment settled from the water column and was stored.

At the downstream site, median suspended-sediment concentration decreased from 556 mg/L before restoration to 74 mg/L after restoration (p-value < 0.0001; fig. 10). This change in sediment concentration is consistent with the large reduction in sediment loading that can be attributed to the restoration. The mean annual sediment load conveyed to the restoration area from the two upstream sites in the postrestoration period was 839 tons. More than 70 percent (597 tons) of this sediment load was removed as the stream traversed through the wetland environment and suspended sediment settled out of the water column; therefore, the mean annual suspended-sediment load downstream of the restoration was only 242 tons (table 6).

The restoration BMP was compared with other BMPs intended to reduce sediment in streams (fig. 10). Galeone and others (2006) compared suspended-sediment concentrations measured at two sites in a 1.42-mi^2 watershed, adjacent to Big Spring Run, where streambank fencing was installed along a 2-mi reach approximately 5–12 ft landward of the streambank. The intent of the fencing was to prohibit livestock from accessing the stream and to promote streambank stability. Samples for suspended-sediment concentration were collected before and after the fencing was installed. Although statistically significant reductions in suspended-sediment concentration were realized from the fencing, they were an order of magnitude less than the reductions observed in the current study. The median suspended-sediment concentration was reduced by 482 mg/L in the current study compared to only 30–46 mg/L as a result of streambank fencing (fig. 10).

Summary statistics for suspended-sediment loads for the three Big Spring Run sites on a daily, monthly, and annual basis are presented in table 6. The data used to compute the summary statistics are available in Langland (2019b). It should be noted the turbidity record that was missing (because data to fill the missing record were also missing from the sites used for predictions), could impact before-and-after implementation comparisons, especially at the west and east sites. However, the downstream record was much more complete and conclusions at the downstream site are well supported. Daily suspended-sediment loads at the downstream site varied greatly during the study (fig. 11), ranging from <0.005 ton on multiple days to 201 tons on January 25, 2010 (table 6). The largest proportion of annual sediment load was supplied during storms that occurred on September 7, 2011 (29.5 percent), January 31, 2013 (35.1 percent), and October 15, 2014 (38.1 percent) (table 6). Median daily suspended-sediment load after restoration was about one-tenth of the load prior to restoration (0.892 ton compared to only 0.087 ton in the postrestoration period; fig. 11). These decreases were statistically significant (p-value <0.0001) for daily and monthly time steps (table 6).

Implementing the restoration BMP greatly reduced the sediment load moving from the upstream sampling sites to the downstream sampling site. Prerestoration sediment loads increased by a mean of 106 percent between upstream sites and the downstream site, indicating sediment was added from the upstream sites and the unrestored reach. As part of the restoration process, sediment supply was greatly reduced or eliminated by mechanically removing streambanks to restore a natural stream and wetland complex. Postrestoration sediment loads decreased by a mean of 69.3 percent, indicating that sediment from the upstream area was trapped in the restoration area. Potential explanations for the observed reductions

