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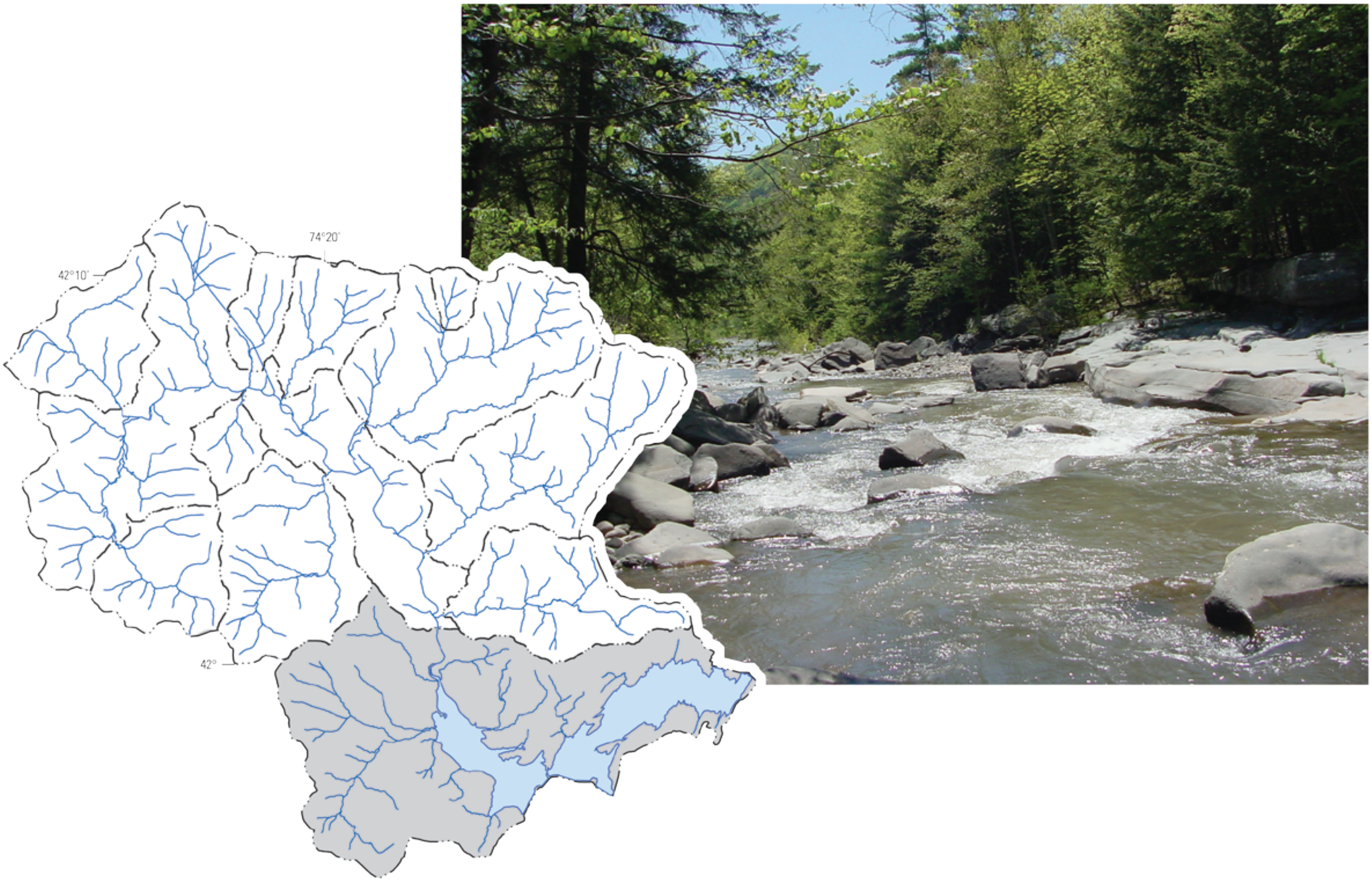
Prepared in cooperation with the
New York City Department of Environmental Protection, the
New York State Department of Environmental Conservation, and the
Cornell Cooperative Extension of Ulster County

Turbidity and Suspended Sediment in the Upper Esopus Creek Watershed, Ulster County, New York



Scientific Investigations Report 2014–5200

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

Cover. Stony Clove Creek downstream from Chichester, New York

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U.S. Department of the Interior
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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
ton, short	0.9072	ton, metric (megagram)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as
°F = (1.8 × °C) + 32.

Datum

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 distance above the vertical datum.

Supplemental Information

Suspended-sediment concentrations are given in milligrams per liter (mg/L).

Abbreviations

CCE	Cornell Cooperative Extension of Ulster County
FAD	filtration avoidance determination
FNU	formazin nephelometric units
GCLAS	USGS Graphical Constituent Loading Analysis System
LabTurb	turbidity measured in the laboratory
NTU	nephelometric turbidity unit
NTRU	nephelometric turbidity ratio unit
NYC–DEP	New York City Department of Environmental Protection
NYS–DEC	New York State Department of Environmental Conservation
NYS–DOH	New York State Department of Health
r^2	coefficient of determination
SS7	Hach Surface Scatter 7 Turbidimeter
SSC	suspended-sediment concentration
Turb15	turbidity measured by in situ probes
USGS	U.S. Geological Survey

Turbidity and Suspended Sediment in the Upper Esopus Creek Watershed, Ulster County, New York

By Michael R. McHale and Jason Siemion

Abstract

Suspended-sediment concentrations (SSCs) and turbidity were measured for 2 to 3 years at 14 monitoring sites throughout the upper Esopus Creek watershed in the Catskill Mountains of New York State. The upper Esopus Creek watershed is part of the New York City water-supply system that supplies water to more than 9 million people every day. Turbidity, caused primarily by high concentrations of inorganic suspended particles, is a potential water-quality concern because it colors the water and can reduce the effectiveness of drinking-water disinfection. The purposes of this study were to quantify concentrations of suspended sediment and turbidity levels, to estimate suspended-sediment loads within the upper Esopus Creek watershed, and to investigate the relations between SSC and turbidity. Samples were collected at four locations along the main channel of Esopus Creek and at all of the principal tributaries. Samples were collected monthly and during storms and were analyzed for SSC and turbidity in the laboratory. Turbidity was also measured every 15 minutes at six of the sampling stations with in situ turbidity probes.

The largest tributary, Stony Clove Creek, consistently produced higher SSCs and turbidity than any of the other Esopus Creek tributaries. The rest of the tributaries fell into two groups: those that produced moderate SSCs and turbidity and those that produced low SSCs and turbidity. Within those two groups the tributary that produced the highest SSCs and turbidity varied from year to year depending on the hydrologic conditions within each subwatershed. During the 3-year study, Stony Clove Creek accounted for an average of 40 percent of the annual suspended-sediment load measured at the upper Esopus Creek watershed outlet at Coldbrook, more than all of the other measured tributaries combined. The other tributaries to the upper Esopus Creek, taken together, accounted for an average of about 20 percent of the load at Coldbrook during 2010 and 2011, when most of the tributaries were sampled. Woodland Creek, the third largest tributary in the watershed, also accounted for a substantial amount of the load at Coldbrook, an average of 10 percent during the 3 years. Stony Clove Creek appeared to be a persistent source of sediment to Esopus Creek; it had the highest sediment yield (load per unit area) of all monitoring sites, including the outlet at Coldbrook.

Discharge, SSC, and turbidity were strongly related at the Coldbrook site but not at every monitoring site. In general, relations between discharge and SSC and turbidity were strongest at sites with high SSCs, with the exception of Stony Clove Creek. Stony Clove Creek had high SSCs and turbidity regardless of discharge, and although concentrations and turbidity values generally increased with increasing discharge, the relation was not strong. Five of the six sites used to investigate the relations between SSC and laboratory turbidity had a coefficient of determination (r^2) greater than 0.7. Relations were not as strong between SSC and the turbidity measured by in situ probes because the period of record was shorter and therefore the sample sizes were smaller. Data from in situ turbidity probes were strongly related to turbidity data measured in the laboratory for all but one of the monitoring sites where the relation was strongly leveraged by one sample. Although the in situ turbidity probes appeared to provide a good surrogate for SSC and could allow more accurate calculations of suspended-sediment load than discrete suspended-sediment samples alone, more data would be required to define the regression models throughout the range in discharge, SSCs, and turbidity levels that occur at each monitoring site. Nonetheless, the in situ probes provided much greater detail about the relation between discharge and turbidity than did the grab samples and storm samples measured in the laboratory.

Introduction

Suspended-sediment concentration (SSC) and turbidity are primary water-quality concerns in the New York City water-supply system (U.S. Environmental Protection Agency, 2007). This water supply is the largest nonfiltered water-supply system in the world; it consists of 19 surface-water reservoirs, 13 of which are east of the Hudson River and 6 are west of the Hudson River in the Catskill/Delaware watershed system (fig. 1). The reservoirs supply water to more than 9 million residents of New York City and surrounding communities. The Catskill/Delaware system contributes about 90 percent of the water to the total New York City water supply. In 1993, the New York City Department of Environmental Protection (NYC–DEP) and

Figure 1. The New York City water-supply system; from New York City Department of Environmental Protection (n.d.).

the U.S. Environmental Protection Agency (EPA) agreed upon a filtration avoidance determination (FAD) that allowed the NYC–DEP to take specific actions to avoid construction of a water supply filtration plant (U.S. Environmental Protection Agency, 2007). Since then, additional FADs have been implemented, the most recent in May 2014 that places emphasis on controlling turbidity in the Catskill part of the Catskill/Delaware system where elevated levels of turbidity in streams and reservoirs are most common.

Turbidity can make water appear cloudy or muddy; it is caused by the presence of suspended and dissolved matter (such as clay, silt, fine organic matter, plankton and other microscopic organisms, organic acids, and dyes) (ASTM International, 2003). Turbidity measurements are affected by the color of water, whether that color results from dissolved compounds or suspended particles (Anderson, 2005). Turbidity measurements are a quantification of the optical properties of a liquid that cause light rays to be scattered and absorbed rather than transmitted through a water sample (ASTM International, 2003). The U.S. Geological Survey (USGS) quantifies turbidity levels as nephelometric turbidity units (NTUs) for instruments that use white light (a broadband light source) or as formazin nephelometric units (FNUs) for instruments that use a monochrome light source (Anderson, 2005). Although turbidity has no direct health effects, it can interfere with drinking-water disinfection and provide a medium for microbial growth. The EPA limits turbidity to 5 NTUs in unfiltered water entering a water-supply distribution system such as that of New York City. Turbidity was identified as a source of water-quality impairment in the management plan for the New York City watershed because it is aesthetically unpleasing, may reduce the effectiveness of drinking-water disinfection, and can indicate the presence of bacteria and viruses. During large storms, high turbidity levels can also limit the use of parts of the drinking-water-supply system.

Reservoir operations control turbidity in the water-supply system by limiting the use of high-turbidity water sources and increasing the use of low-turbidity water sources. If operational strategies are not effective enough to maintain water quality, then as a last resort turbidity can be controlled by adding alum to the Catskill Aqueduct prior to the water entering the Kensico Reservoir. The addition of alum causes suspended solids to flocculate and removes them from the water column. However, adding alum is costly, and the flocculated solids accumulate as reservoir sediments near the Catskill influent to Kensico Reservoir. As part of the 2007 FAD, the NYC–DEP is required to dredge alum-containing sediments from the Kensico Reservoir (the main receiving reservoir for the six reservoirs in the Catskill/Delaware system), which is also expensive (U.S. Environmental Protection Agency, 2007). Turbidity can also potentially be reduced by remediating sources of sediment within the Catskill system watersheds.