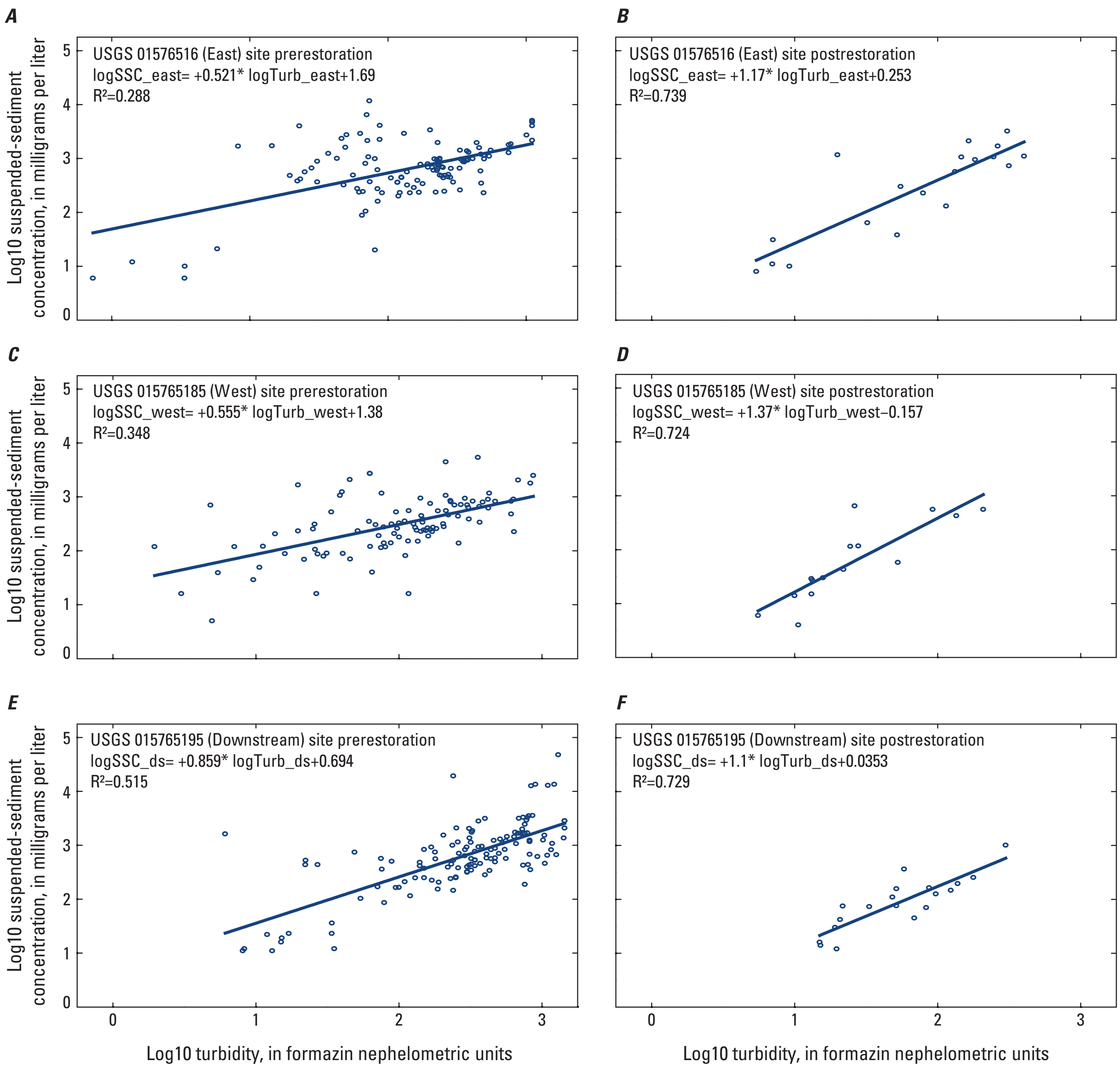


Figure 8. Sediment concentration in relation to turbidity at three sites in Big Spring Run, Lancaster County, Pennsylvania. All date ranges are in water years. *A*, Site 01576516 (east), 2009–11; *B*, site 01576516 (east), 2012–15; *C*, site 015765185 (west), 2009–11; *D*, site 015765185 (west), 2012–15; *E*, site 015765195 (downstream), 2009–11; and *F*, site 015765195 (downstream), 2012–15

Figure 9. Photograph showing example of mass wasting in the streambank below the downstream site in Big Spring Run near Mylin Corners, Pennsylvania. Photograph taken by U.S. Geological Survey on October 16, 2014.

are (1) removal of streambanks and (2) restoration of a natural stream and wetland complex that trapped sediment supplied by upstream sources.