In the New York City water-supply system, turbidity predominantly results from inorganic particles, mainly aluminosilicate clay and quartz (Effler and others, 1998; Peng and others, 2002, 2004)—in other words, clay and sand that is transported as suspended sediment. Two areas contribute eroded sediment and related turbidity within watersheds: the terrestrial part of the watershed (the land surface) and the stream channel itself (through stream-bank and stream-bed erosion; Walling, 2005). Terrestrial sources of sediment and turbidity are created when areas of erodible sediments coincide with areas of transport to the stream (Lane, 1955; Church, 2002). To mitigate the effects of sediment and turbidity from terrestrial sources, the source areas and transport pathways must be identified, then the source of turbidity must be stabilized or the transport pathway must be disconnected from the source; in some cases, both alternatives must be addressed. Streambank and streambed sources of sediment and related turbidity are often addressed through stream-stabilization projects (Rosgen, 1997); the pathway, in this case the stream, cannot be disconnected from the sources of sediment and turbidity, so the only solution is to identify and stabilize the sources.

For terrestrial and instream sources, understanding the processes responsible for producing the source and transport of sediment and turbidity is an important component of remediation. Without a process-level understanding of the sources and transport pathways of sediment and turbidity, efforts to reduce them will amount to a stopgap approach to remediation (Rosgen, 1997). This type of remediation often produces improvements that are short lived because problem areas are simply shifted to other areas of the watershed or stream, and in some cases attempts to reduce sediment and turbidity actually worsen the situation because new, larger sources are inadvertently linked to transport pathways (Rosgen, 1997).

The Catskill part of the Catskill/Delaware water-supply system is the primary source of turbidity in the New York City water supply system (Cornell Cooperative Extension of Ulster County, 2007). The Catskill water-supply watershed includes the Ashokan and Schoharie Reservoirs, which are connected by the Shandaken Tunnel, an aqueduct that delivers water from the Schoharie Reservoir to the Esopus Creek, about 11 miles (mi) upstream from the Ashokan Reservoir (fig. 1). Through watershed geomorphic assessments and watershed modeling, the NYC–DEP, in cooperation with the New York State Museum and the State University of New York at New Paltz, has identified stream-bank and streambed erosion of fine sediments from glacial-lake deposits as the primary source of suspended sediment and turbidity in the Catskill water-supply watershed (Cornell Cooperative Extension of Ulster County, 2007). As a result, reduction of stream sediment and turbidity has been a focus of stream-stabilization projects within the watershed. The USGS, in cooperation with the NYC–DEP, developed a monitoring strategy to elucidate the spatial and temporal variability of suspended sediment and turbidity in the upper Esopus Creek watershed. These monitoring data will also be used to support the water-quality-modeling efforts that require more detailed spatial and temporal turbidity and suspended-sediment data than existed before this study.

Objectives

The USGS measured SSC and turbidity at 14 monitoring sites within the upper Esopus Creek watershed (table 1). Six of the sites were chosen to coincide with existing USGS streamgaging stations to take advantage of existing infrastructure and streamflow data. The objectives of the project were to:

- examine temporal and spatial patterns in turbidity and suspended sediment in the upper Esopus Creek watershed
- quantify SSC and turbidity at each of 14 monitoring sites in the upper Esopus Creek, and estimate suspended-sediment loads at each site
- evaluate the relations between SSC and turbidity, and construct SSC and turbidity rating curves at six USGS streamgaging stations within the upper Esopus Creek watershed

This report combines data from two studies. The first, which took place from 2009 to 2011, was supported by the New York State Department of Environmental Conservation (NYS–DEC), the Cornell Cooperative Extension of Ulster County (CCE), and the USGS. The purpose was to quantify SSC and turbidity levels and estimate suspended sediment loads at 13 locations throughout the upper Esopus watershed (table 1). The second study, which took place from 2010 to 2012, was supported by the NYC–DEP and the USGS and focused on the six sites coincident with long-term USGS streamgaging stations in the upper Esopus Creek watershed. All those sites were included in the first study except Hollow Tree Brook (USGS streamgaging station 01362342). Data from both studies are included in this report to provide the most complete spatial and temporal dataset.

Purpose and Scope

This report describes the results of SSC and turbidity monitoring within the upper Esopus Creek watershed (fig. 2), the main tributary to the Ashokan Reservoir, from October 1, 2009, through September 30, 2012.

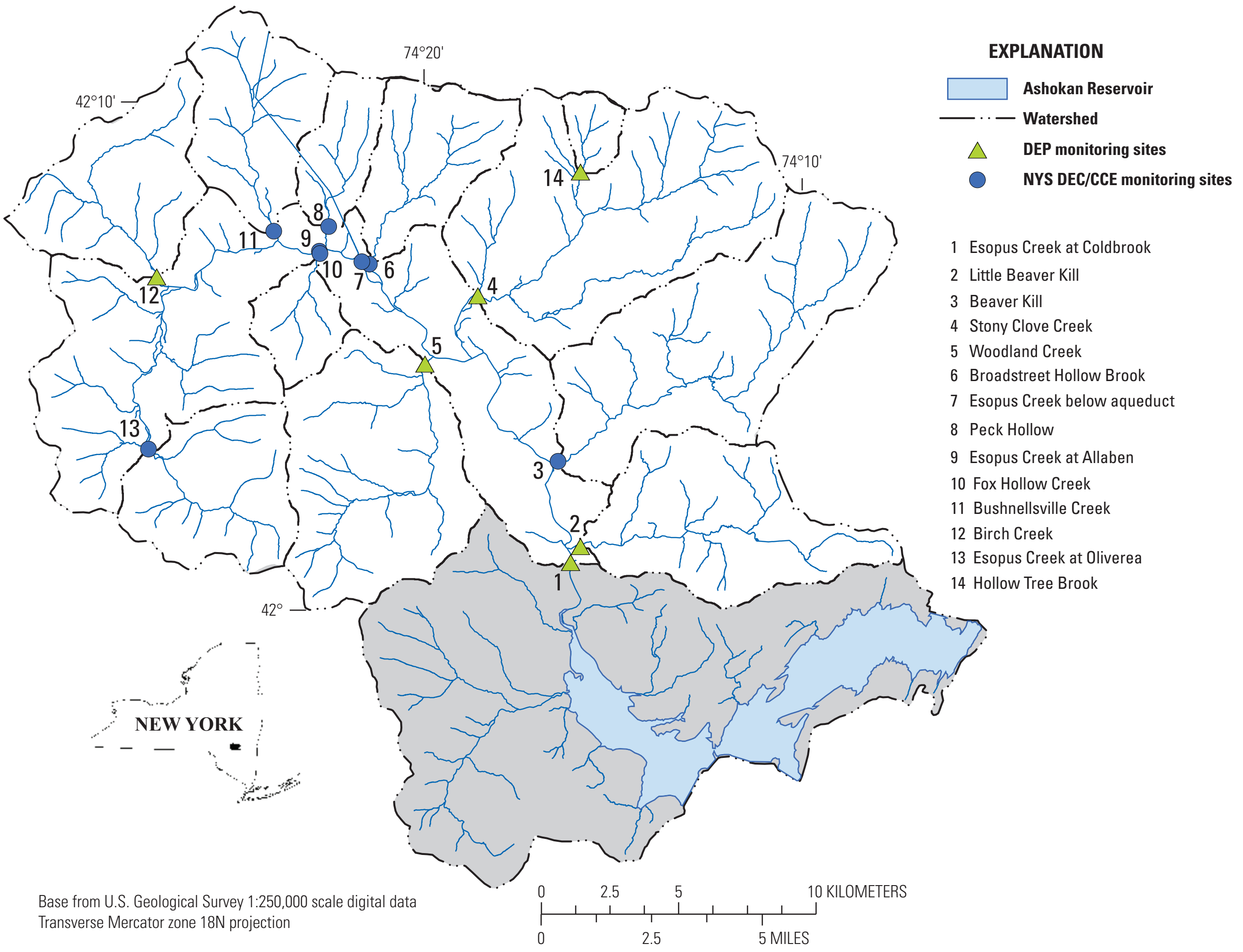
Table 1. Watershed characteristics at 14 monitoring sites within the upper Esopus Creek watershed, Ulster County, New York.

[See figure 2 for site locations. USGS, U.S. Geological Survey; mi^2, square miles; %, percent]

Monitoring site name	USGS streamgaging station number	Watershed characteristics				
		Area, in mi^2	Mean basin slope, in %	Main channel slope, in %	Period of discharge record	Period of USGS continuous turbidity record
Esopus Creek at Oliverea[1]	0136219203	12	28.8	4.8	2010 to 2011	2011
Birch Creek at Big Indian[1,2]	013621955	13	25.6	3.5	1999 to 2011	2012 to present
Bushnellsville Creek at Shandaken[1]	01362197	11	33.0	2.7	2010 to 2011	Not available
Fox Hollow Creek at Allaben[1]	01362199	4	38.1	8.2	2010 to 2010	Not available
Esopus Creek at Allaben[1]	01362200	63	31.6	1.5	1963 to present	2011
Esopus Creek tributary at Peck Hollow Road at Allaben[1]	01362215	5	31.6	7.8	2010 to 2011	Not available
Esopus Creek below aqueduct at Allaben[1]	0136223005	70	31.4	1.4	2010 to 2011	2011
Broadstreet Hollow Brook at Allaben[1]	01362232	9	33.0	5.4	2010 to 2011	2011
Woodland Creek at Phoenicia[1,2]	0136230002	21	36.7	3.0	2003 to present	2012 to present
Hollow Tree Brook[2]	01362342	2	47.2	11.6	1997 to present	2012 to present
Stony Clove Creek at Chichester[1,2]	01362370	31	37.9	2.3	1997 to present	2011 to present
Beaver Kill at Mount Tremper[1]	01362487	25	27.3	2.0	2010 to 2011	2011
Little Beaver Kill at Beechford[1,2]	01362497	17	19.5	0.5	1997 to present	2011 to present
Esopus Creek at Coldbrook[1,2]	01362500	192	31.4	0.9	1931 to present	2011 to present

[1] Site was included in the New York State Department of Environmental Conservation and Cornell Cooperative Extension of Ulster County (NYS–DEC/CCE) project.

[2] Site was included in the New York City Department of Environmental Protection (NYC–DEP) project.



Base from U.S. Geological Survey 1:250,000 scale digital data
Transverse Mercator zone 18N projection

Figure 2. The upper Esopus Creek watershed and the locations of 14 monitoring sites, Ulster County, New York. Monitoring sites included in the current study by the U.S. Geological Survey (USGS) and the New York City Department of Environmental Protection (DEP) are shown as triangles, and additional monitoring sites used in the previous study by USGS, the New York State Department of Environmental Conservation (NYS–DEC), and the Cornell Cooperative Extension of Ulster County (CCE) are shown as circles. Hollow Tree Brook is the only site not included in the NYS–DEC and CCE study.

Study Area

Esopus Creek is in the Catskill Mountains of New York State. In 1915, a part of the creek was dammed to form the Ashokan Reservoir, splitting the creek into upper (upstream of the reservoir) and lower (downstream of the reservoir) segments. The area of the upper Esopus Creek watershed is approximately 192 square miles (mi^2) and is defined by USGS streamgaging station 01362500 Esopus Creek at Coldbrook, N.Y., about 0.6 mi upstream from the Ashokan Reservoir near Boiceville, N.Y. (fig. 2; Smith and others, 2008). The watershed is mainly in Ulster County, although small areas of the watershed are in Greene and Delaware Counties, N.Y. Elevations in the watershed range from 621.5 feet (ft) at the Esopus Creek at Coldbrook streamgaging station to 4,190 ft at the top of Slide Mountain, which is the highest peak in the Catskill Mountains. The upper Esopus Creek watershed is 98-percent forested (Cornell Cooperative Extension of Ulster County, 2007), and according to a stream macroinvertebrate biological assessment completed by the NYS–DEC, water quality in the upper Esopus Creek has historically been very good with only minor impairments (Bode and others, 2004). Nonetheless, elevated turbidity levels have been recognized as a problem in the watershed for many decades as evidenced by the design of the Ashokan Reservoir that includes a settling basin to allow turbidity to settle out of the water column and a supply basin.

The Schoharie Reservoir is also part of the Catskill Reservoir system. The Schoharie watershed is the third largest of the New York City reservoir watersheds with an area of 316 mi^2 and is 27 mi north of the Ashokan Reservoir. Water from the Schoharie Reservoir is transported to the Ashokan Reservoir by way of the Shandaken Tunnel, an 18-mi aqueduct that delivers water to the upper Esopus Creek through the Shandaken portal. From there, the water travels another 11 mi down the Esopus Creek to the Ashokan Reservoir (fig. 1). The Schoharie and Ashokan Reservoirs together account for approximately 40 percent of New York City's mean annual water supply (Cornell Cooperative Extension of Ulster County, 2007).

The three sources of turbidity to the upper Esopus Creek are (1) streambank and streambed erosion, (2) surface runoff from terrestrial parts of the watershed, and (3) the Shandaken Tunnel, which delivers water from the Schoharie Reservoir to Esopus Creek (Cornell Cooperative Extension of Ulster County, 2007). Bedrock in the watershed consists primarily of nearly flat-lying siltstone, shale, conglomerate, and sandstone (Rich, 1934; Caldwell and Skiba, 1986; Arscott and others, 2006). Unconsolidated deposits include alluvium, outwash and kame sand and gravel, glacial-lake silt and clay, and till (Rich, 1934; Cornell Cooperative Extension of Ulster County, 2007; Nagle and others, 2007). Glacial-lake deposits and till are the primary in-stream and terrestrial sources of sediment and turbidity in the Ashokan Reservoir and the Schoharie Reservoir watersheds.

Monitoring sites.—Watershed characteristics, period of discharge record, and period of continuous turbidity record for each monitoring site are listed in table 1. Six of the sites were the focus of the NYC–DEP study, and nine were part of the NYS–DEC and CCE more spatially extensive study (table 1). Four of the monitoring sites were on the main channel of upper Esopus Creek. An additional nine sites were on the main tributaries to the upper Esopus Creek. Hollow Tree Brook, a tributary to Stony Clove Creek, was added to the study during water years 2011 and 2012 as a reference tributary because a streamgaging station with 16 years of discharge data was already available at the site and because SSC and turbidity values in runoff from the watershed were low. Hollow Tree Brook serves as a reference tributary because it did not undergo any large bank failures or contain any chronic sources of suspended sediment. Hollow Tree Brook and Stony Clove Creek were also part of a 14-site monitoring network across the Catskill Mountains that collected data from 1999 to 2009 (McHale and Siemion, 2010).

Although the 3 years of data collected for this study allow spatial patterns in SSC and turbidity to be examined, 3 years is a short time period during which to examine temporal patterns in SSC and turbidity caused by long-term erosion and large storms. Not all storms were sampled during the two different study periods, and during some of the largest storms, equipment was damaged, and samples could not be collected throughout the entire range of flow. On average, 103 samples were collected at each site between water years 2010 and 2012, and 35 samples were collected at each site annually. No samples were collected during water year 2010 at Hollow Tree Brook.

Previous Studies

The upper Esopus Creek watershed and the Ashokan Reservoir have been the focus of research during the last several years because of concerns about turbidity levels in the reservoir and the potential water-quality effects of turbidity on the drinking-water-supply system. Turbidity has been recognized as a problem in the reservoir since its completion in 1915; indeed, the reservoir is designed as two basins, a receiving (or settling) basin and a water-supply basin, to allow turbidity-causing particles to settle out of the water column before entering the water-supply intakes. An alum plant was also built at the time the reservoir came into service to further reduce turbidity in the reservoir during large storms. Nonetheless, during a study to quantify turbidity throughout the reservoir, high turbidity values were measured after storms in the receiving basin and at the water supply intakes (Effler and others, 1998).

Subsequent work showed that most of the turbidity measured in the Ashokan was caused by inorganic particles, primarily aluminosilicate clay and quartz, rather than organic matter, and recommended a focus on controlling those sources rather than controlling nutrient inflows to the reservoir (Effler and others, 2002; Peng and others, 2002, 2004). These inorganic particles were further characterized and linked to the upper Esopus Creek as the primary source of particles in the reservoir (Peng and others, 2009). The particle-size distribution was consistent throughout a wide range in turbidity values (Peng and others, 2009). Particle-size distribution is an important consideration in evaluating SSC and turbidity measurements because small changes in particle-size distribution can increase error and bias in measurements and can indicate changes in sediment sources (Landers and Sturm, 2013). A reservoir turbidity model was developed for the Ashokan Reservoir to aid in managing the water-supply reservoir and allow simulations of possible future reservoir conditions under different climate-change scenarios (Gelda and others, 2009).

Continuous monitoring of New York City water-supply reservoirs and their major tributaries has continued with the goal of developing a near-real-time decision-support tool (Effler and others, 2013). The decision-support tool will require near-real-time measurements of turbidity inputs to the reservoirs. The relation between turbidity and discharge at sites throughout the upper Esopus Creek watershed must be understood to better define the spatial variations in turbidity sources and improve predictive turbidity models. Predictive models of reservoir-turbidity input are needed to provide short-term forecasts of inflow turbidity and simulations of possible future reservoir conditions under different climate-change scenarios (Gelda and others, 2009).

Researchers have examined the sources of turbidity across the Catskill Mountains (Nagle and others, 2007) and specifically in the upper Esopus Creek watershed (Mukundan and others, 2013; Samal and others, 2013). Nagle and others (2007) identified streambank erosion as a primary source of sediment to streams in the Schoharie and Cannonsville Reservoir watersheds part of the New York City water-supply watershed. The amount of sediment produced by bank erosion was related to the presence of glacial-lake deposits (Nagle and others, 2007), that are common within the upper Esopus Creek watershed. Discharge and SSC in the upper Esopus Creek watershed were directly related: 80 percent of the suspended-sediment load was transported during large storms during 4 percent of the time throughout an 8-year period (Mukundan and others, 2013). Analyses of in situ, high-frequency (15-minute interval) turbidity measurements indicated that daily mean discharge, antecedent moisture conditions, and season were also useful predictors of suspended-sediment load in the upper Esopus Creek watershed (Mukundan and others, 2013).

Burns and others (2007) reported a significant increase of 0.6 degrees Celsius (°C) in regional mean air temperature and an increase of 136 millimeters of precipitation for the Catskills from 1952 to 2005. There was also a trend toward earlier spring snowmelt by as much as 10 days, as indicated by the winter-spring center of discharge volume (Burns and others, 2007). The effects of climate change in the Catskill region were modeled 100 years into the future by using Global Climate Model simulations of future climate (Zion and others, 2011). Results from the model simulations suggested a continued shift toward earlier snowmelt of 15 to 20 days during the next 100 years, which would likely affect the timing of streamflow, sediment, and nutrient delivery to reservoirs (Zion and others, 2011). A study that investigated the potential effect of changes in climate on soil erosion and sediment yield in the Cannonsville watershed indicated the potential for a marked increase in soil erosion, although no coincident increase in sediment yield was predicted (Mukundan and others, 2012). Much of the increase in soil erosion was predicted for the winter because of a predicted increase in precipitation falling as rain rather than snow (Mukundan and others, 2012). A recent study, focused on the effects of climate change on winter turbidity in the Ashokan Reservoir, predicted increases in winter reservoir inflows that would result in increases in reservoir turbidity during the winter of as much as 17 percent by 2100 (Samal and others, 2013). In addition, settling velocities of particles would be substantially lower at lower temperatures (Samal and others, 2013).

Methods

Field Methods

All field data were collected according to standard USGS protocols (Wilde and others, 1999). Stream suspended-sediment and turbidity grab samples were collected monthly throughout the study from a well-mixed area of the stream (identified through flow measurements) at each sampling station. Storm samples were collected with automated samplers triggered to sample in response to changes in stream stage. Grab samples, automated samples, and turbidity measurements from in situ probes were all collected in as close proximity to one another as was possible at each station to minimize differences caused by sampling location. The goal was to collect samples throughout the range of flow conditions and during every season at each site throughout the study period. Field quality assurance and quality control were assessed through approximately quarterly collection of triplicate samples and equal width-depth integrated samples.

Turbidity was monitored at 15-minute intervals using in situ turbidity probes at 10 of the stations. Two types of turbidimeters were used: (1) the Forest Technology Systems DTS–12 probe and (2) the Hach Surface Scatter 7 Turbidimeter (SS7). The DTS–12 probe is a true in situ probe that is deployed instream; it uses a side-scatter optical nephelometer with an infrared laser light source, a specified range of 0 to 1,600 nephelometric turbidity units (NTU), and a resolution of 0.01 NTU. The DTS–12 is specified to be accurate to within ±2 percent in the range of 0–399 NTU and ±4 percent in the range 400 to 1,600 NTU. The SS7 is a flow-through system mounted on the wall of a gage house, and water is pumped into it from the stream. Eccentric Pumps SLP/Mini 10 peristaltic pumps delivered water to the SS7 at a rate of 2 liters per minute. The SS7 uses a photocell, positioned at a 90-degree angle to the broad-spectrum light source, with a specified range of 0 to 9999 NTU and a resolution of 0.01 NTU below 100 NTU and 0.1 NTU above 100 NTU. The SS7 is specified with an accuracy of ±5 percent from 0 to 1999 NTU and ±10 percent from 2000 to 9999 NTU. Both types of probes were calibrated and checked monthly using Formazin standard solutions. Measurements from the DTS–12 probes are reported as formazin nephelometric units (FNU). Measurements from the SS7 are reported as nephelometric turbidity units (NTU). The U.S. Geological Survey national field manual states, "These reporting units are equivalent when measuring a calibration solution …, but their respective instruments may not produce equivalent results for environmental samples" (Anderson, 2005, p. 9). At one site, Stony Clove Creek at Chichester, N.Y., both probes were installed within 0.5 meters of each other. The probes performed similarly for values below about 450 FNU and NTU, but at values greater than 450 FNU and NTU the SS7 tended to underestimate turbidity compared to the DTS–12 (fig. 3). The differences in turbidity measurements can probably be attributed partly to the differences in instrument design but are also likely caused by the differences in in situ and flow-through sampling methods.

This study was not designed to evaluate the accuracy of the individual probes, but results suggest that at the Stony Clove site the SS7 flow-through system does not capture the highest turbidity levels well. The problem is likely caused by a combination of the need to pump water to the instrument and the need for the sample to pass through a bubble trap that allows some suspended sediment to settle out of the water. Cleaning and fouling data corrections were applied to the turbidity data according to standard methods (Wagner and others, 2006).