The continuous suspended-sediment regression method of computing annual loads was compared to a commonly used load-calculation method. The method, Weighted Regressions on Time, Discharge, and Season (WRTDS; Hirsch and others, 2010) is currently used to compute annual loads in the Chesapeake Bay watershed. Loads from WRTDS were not available in the prerestoration period of the study but were available for comparison in the postrestoration period of the study (WY2012–WY2015). The loads computed by the continuous suspended-sediment regression method and WRTDS are similar (fig. 12), with little variation observed between the predicted loads of each method. Precise comparisons of statistical significance between the two methods were not quantified because there were no reliable measures of error associated with either method and there were only four comparisons possible (WY2012–WY2015). Longer-term comparisons (greater than 10 years) integrating measurement error should be made for more effective statistical comparison of these methods of load computation. The continuous suspended-sediment regression method used in this study effectively quantified the prerestoration to postrestoration suspended-sediment load reduction observed from implementation of the restoration BMP at the downstream site.

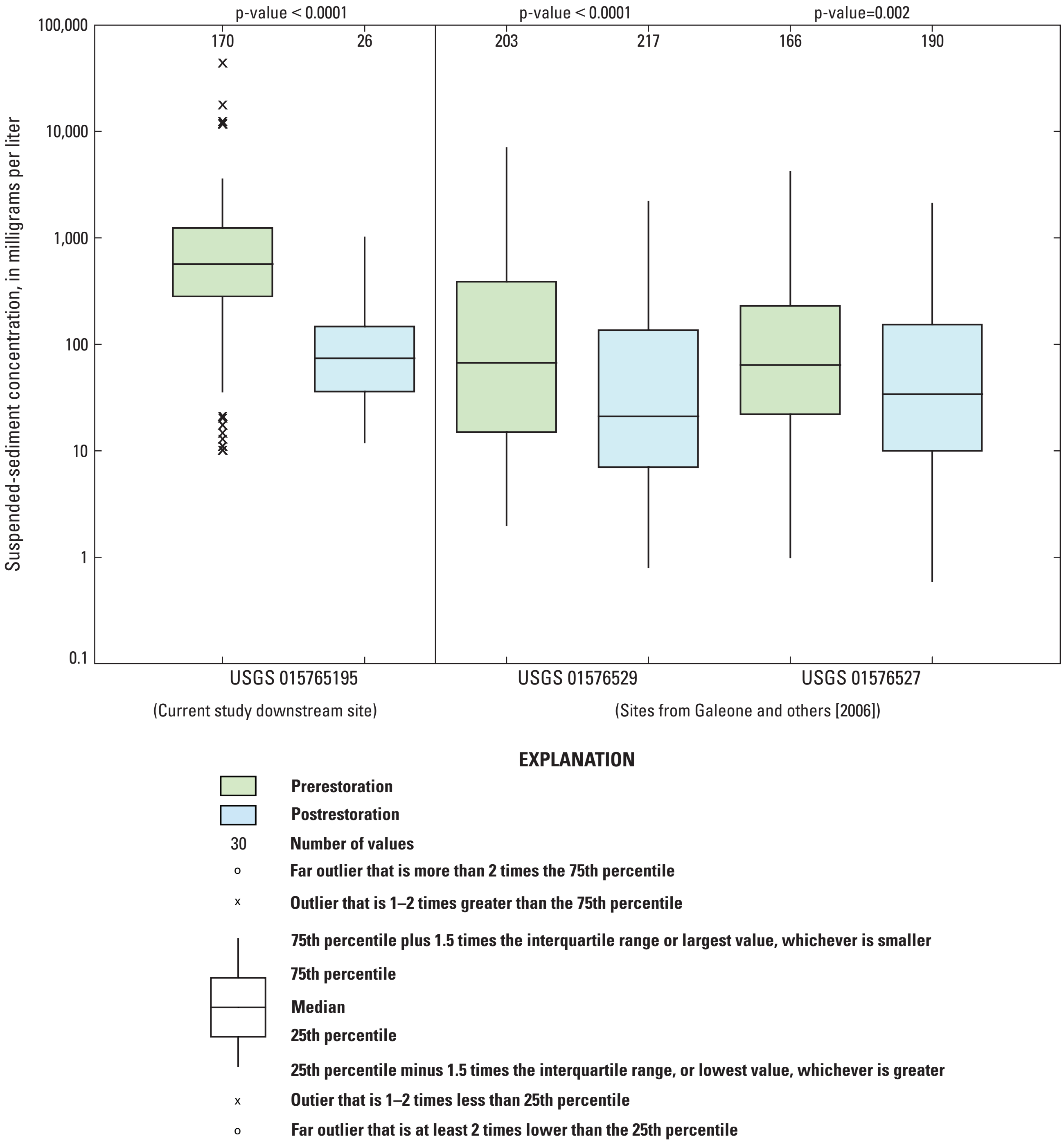


Figure 10. Comparison of suspended-sediment concentrations at site 015765195 (downstream), Big Spring Run, Lancaster County, Pennsylvania, to two sites in an adjacent watershed from Galeone and others (2006).

Table 6. Summary of daily, monthly, and annual suspended-sediment loads at three sites in Big Spring Run, Lancaster County, Pennsylvania, water years 2009–15.

[Max, maximum; Min, minimum; USGS, U.S. Geological Survey]