Laboratory Methods

All water-quality samples were transported to the USGS Soil and Low-Ionic-Strength Water Quality Laboratory in Troy, N.Y., where turbidity was determined using a Hach Model 2100AN Turbidimeter. The Hach Model 2100AN used a tungsten lamp assembly (white light) and was set to ratio mode. This method complies with the EPA interim enhanced surface water treatment rule regulations and standard method 2130B and produces results in nephelometric turbidity ratio units (NTRUs; Clesceri and others, 1998). Operating the Hach 2100AN in ratio mode is acceptable under EPA 180.0 method for determination of turbidity and produces results through a wide range of turbidity levels without the need for dilution (range of 0 to 10,000 NTRUs). The measurement technique applies the same light source as the EPA 180.1 design but uses several detectors in the measurement. A primary detector is centered at 90° relative to the incident beam plus other detectors located at other angles. An instrument algorithm uses a combination of detector readings to generate the turbidity reading (Clesceri and others, 1998).

Results for laboratory turbidity (LabTurb) are reported in NTRUs as required by the U.S. Geological Survey national field manual; the U.S. Geological Survey began making

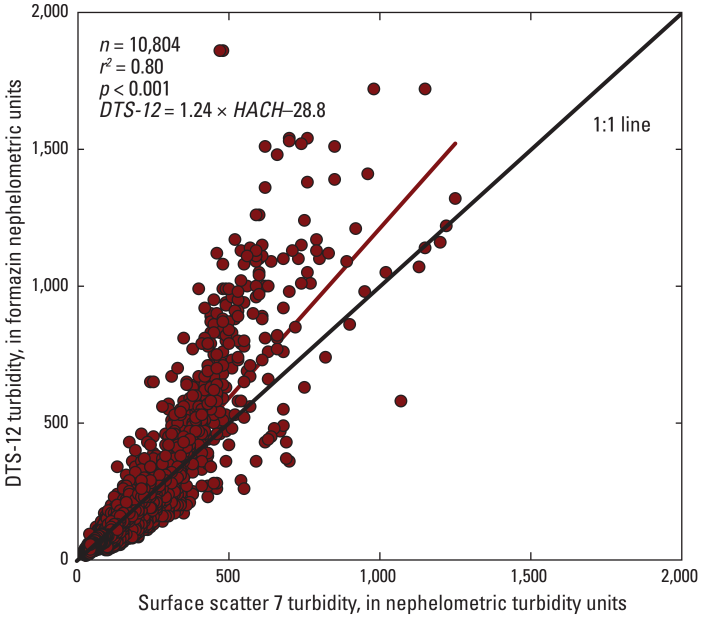


Figure 3. The relation between continuous turbidity values measured every 15 minutes by the DTS–12 in situ probe and the Hach Surface Scatter 7 flow-through system at Stony Clove Creek (U.S. Geological Survey streamgaging station 01362370) from August 17, 2011, to February 7, 2012. See figure 2 for location. n, number of samples; r^2, coefficient of determination; p, level of significance of the relation.

distinctions in the various methods of measuring turbidity (Anderson, 2005) on October 1, 2004. Suspended-sediment concentration was analyzed at the USGS Sediment Laboratory in Louisville, Kentucky, using the ASTM D3977–97(2002) standard test methods for determining sediment concentration in water samples (Guy, 1969).

Data Analyses

Flow-weighted means were calculated for all discrete SSC and turbidity samples (grab samples and samples from automated samplers) to be compared among sites. Suspended-sediment loads were calculated using the USGS Graphical Constituent Loading and Analysis System (GCLAS; Koltun and others, 2006) to estimate concentrations for periods between measured concentrations based on the relation between SSC and discharge. Loads were calculated in GCLAS by interpolating SSC to the same temporal frequency as the 15-minute discharge data (McKallip and others, 2001). Discharge and SSC were multiplied at a 15-minute time step and then totaled for each day, resulting in a daily load. Continuous turbidity was used when available to confirm the timing of peak sediment concentrations during storms.

Linear regression models were developed for SSC and discharge, turbidity and discharge, and SSC and turbidity for the monitoring sites at the six USGS long-term streamgaging stations (table 2). Turbidity measurements from the laboratory (LabTurb) and the in situ probes (Turb15) were considered separately. Other models (polynomial, power, exponential, and logarithmic) were also considered. In some cases second-order polynomial or power models produced similar or slightly higher coefficient of determination (r^2) values than linear regressions did, but these high r^2 values were often at the cost of accurate model fits at the high end of the measurement range. For the purposes of this report, results from linear model fits are reported for all stations and all variables to allow comparisons of model fit among the sampling stations. Some of the models produce negative values at the low end of the measurement range; however, at these levels SSC and turbidity were typically close to zero. Log-transforming the discharge data did not produce better model fits because the range in discharge was similar to the range in SSC and turbidity for most of the stations. Models were considered significant at p-values less than or equal to 0.01.

Bankfull discharge was estimated for each sampling location by using the equation given in Mulvihill and Baldigo (2012) for region 4. The equation is described as follows:

$$Q_{bkf} = 117.2DA^{0.780}, \tag{1}$$

where

Q_{bkf} is bankfull discharge in cubic feet per second, and

DA is drainage area in square miles.

Bankfull discharge calculations were used to quantify the number of storms that had the potential to move large amounts of suspended sediment at each site and to inform the interpretation of differences in suspended-sediment loads among the study years. Mean basin slope and main channel slope were calculated in Esri ArcMap with the Hydrology tools for each watershed. These data were used to examine differences among the study watersheds to aid in interpretation of suspended-sediment loads.

Results and Discussion

Temporal and Spatial Patterns of Turbidity and Suspended Sediment

The first objective of the study was to examine temporal and spatial patterns in turbidity and suspended sediment in the upper Esopus Creek watershed. We combined data from grab samples and storm samples from this study with long-term data collected at Hollow Tree Brook and Stony Clove Creek to examine the temporal patterns of SSC and turbidity and to put data collected during the current study into context with data collected during the last 12 years. Hollow Tree Brook had much lower SSCs and turbidity than Stony Clove Creek during the last 12 years, and high concentrations were often related to large storms at both sites (fig. 4). A series of large storms during 2005 and 2006 resulted in the highest SSCs and turbidity measured to that point in time at the Stony Clove Creek site and concentrations remained elevated for 2 years after those storms. Storms of moderate discharge that produced small increases in concentrations before 2005–06 resulted in much higher concentrations during 2007–08. This was also true of suspended-sediment concentrations at Hollow Tree Brook though to a lesser extent (fig. 4).

Flow was generally higher during the study period (2010 to 2012) than during the previous 10 years, especially at Hollow Tree Brook (fig. 4). The increase resulted in a greater frequency of high suspended-sediment concentrations and turbidity values at Hollow Tree Brook and Stony Clove Creek than during the previous 10 years (fig. 4). During water years 2010 and 2011 there were 8 bankfull discharge events at Hollow Tree Brook and 10 at Stony Clove Creek, compared to a total of 3 at Hollow Tree Brook and 33 at Stony Clove Creek during the entire 12-year period from 1997 to 2009. The number of bankfull discharge events at a station is important because bankfull discharge is often cited as the condition during which channel formation and alteration occur (Miller and Davis, 2003). In the upper Esopus Creek watershed, which has high rates of streambed and bank erosion, large amounts of suspended sediment are mobilized during bankfull storms.

Table 2. Results of regression analyses among discharge, suspended-sediment concentration, laboratory turbidity, and in situ turbidity at six monitoring sites located at U.S. Geological Survey streamgaging stations in the upper Esopus Creek watershed.

[See figure 2 for site locations. Turbidity units are nephelometric turbidity ratio units for laboratory turbidity, nephelometric turbidity units for the Hach Surface Scatter 7, and formazin nephelometric units for DTS–12. r^2, coefficient of determination; p, significance level; n, sample number; *Q*, discharge, in cubic feet per second; *SSC*, suspended-sediment concentration, in milligrams per liter; *LabTurb*, laboratory turbidity measured with a Hach 2100AN Turbidimeter; *Turb15*, in situ turbidity measured with either a DTS–12 or a Hach Surface Scatter 7 in situ probe]

Variable		Regression results			Equation
Independent	**Dependent**	**r^2**	**p**	**n**	
Esopus Creek at Coldbrook—Hach Surface Scatter 7					
Q	*SSC*	0.91	<0.001	102	$SSC = 0.09 \times Q - 37.9$
Q	*LabTurb*	0.83	<0.001	105	$LabTurb = 0.06 \times Q - 67.2$
Q	*Turb15*	0.61	<0.001	39,360	$Turb15 = 0.05 \times Q - 3.21$
LabTurb	*SSC*	0.82	<0.001	92	$SSC = 1.36 \times LabTurb + 116.9$
Turb15	*LabTurb*	0.96	<0.001	30	$LabTurb = 1.14 \times Turb15 - 7.8$
Turb15	*SSC*	0.86	<0.001	31	$SSC = 2.02 \times Turb15 - 26.3$
Little Beaver Kill at Beechford—DTS–12					
Q	*SSC*	0.56	<0.001	103	$SSC = 0.42 \times Q - 8.0$
Q	*LabTurb*	0.45	<0.001	98	$LabTurb = 0.15 \times Q + 0.37$
Q	*Turb15*	0.37	<0.001	52,685	$Turb15 = 0.08 \times Q - 0.91$
LabTurb	*SSC*	0.77	<0.001	92	$SSC = 2.54 \times Q + 6.2$
Turb15	*LabTurb*	0.40	<0.001	56	$LabTurb = 0.38 \times Turb15 + 19.3$
Turb15	*SSC*	0.32	<0.001	59	$SSC = 0.97 \times Turb15 + 46.2$
Stony Clove Creek at Chichester—DTS–12					
Q	*SSC*	0.64	<0.001	118	$SSC = 0.53 \times Q + 228.6$
Q	*LabTurb*	0.60	<0.001	103	$LabTurb = 0.37 \times Q + 182.8$
Q	*Turb15*	0.29	<0.001	24,955	$Turb15 = 0.16 \times Q + 85.6$
LabTurb	*SSC*	0.72	<0.001	100	$SSC = 1.4 \times LabTurb + 45.1$
Turb15	*LabTurb*	0.79	<0.001	32	$LabTurb = 1.5 \times Turb15 - 15.4$
Turb15	*SSC*	0.66	<0.001	39	$SSC = 2.2 \times Turb15 - 120.7$
Stony Clove Creek at Chichester—Hach Surface Scatter 7					
Q	*Turb15*	0.25	<0.001	32,544	$Turb15 = 0.27 \times Q + 69.6$
Turb15	*LabTurb*	0.74	<0.001	33	$LabTurb = 1.93 \times Turb15 - 42.2$
Turb15	*SSC*	0.52	<0.001	39	$SSC = 3.2 \times Turb15 - 98.6$
Hollow Tree Brook—DTS–12					
Q	*SSC*	0.50	<0.001	60	$SSC = 2.3 \times Q - 29.6$
Q	*LabTurb*	0.61	<0.001	53	$LabTurb = 0.31 \times Q - 3.2$
Q	*Turb15*	0.02	<0.001	23,986	$Turb15 = 0.37 \times Q + 3.0$
LabTurb	*SSC*	0.58	<0.001	51	$SSC = 6.4 \times LabTurb + 0.72$
Turb15	*LabTurb*	0.96	<0.001	16	$LabTurb = 0.64 \times Turb15 + 0.84$
Turb15	*SSC*	0.63	<0.001	16	$SSC = 2.8 \times Turb15 + 15.6$
Woodland Creek at Phoenicia—DTS–12					
Q	*SSC*	0.68	<0.001	86	$SSC = 0.38 \times Q + 27.8$
Q	*LabTurb*	0.57	<0.001	81	$LabTurb = 0.31 \times Q + 35.8$
Q	*Turb15*	0.30	<0.001	22,345	$Turb15 = 0.26 \times Q + 2.8$
LabTurb	*SSC*	0.79	<0.001	79	$SSC = 2.4 \times LabTurb - 100.6$
Turb15	*LabTurb*	0.98	<0.001	17	$LabTurb = 0.90 \times Turb15 + 1.92$
Turb15	*SSC*	0.65	<0.001	17	$SSC = 1.2 \times Turb15 + 15.9$

Table 2. Results of regression analyses among discharge, suspended-sediment concentration, laboratory turbidity, and in situ turbidity at six monitoring sites located at U.S. Geological Survey streamgaging stations in the upper Esopus Creek watershed.—Continued

[See figure 2 for site locations. Turbidity units are nephelometric turbidity ratio units for laboratory turbidity, nephelometric turbidity units for the Hach Surface Scatter 7, and formazin nephelometric units for DTS–12. r^2, coefficient of determination; p, significance level; n, sample number; *Q*, discharge, in cubic feet per second; *SSC*, suspended-sediment concentration, in milligrams per liter; *LabTurb*, laboratory turbidity measured with a Hach 2100AN Turbidimeter; *Turb15*, in situ turbidity measured with either a DTS–12 or a Hach Surface Scatter 7 in situ probe]

Variable		Regression results			Equation
Independent	Dependent	r^2	p	n	
Birch Creek—DTS–12 and Hach Surface Scatter 7[a]					
Q	*SSC*	0.75	<0.001	104	$\mathit{SSC} = 2.74 \times Q - 91.0$
Q	*LabTurb*	0.65	<0.001	91	$\mathit{LabTurb} = 0.95 \times Q - 12.2$
LabTurb	*SSC*	0.79	<0.001	85	$\mathit{SSC} = 2.3 \times \mathit{LabTurb} + 9.6$
Turb15	*LabTurb*	0.99	<0.001	11	$\mathit{LabTurb} = 0.68 - \mathit{Turb15} + 0.40$
Turb15	*SSC*	0.99	<0.001	12	$\mathit{SSC} = 1.0 \times \mathit{Turb15} - 4.4$
Birch Creek—DTS–12 only					
Q	*Turb15*	0.62	<0.001	11,223	$\mathit{Turb15} = 1.65 \times Q - 5.2$
Birch Creek—Hach Surface Scatter 7 only					
Q	*Turb15*	0.29	<0.001	6,920	$\mathit{Turb15} = 0.40 \times Q - 2.4$

[a] Data were combined for *Turb15* values for regressions with *LabTurb* and *SSC* because of low sample numbers.

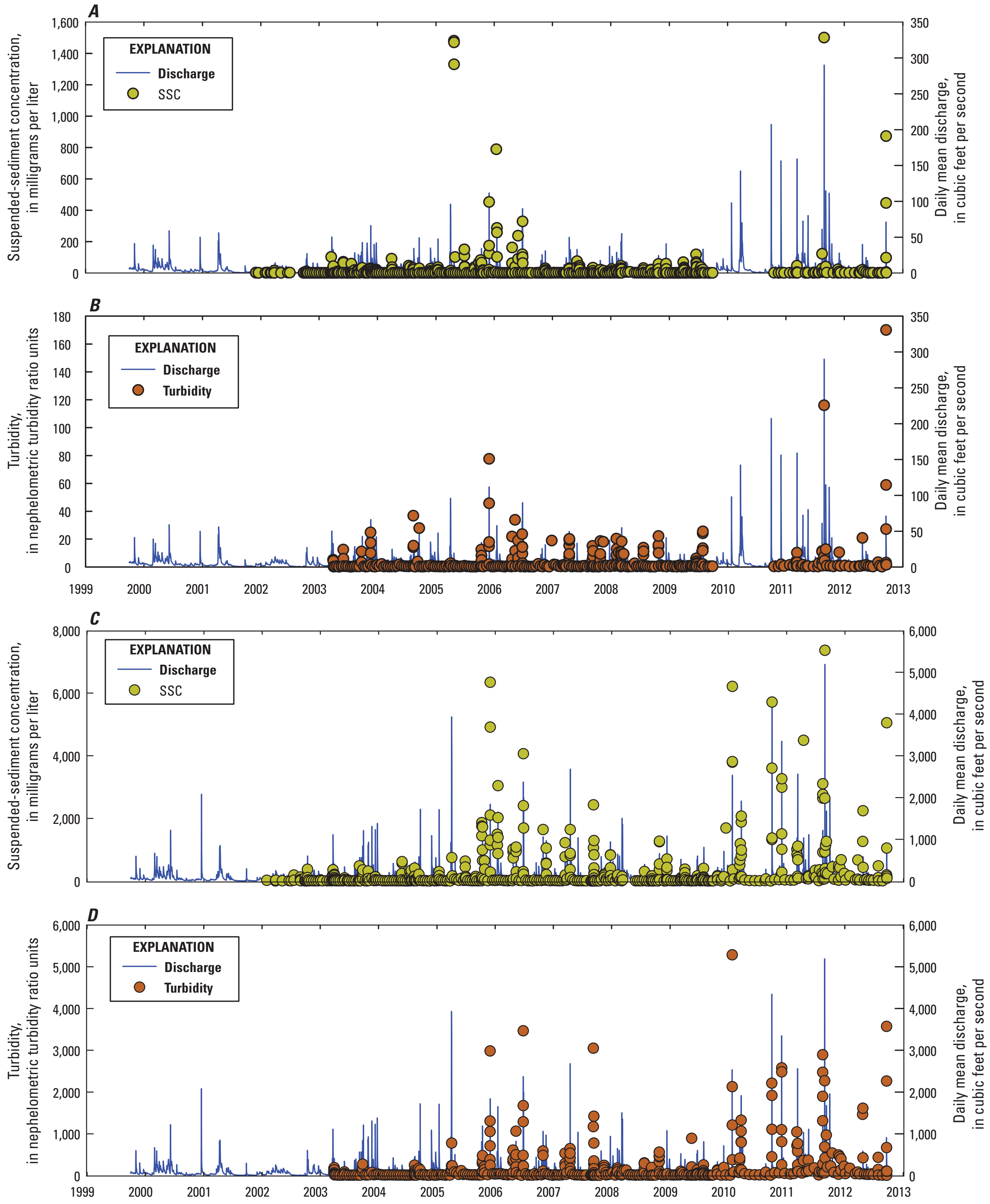


Figure 4. *A*, Suspended-sediment concentration (SSC) and *B*, laboratory turbidity at the Hollow Tree Brook monitoring site and *C*, suspended-sediment concentration and *D*, laboratory turbidity at the Stony Clove Creek monitoring site. Turbidity values are from grab and storm samples measured in the laboratory using a Hach 2100AN. Yellow circles indicate suspended-sediment concentrations, brown circles indicate turbidity levels, and the blue line shows daily mean discharge. Note the change in scale between sites. See figure 2 for site locations.

Only one bankfull discharge event was recorded at each of the six sites included in the NYC–DEP study during the 2012 water year. At the outlet of the upper Esopus Creek watershed at the Coldbrook site, annual flows varied markedly during the 3-year study period. Annual mean flow for water year 2010 was 10 percent less than the 70-year mean annual flow (from 1932 to 2012), annual mean flow for water year 2011 was 30 percent greater than the long-term mean, and annual mean flow for water year 2012 was 20 percent less than the long-term mean. The Shandaken Tunnel accounted for 24 percent of the annual discharge at Coldbrook during 2010, 7 percent during 2011, and 22 percent during 2012. The tunnel accounted for a small percentage of annual flow during 2011 because it was closed from August 27 to October 26, 2011 to keep turbid water from the Schoharie Reservoir from entering upper Esopus Creek during and following Tropical Storm Irene and the remnants of Tropical Storm Lee. With few exceptions the Shandaken Tunnel is closed when turbidity levels are greater than 100 NTU (New York State Department of Environmental Conservation, 2006). The highest SSC and turbidity levels were measured during the first 2 years of the study, and the low-flow volumes during water year 2012 resulted in low SSC and turbidity levels compared to 2010 and 2011 at all the sites (see appendix 1, figs. 1–1—1–6).

The second objective of this study was to quantify SSC and turbidity levels and suspended-sediment loads at each of 14 monitoring sites in the upper Esopus Creek for a period of 2 to 3 years, depending on the period of record for each site. The range and median concentrations of suspended sediment and turbidity were calculated with data from grab samples and storm samples from automated samplers and used to investigate the spatial patterns of SSC and turbidity in the upper Esopus Creek watershed (figs. 5–7).

We separated the results by water year to examine how differences in flow among the 3 study years affected concentrations at each site. Stony Clove Creek had the highest annual median SSC and turbidity of any of the upper Esopus Creek tributaries; in fact, concentrations at the Stony Clove Creek station were as high as or higher than those measured at the Coldbrook station. Concentrations generally increased downstream along the main channel (figs. 5–7) although during 2011 the station at Esopus below the Shandaken aqueduct had much lower maximum and median concentrations than the Allaben station only 0.5 mi upstream. This inconsistency occurred because the station below the aqueduct was destroyed by tropical storm Irene, so no samples were collected at the site during that storm, which produced the highest concentrations measured during the study period at the other sites. Although many of the tributaries produced comparable maximum SSCs and turbidity, they generally fell into three groups. Stony Clove Creek was in a group by itself, consistently producing higher mean SSC and turbidity than any other tributary or, indeed, any main-stem monitoring site, including Esopus Creek at Coldbrook. Woodland Creek, Beaver Kill, Broadstreet Hollow Brook, and Birch Creek all produced moderately high concentrations, and Fox Hollow Creek, Bushnellsville Creek, Peck Hollow Creek, Hollow Tree Brook, and the main-stem Esopus Creek site in the headwaters at Oliverea all produced low SSCs and turbidity.

In situ turbidity measurements.—Turbidity data were also collected using in situ probes at the six sites included in the NYC–DEP study. Difficulty in obtaining landowner permission and connecting power at several sites delayed installation of the probes. As a result, the period of record for in situ measurements was shorter than that for discrete samples (grab samples and storm samples collected with automated samplers) at every site (table 1). Stony Clove Creek had the highest mean turbidity levels of the six sites with in situ probes, followed by Coldbrook, Woodland Creek, Birch Creek, Little Beaver Kill, and Hollow Tree Brook. This ranking was consistent whether considering the entire period of record for in situ measurements at each site or considering only the time period when probes were in operation at all sites (January 1, 2012 to September 30, 2012).

Results from the in situ probes generally agreed with results from discrete samples measured in the laboratory, but the in situ probes provided much greater detail than the automated samplers and grab samples (appendix 1, figs. 1–1—1–6). Indeed, the probes show that during interstorm periods or small storms when the automated samplers did not sample, substantial amounts of turbidity were measured at some of the sites, particularly Stony Clove Creek. In addition, the probe data show that even when the automatic samplers collect samples throughout a storm, they often do not record the full range in turbidity levels at each site.

Suspended-Sediment Loads

Suspended-sediment loads were calculated using the GCLAS computer program for each monitoring site to identify the watersheds that produced the largest suspended-sediment loads. Suspended-sediment loads were compared among sites, and the percentage of the total load computed for the upper Esopus Creek watershed outlet at Coldbrook was calculated for each tributary. These comparisons are not meant to imply that loads from individual tributaries are immediately delivered to the Coldbrook site; there is deposition and resuspension of sediment throughout the watershed. These computations are presented, rather, as the net contribution of suspended sediment annually. As would be expected, the largest suspended-sediment loads were measured at the outlet of the upper Esopus Creek watershed at the Coldbrook site (fig. 8).