Water year[1]	Daily suspended-sediment load (tons)				Monthly suspended-sediment load (tons)				Annual suspended sediment load (tons)	Ratio of max daily suspended-sediment load to annual suspended-sediment load (percent)	Ratio of max monthly suspended- sediment load to annual suspended- sediment load (percent)
	Max	Median	Mean	Min	Max	Median	Mean	Min			
USGS site number 01576516 (East)											
2009	25.5	0.58	1.25	0.005	67	26.4	29.6	2.73	325	7.85	20.7
2010	37.1	0.39	1.00	0.003	76	23.3	29.2	3.14	347	10.69	21.9
2011	36.0	0.60	1.64	0.003	82.9	33.3	37.4	1.05	377	9.55	22.0
2012	56.0	0.14	1.10	0.002	108	14.8	31.5	4.9	378	14.81	28.5
2013	44.1	0.041	0.58	0.0004	56	9.7	14.7	0.337	147	30.0	37.9
2014	46.5	0.060	0.61	0.0002	68	8.0	18.2	1.2	219	21.2	31.1
2015	43.6	0.028	0.38	0.001	62	2.0	11.0	0.28	133	32.78	46.4
Prerestoration period	37.1	0.53	1.25	0.003	82.9	29.0	31.8	1.05	350 (mean)	9.4 (mean)	21.5 (mean)
Postrestoration period	56.0	0.061	0.671	0.0002	108	8.4	19.1	0.278	219 (mean)	24.7 (mean)	36 (mean)
USGS site number 015765185 (West)											
2009	31	0.19	1.45	0.00237	64	26	24	3.15	264	11.7	24.2
2010	35	0.33	1.86	0.0011	78	33	33	0.40	365	9.6	21.3
2011	42	0.26	2.62	0.0017	82	18	26	2.29	180	23.4	45.6
2012	55	0.142	1.57	0.001	103	16	28	0.014	331	16.6	31.3
2013	250	0.046	8.4	0.000014	423	25	97	0.008	967	25.9	43.8
2014	125	0.040	3.53	0.000004	159	60	65	0.304	774	16.1	20.5
2015	150	0.024	2.77	0.000004	151	2	34	0.79	413	36.3	36.6
Prerestoration period	42	0.26	2.0	0.001	82	26	28	0.40	270 (mean)	14.9 (mean)	30.3 (mean)
Postrestoration period	250.0	0.043	4.07	0.000004	423	20.5	55.8	0.008	620 (mean)	23.7 (mean)	33 (mean)
USGS site number 015765195 (Downstream)											
2009	103	0.67	3.68	0.018	241	78	95	10.9	1,140	9.04	21.1
2010	201	1.50	7.5	0.005	376	280	201	4.24	2,210	9.10	17.0
2011	190	0.78	4.17	0.009	359	32.6	80	12.4	643	29.5	55.9
2012	43.3	0.138	1.09	0.002	95	13.8	23.3	0.10	279	15.5	34.1