During water years 2010 and 2011, we sampled all the main tributaries and the Esopus Creek upstream site at Oliverea that contributed to the sediment load at the Coldbrook site; those sources accounted for about 80 percent of the load calculated for the Coldbrook site, indicating that about 20 percent of the load at the Coldbrook site was caused by resuspension and transport of previously deposited channel sediment, contributions from unsampled tributaries, and

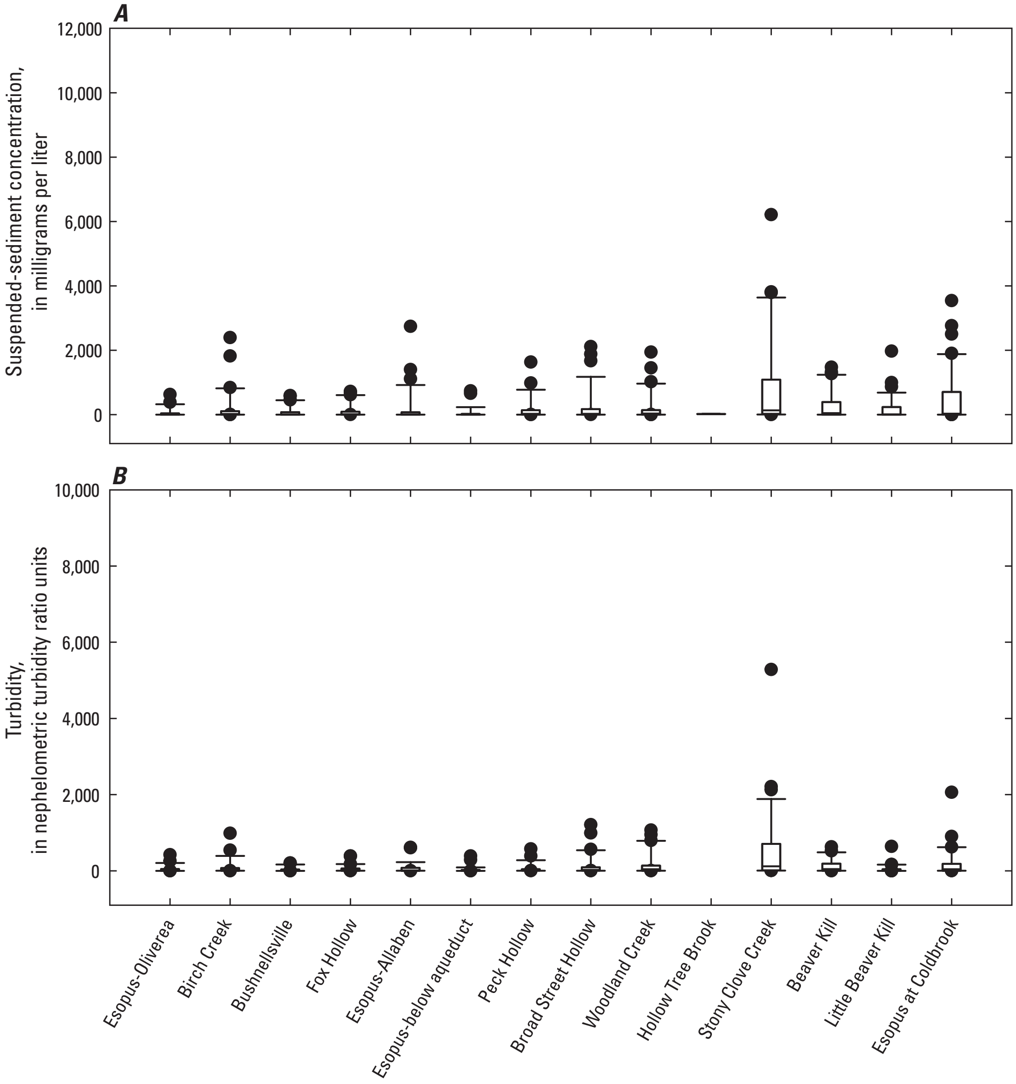


Figure 5. *A*, Suspended-sediment concentration and *B*, laboratory turbidity (LabTurb) levels at 14 monitoring sites throughout the upper Esopus Creek watershed for water year 2010. The boxes show the 25th and 75th percentiles, the whiskers show the 10th and 90th percentiles, the black circles show outlier values, and the lines through the boxes show the median concentrations. The four sites preceded with Esopus are main-channel sites. See figure 2 for site locations.

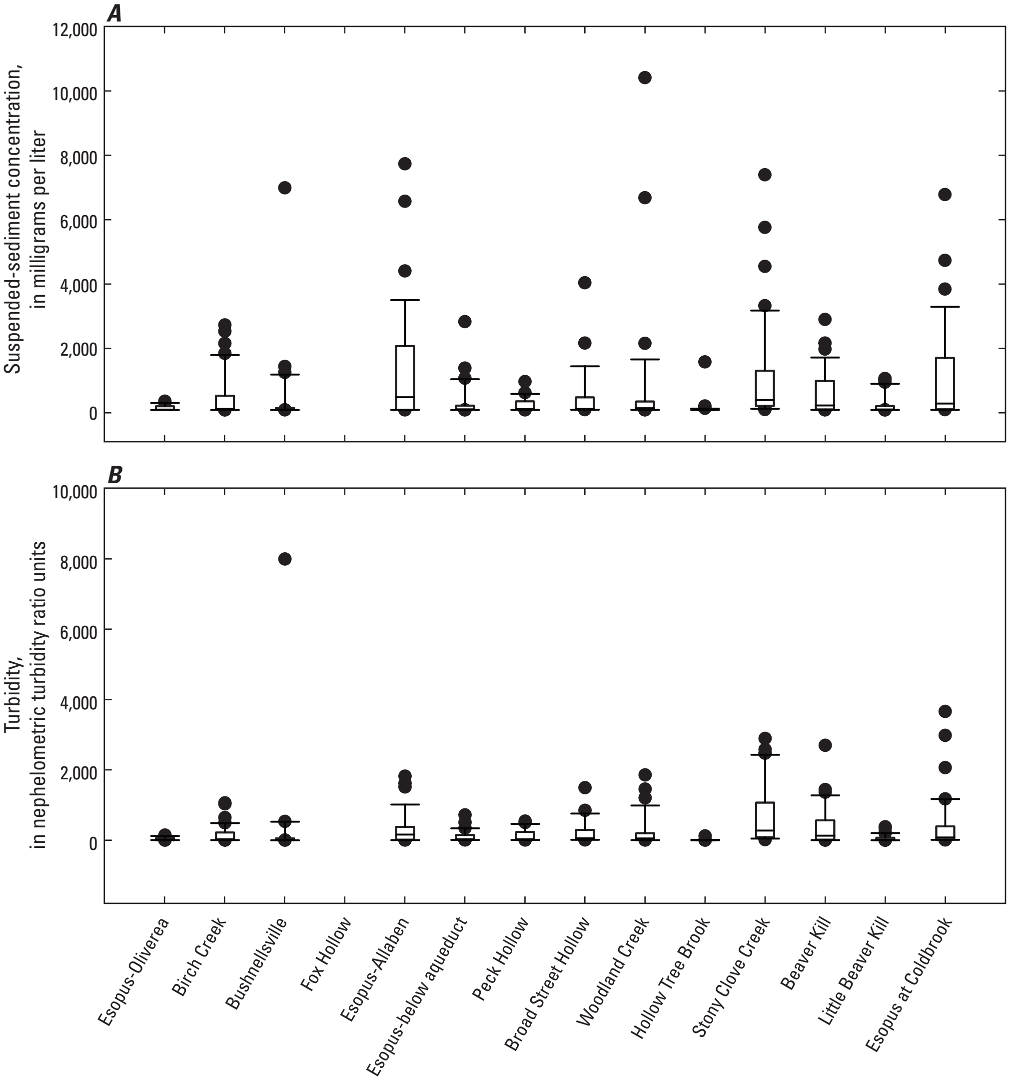


Figure 6. *A*, Suspended-sediment concentration and *B*, laboratory turbidity (LabTurb) levels at 14 monitoring sites throughout the upper Esopus Creek watershed for water year 2011. The boxes show the 25th and 75th percentiles, the whiskers show the 10th and 90th percentiles, the black circles show outlier values, and the lines through the boxes show the median concentrations. The four sites preceded with Esopus are main-channel sites. See figure 2 for site locations.

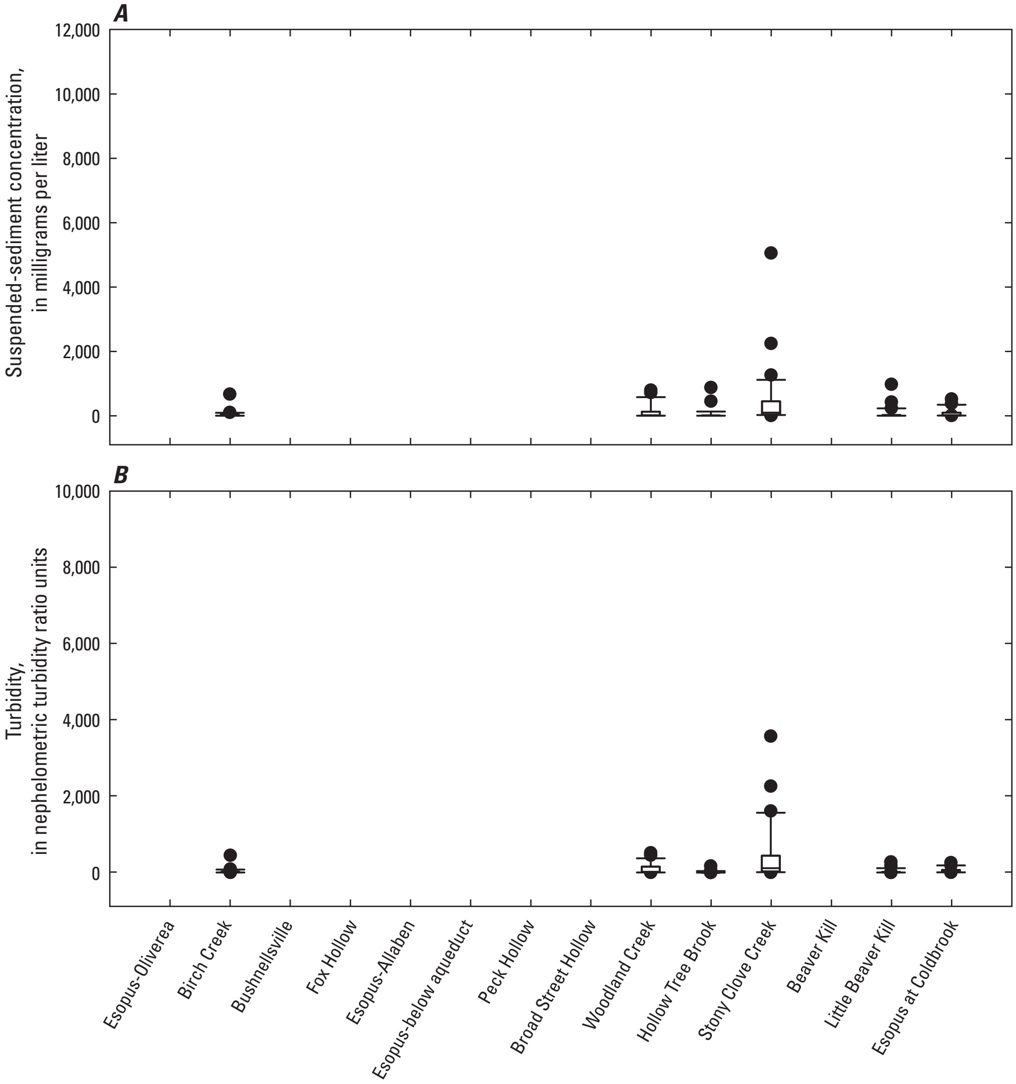


Figure 7. *A*, Suspended-sediment concentration and *B*, laboratory turbidity (LabTurb) levels at 6 of 14 monitoring sites throughout the upper Esopus Creek watershed for water year 2012. The boxes show the 25th and 75th percentiles, the whiskers show the 10th and 90th percentiles, the black circles show outlier values, and the lines through the boxes show the median concentrations. The four sites preceded with Esopus are main-channel sites. See figure 2 for site locations.