Table 6. Summary of daily, monthly, and annual suspended-sediment loads at three sites in Big Spring Run, Lancaster County, Pennsylvania, water years 2009–15.—Continued

[Max, maximum; Min, minimum; USGS, U.S. Geological Survey]

Water year[1]	Daily suspended-sediment load (tons)				Monthly suspended-sediment load (tons)				Annual suspended sediment load (tons)	Ratio of max daily suspended-sediment load to annual suspended-sediment load (percent)	Ratio of max monthly suspended-sediment load to annual suspended-sediment load (percent)
	Max	Median	Mean	Min	Max	Median	Mean	Min			
2013	89	0.042	1.10	0.00002	130	3.30	21.1	0.36	253	35.1	51.6
2014	42.7	0.111	0.74	0.003	48.9	17.1	19.3	1.29	232	18.4	21.1
2015	78	0.058	0.67	0.000005	80	3.86	17.0	0.50	204	38.1	39.4
Prerestoration period	201	0.892	5.26	0.005	376	48.8	129	4.24	1,331 (mean)	15.9 (mean)	31.3 (mean)
Postrestoration period	89	0.087	0.88	0.000005	130	7.0	20.2	0.096	242 (mean)	26.8 (mean)	36.5 (mean)

[1]Water year is defined as the 12-month period from October 1 through September 30 of the following year. The water year is designated by the calendar year in which it ends.