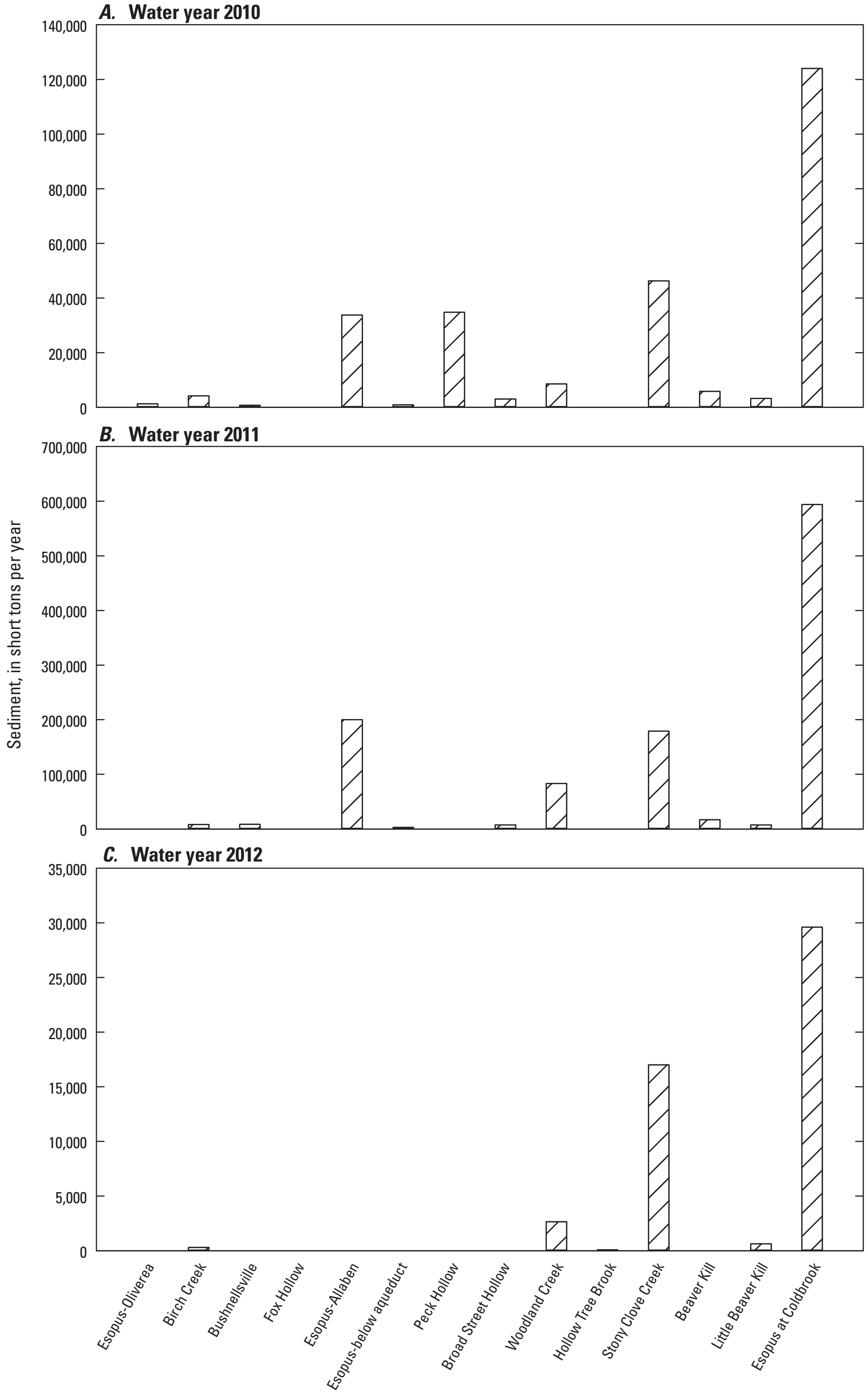


Figure 8. Suspended-sediment loads for water years *A*, 2010, *B*, 2011, and *C*, 2012 at 14 monitoring sites throughout the upper Esopus Creek watershed. In water year 2012 only six sites were sampled: Birch Creek, Woodland Creek, Hollow Tree Brook, Stony Clove Creek, Little Beaver Kill, and Esopus at Coldbrook. Note the change in scale between years. See figure 2 for site locations.

streambank and streambed erosion that occurred along the main channel between the Allaben and Coldbrook sites (fig. 8). Error associated with suspended-sediment-load calculations must also be considered when evaluating the differences between tributary loads and those calculated for the Coldbrook site. GCLAS, because it is not a statistical model, does not provide a load-error estimate but rather uses measurements of concentration and flow to calculate loads. Nonetheless, there is error associated with discharge measurements and with the sediment-flow relations used to guide determination of SSC during periods between samples; there is also analytical error associated with SSC laboratory measurements.

Although flow conditions differed markedly between water years 2010 and 2011, the contributions of suspended sediment from the various tributaries relative to the total remained remarkably similar (fig. 8). Stony Clove Creek contributed by far the largest amount of the total annual suspended-sediment load at the Coldbrook site: 37 percent in water year 2010, 30 percent in 2011, and 57 percent in 2012. Indeed, Stony Clove Creek accounted for a higher percentage of the load calculated for Coldbrook during 2010 and 2011 than all of the other tributaries combined. The large increase in the percent of load accounted for by Stony Clove Creek during the 2012 water year was probably caused by the channel disturbance associated with streambank stabilization work that followed tropical storm Irene. There were several times throughout 2012 when high turbidity values measured by the in situ probes were not accompanied by increases in stream discharge. Woodland Creek also accounted for a substantial percentage of the load at Coldbrook: 7 percent in 2010, 14 percent in 2011, and 9 percent in 2012. The annual load at the Coldbrook site was 4.8 times greater during water year 2011 than during 2010. The annual load at the Stony Clove Creek site was 3.9 times greater in 2011 than in 2010 (fig. 8). The annual load at the Coldbrook site decreased by a factor of 20 from 2011 to 2012 and was about 4 times less in 2012 than in 2010. The annual sediment load at the Stony Clove Creek site decreased by a factor of 10 from 2011 to 2012 and was nearly 3 times less in 2012 than in 2010.

The suspended sediment load generally increased along the main channel of Esopus Creek from the headwater site at Oliverea to the outlet at Coldbrook. During 2010, the only year when all 4 main stem sites were monitored, the load increased from Oliverea to Allaben by a factor of 26. The suspended sediment load increased slightly from 33,800 tons (short) to 34,800 tons from Esopus Creek at Allaben to Esopus Creek below the aqueduct however most of that increase was accounted for by the Peck Hollow tributary (fig. 8). There was a large increase in the suspended sediment load (89,200 tons) from Esopus Creek below the aqueduct to Esopus Creek at Coldbrook a section of the creek in which several tributaries contribute to the load (fig. 8). These results suggest that the Shandaken Tunnel did not contribute substantially to the suspended sediment load of Esopus Creek during 2010, most likely because the aqueduct is typically closed when turbidity levels are greater than 100 NTU. As a result the tunnel does not contribute to the suspended sediment load of Esopus Creek during storms when the majority of suspended sediment is mobilized. Loads were not calculated for the Esopus below the aqueduct station during 2011 or 2012 because the station was destroyed during tropical storm Irene.

Comparing suspended-sediment loads from differently sized watersheds can be misleading because the largest watersheds typically produce the largest sediment loads. Figure 9 shows the same loads presented in figure 8 as tons per hectare—in other words, the loads have been divided by watershed area (in hectares) to normalize for watershed area. Viewed in this way, Stony Clove Creek produces more sediment per hectare than any other tributary and indeed more than the entire upper Esopus Creek watershed. The contribution from Woodland Creek is also consistently high although not nearly as high as Stony Clove. The per hectare load from each of the different tributaries varies substantially from year to year: the Stony Clove Creek watershed appears to be a chronic source of suspended sediment and turbidity to the Esopus Creek; it produced the most suspended sediment regardless of the hydrologic conditions, whereas the rest of the tributaries do not rank in consistent order in terms of largest to smallest contributors of suspended sediment from year to year.

Relations Between Concentrations of Suspended Sediment and Turbidity

The third objective of the study was to evaluate the relations between SSC and turbidity and to construct sediment and turbidity rating curves for each site. Data from the six sites colocated with long-term USGS streamgaging stations were used for these analyses because these were the stations with the most reliable discharge data (table 2). Discharge data from the other sites were based on 2 years of discharge measurements, and therefore the stage-discharge rating curves from these sites are not as reliable as the curves from the sites with 10 or more years of record. Three types of data were used to examine the relations between SSC and turbidity: suspended-sediment concentrations and turbidity values from discrete sampling (grab samples and samples collected with automatic samplers) that were both analyzed in the laboratory and turbidity values from in situ turbidity probes (fig. 10). The relations between discharge, SSC, and turbidity were also investigated for each station. The relation between discharge and SSC was strongest at the Coldbrook station at the outlet of the upper Esopus Creek watershed and weakest at Hollow Tree Brook (table 2). This pattern was consistent with results from regression analyses of discharge and laboratory turbidity (table 2). The two stations with the lowest SSC and turbidity levels, Little Beaver Kill and Hollow Tree Brook, had the weakest relations to discharge. The two watersheds did not produce high SSC and turbidity, and therefore the concentrations did not increase as strongly with increasing discharge as at the other stations.