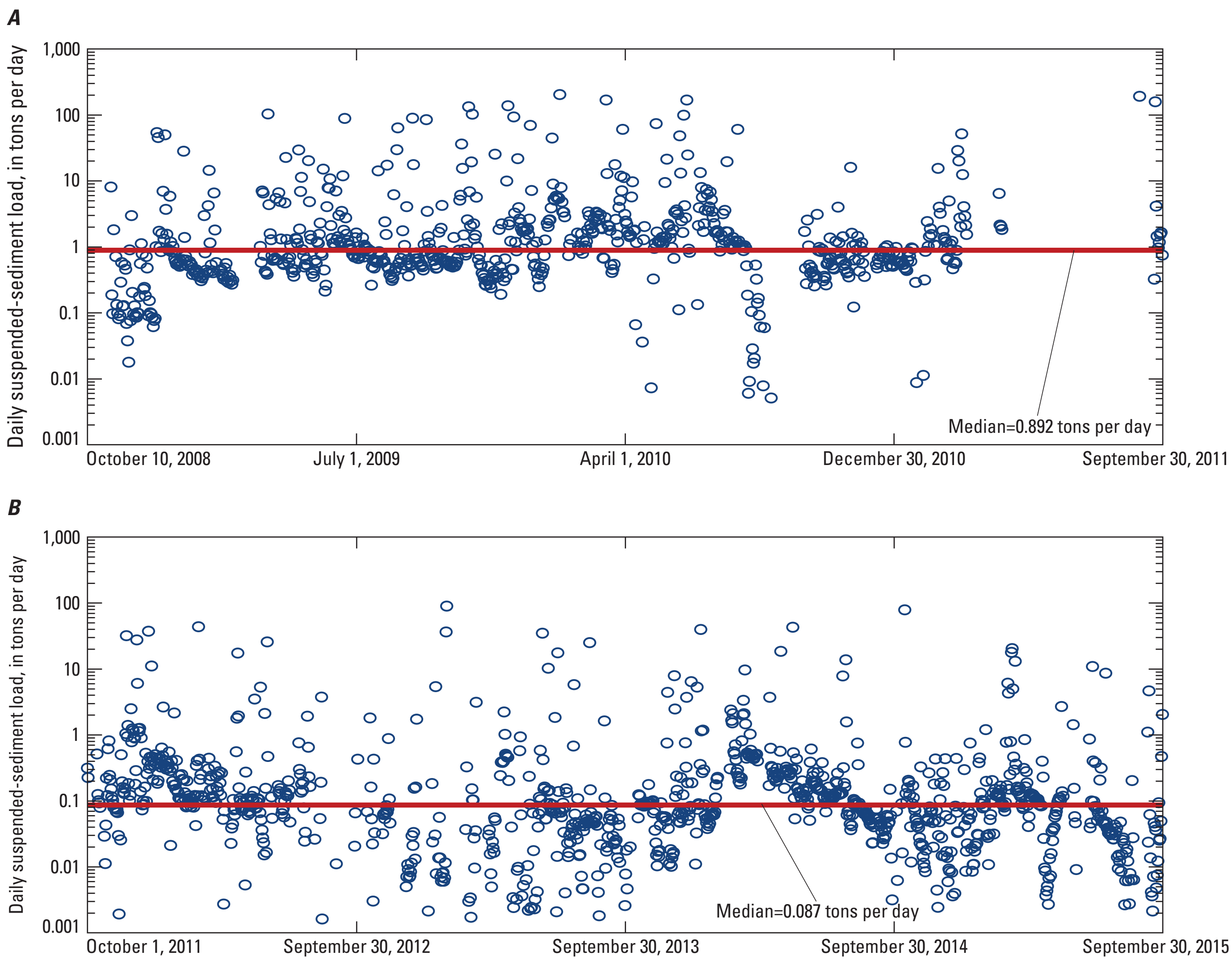


Figure 11. Daily suspended-sediment loads at site 015765195 (downstream), Big Spring Run, Lancaster County, Pennsylvania. *A*, Water years 2009–11 (prerestoration period), and *B*, water years 2012–15 (postrestoration period).

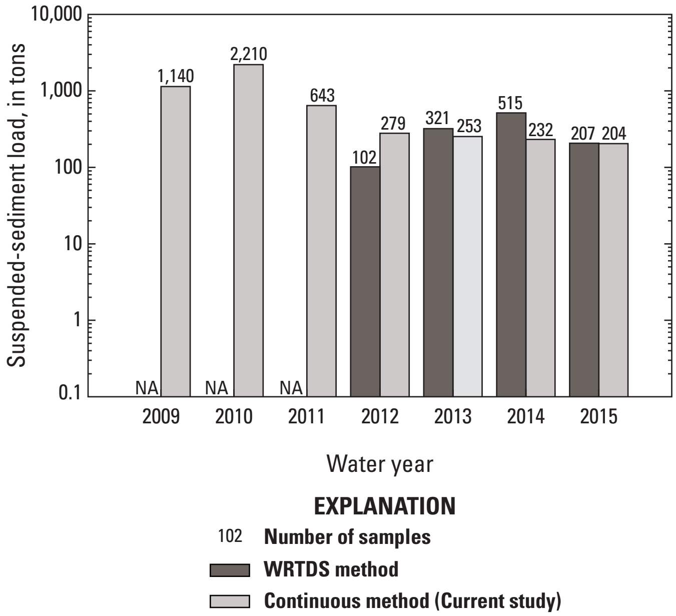


Figure 12. A comparison of suspended-sediment loads in the postrestoration period (water years 2012–15) using the Weighted Regressions on Time, Discharge, and Season (WRTDS) method and the continuous method. NA, not applicable.

Summary

This report presents the results of a study of a restoration area within the Big Spring Run watershed, with a 1.68-mi^2 drainage area near the town of Willow Street, approximately 4 miles south and southeast of the city of Lancaster in Lancaster County, Pennsylvania. The study evaluated the effects of a restoration best management practice (BMP) that removes legacy sediment to restore natural aquatic resources within Big Spring Run. There were three USGS streamgages installed—two upstream of the restoration area (referred to as the east and west sites for USGS 01576516 and USGS 015765185, respectively) and one downstream of the restoration area (referred to as the downstream site for USGS 015765195).

Samples were collected over a wide range of streamflows at the downstream site, providing good representation of nutrient and sediment concentrations during baseflow and storms in the pre- and postrestoration periods. As a result of implementing the restoration BMP, suspended-sediment concentrations in surface water at the downstream site decreased significantly; phosphorus that had adsorbed onto sediment particles was also removed from the water column (0.19 mg/L prerestoration period compared to 0.04 mg/L postrestoration period). There was no concurrent reduction in orthophosphate and nitrate, which are typically soluble in water and not adsorbed to sediment particles. There was also no concurrent decrease in total nitrogen in the postrestoration period when compared to the prerestoration period because 92.3 percent of the total nitrogen in the study area was present as soluble nitrate-nitrogen. Owing to nitrate's solubility, it is unlikely to be affected by management practices that primarily affect groundwater and not the full range of surface-water samples analyzed in this study.

All storms, at all sites, during the study period were defined on the basis of streamflow at the downstream site in the prerestoration data. A storm in Big Spring Run was defined as an event with a probability exceedance of 5 percent or less and a duration of at least 15 minutes, which corresponded to a streamflow value of 7.84 ft^3/s at the downstream site (USGS 015765195). Streamflow exceedance probabilities in pre- and postrestoration periods at the downstream site were nearly identical, indicating that streamflow attenuation resulting from the restoration was not apparent in the streamflow record at the downstream site.

During the study period, increases and decreases in turbidity were strongly related to changes in streamflow, as is true in most non-point source-dominated watersheds. Peak turbidity in Big Spring Run typically occurred before streamflow peaks. The hysteresis observed for storms at the downstream site (USGS 015765195) indicate that sediment in Big Spring Run is predominately from the stream channel. This finding supports previously published results that indicate streambanks are a major source of sediment in Big Spring Run.

At the downstream site, median suspended-sediment concentration decreased from 556 mg/L in the prerestoration period to 74 mg/L in the postrestoration period. During the prerestoration period, suspended-sediment concentrations at the three sites in Big Spring Run were greatly affected by mass wasting. When streambanks were excavated and pared back during restoration, mass wasting decreased and the restoration area changed from a sediment source to a sediment sink, an area where sediment settled from the water column and was stored. Mean annual sediment load conveyed to the restoration area from the east and west sites, in the postrestoration period was 839 tons. This load was reduced between the east and west sites and the downstream sites by 597 tons, as indicated by the mean annual load at the downstream site in the same period of 242 tons. Single storms were found to account for a large proportion of the load throughout the study period. The largest single-storm contributions to the annual sediment loads were supplied during storms that occurred on September 7, 2011 (29.5 percent of the annual load), January 31, 2013 (35.1 percent of the annual load), and October 15, 2014 (38.1 percent of the annual load).

Implementing the restoration BMP reduced the concentration of suspended sediment 10 times more than a streambank-fencing BMP described in a previous study in a small adjacent watershed in the Mill Creek drainage basin. In this study, median suspended-sediment concentration was reduced by 482 mg/L at the downstream site when compared to the prerestoration period. In contrast, the streambank-fencing BMP reduced median suspended-sediment concentrations by 30 and 46 mg/L (site 01576527 and site 01576529, respectively) when compared to paired watersheds that did not have fences.

Implementing the restoration BMP greatly reduced the suspended-sediment load delivered to the site downstream of the restoration area. During the prerestoration period, suspended-sediment load increased by 106 percent as the stream traversed the unrestored area. In contrast, there was a decrease of 69.3 percent as the stream traversed the restored area in the postrestoration period. This finding supports the conclusion that the BMP restored the stream reach of Big Spring Run from a sediment source, driven by non-point sources and mass streambank wasting, to a sediment trap that reconnected the stream to a naturalized wetland in the floodplain. Suspended-sediment concentration, phosphorus concentration, and mean annual suspended-sediment load were all reduced after implementation of the BMP.

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