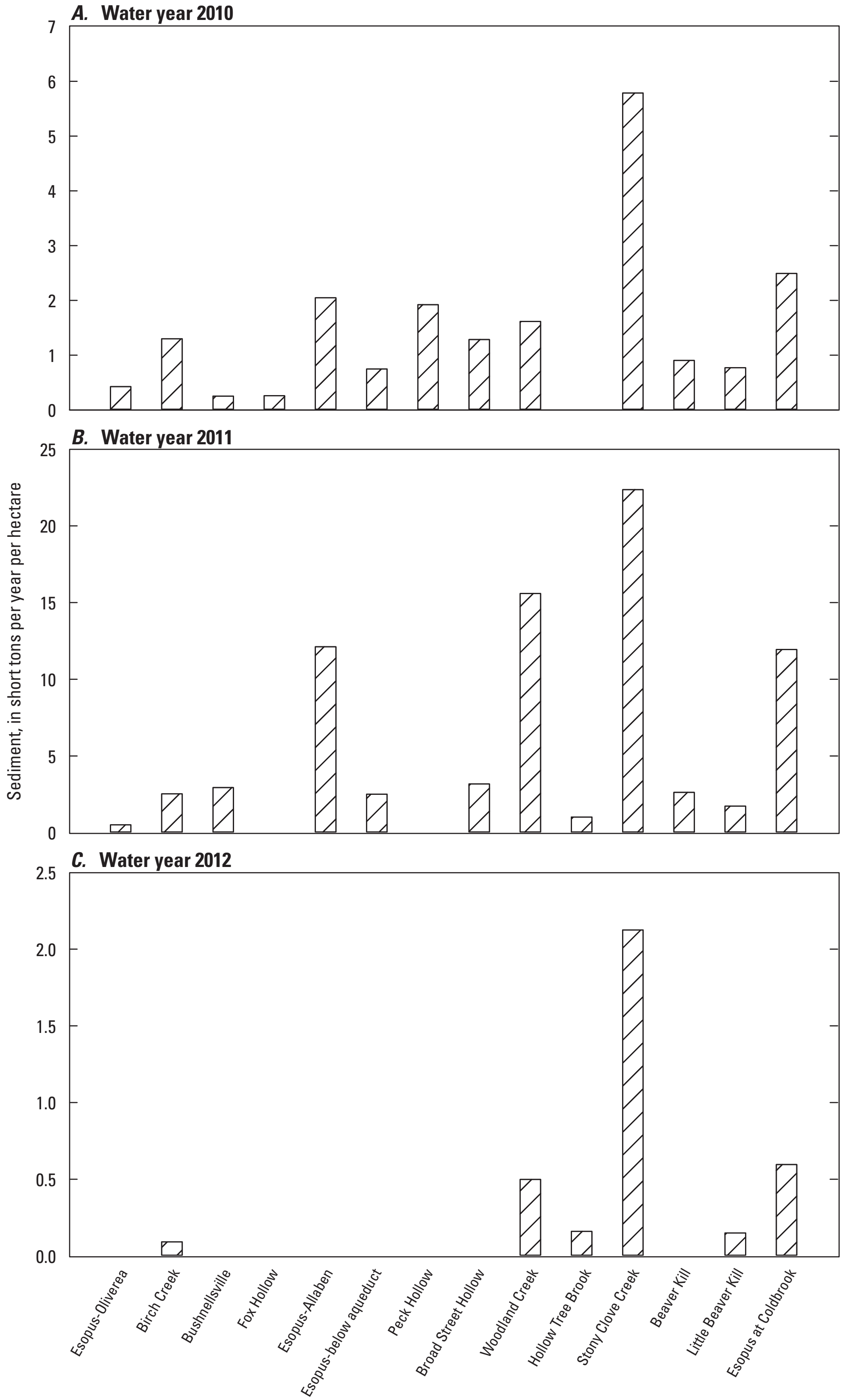


Figure 9. Suspended-sediment loads per unit area (in hectares) for water years *A*, 2010, *B*, 2011, and *C*, 2012 at 14 monitoring sites throughout the upper Esopus Creek watershed. In water year 2012 only six sites were sampled: Birch Creek, Woodland Creek, Hollow Tree Brook, Stony Clove Creek, Little Beaver Kill, and Esopus at Coldbrook. Note the change in scale between years. See figure 2 for site locations.

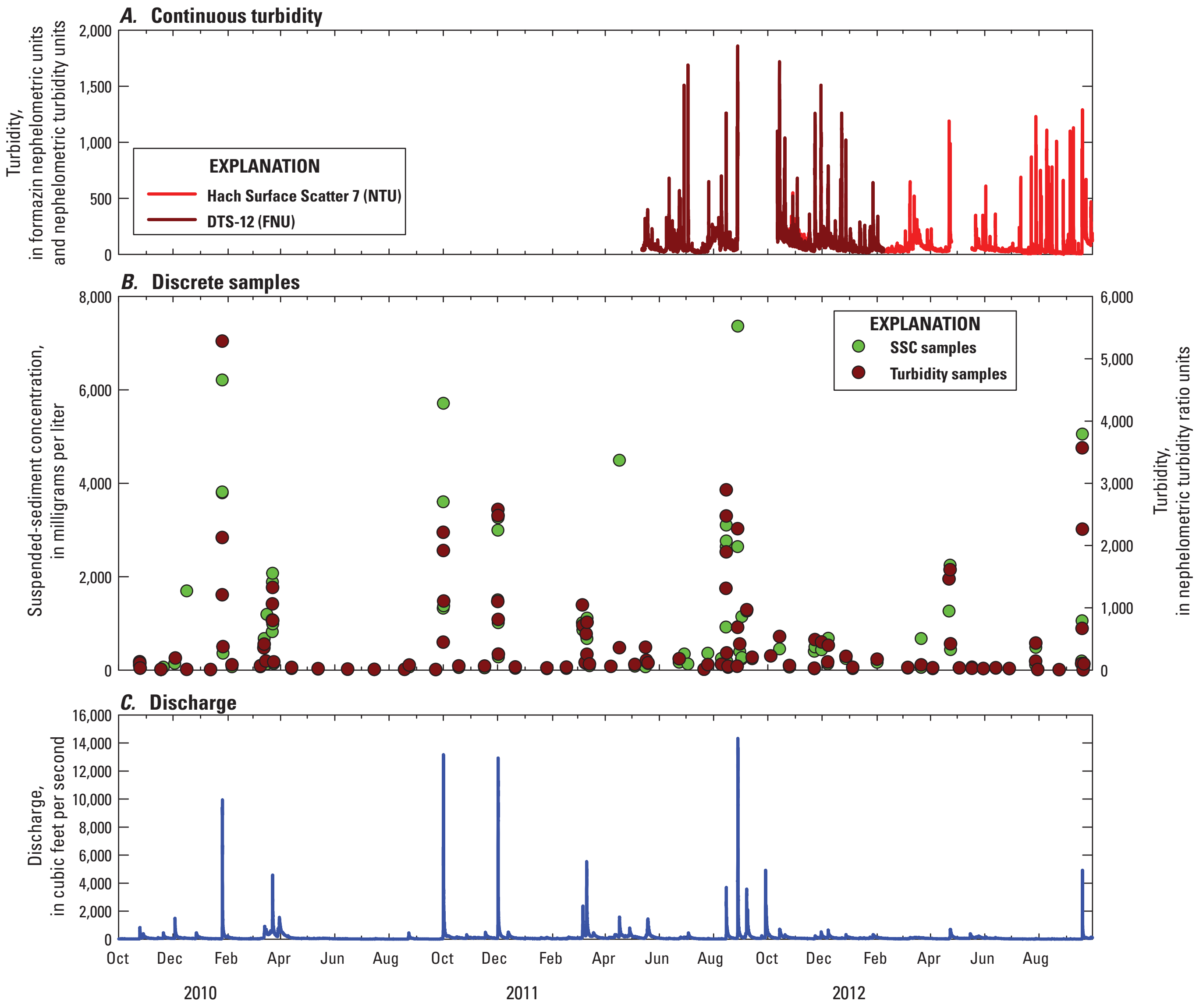


Figure 10. *A*, Continuous turbidity, *B*, discrete samples of suspended-sediment concentration (SSC) and turbidity, and *C*, daily mean flow for the Coldbrook monitoring site (U.S. Geological Survey streamgaging station 01362500). See figure 2 for site location.

In general the stations with the highest concentrations had the strongest relations between discharge and suspended sediment or turbidity; however, this was not true for Stony Clove Creek, which had the highest volume-weighted mean concentrations of any of the watersheds in the study. This inconsistency might be caused by several streambank failures along the length of the stream that might have produced high concentrations throughout the range in flow conditions in the watershed. Therefore, although SSC and turbidity are consistently high at the station, those concentrations are not strongly related to discharge (table 2). Regression results between discharge, SSC, and laboratory turbidity at Birch Creek and Woodland Creek were similar to those calculated for Stony Clove Creek, with r^2 values ranging from 0.57 to 0.75 (table 2). There was a positive relation between discharge and SSC and discharge and turbidity at the stations, but there was a large amount of scatter around the regression line (appendix 1, figs. 1–7—1–15).

Relations between SSC and turbidity are of particular interest because of the potential to use turbidity and SSC as surrogates for one another. Relations between SSC and turbidity from samples analyzed in the laboratory were examined (table 2). The relations were stronger than those calculated for discharge and SSC at all of the sites except Coldbrook, which had the strongest relation between SSC and turbidity of any of the monitoring sites. Regression results showed a strong relation between laboratory turbidity and SSC at all the sites, with r^2 values ranging from 0.72 at Stony Clove Creek to 0.82 at Coldbrook. Hollow Tree Brook, the site with the lowest SSC and turbidity values, was an exception. For Hollow Tree Brook, only three points define the upper end of the regression relation, and there is a wide scatter among them (appendix 1, figs. 1–7—1–15). The relation between SSC and turbidity was also strong when data from all of the sites were considered together with SSC and laboratory turbidity data log-transformed (fig. 11).

In situ turbidity.—One of the primary goals of this study was to evaluate the benefit of measuring turbidity with in situ probes (Hach Surface Scatter 7 and DTS–12) that measure at a much more frequent time interval than can be achieved with automated samplers. A 15-minute measurement interval was used for this study to coincide with the recording interval of stage measurements. The short measurement interval for the probes created a large dataset with which to compare discharge; however, the delay in installing the probes limited the dataset available to evaluate relations between Turb15 (turbidity measured by in situ probes) and SSC and between Turb15 and laboratory turbidity. Regressions between discharge and Turb15 were not as strong as those between discharge and laboratory turbidity (table 2). Most of the stations showed the effects of hysteresis with the more plentiful Turb15 data. Turbidity levels were different at the same discharge within a given storm depending on whether the measurements were taken during the rising limb or the falling limb of the hydrograph (appendix 1, figs. 1–7—1–15). Woodland Creek is a particularly good example of this effect. In addition, there were many times when increases in turbidity were not caused by increases in discharge. The automated samplers were triggered by increases in stream stage, which are highly correlated with increases in discharge, so they did not sample during interstorm periods. Although grab samples were collected during those periods, the in situ probes provided much more data during interstorm periods than the grab samples. A model much more complex than the simple linear model used in this study would need to be developed to predict 15-minute turbidity values from discharge.

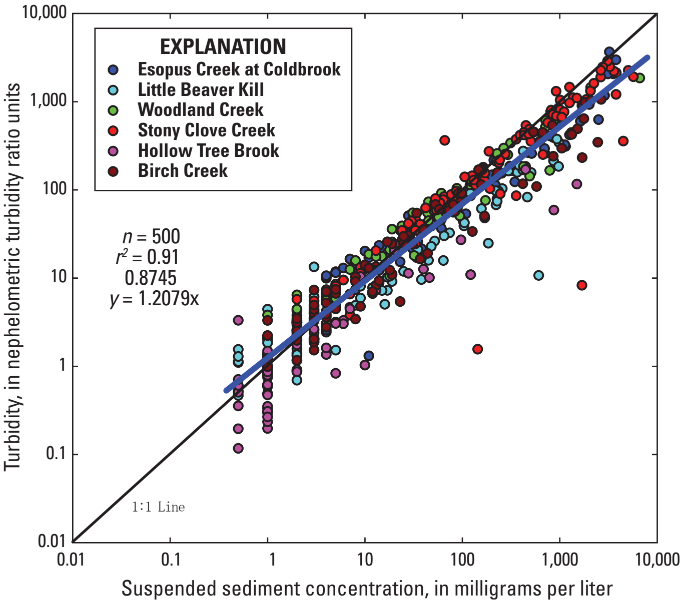


Figure 11. The relation between suspended-sediment concentration and turbidity measured in the laboratory with a Hach 2100AN instrument for data collected from water years 2010–2012 at monitoring sites located at the six long-term U.S. Geological Survey streamgaging stations in the upper Esopus Creek watershed. See figure 2 for site locations. n, number of samples; r^2, coefficient of determination.

Turb15 data were also used to evaluate how well the in situ probes predicted laboratory turbidity measurements and SSC. It is important to note that these results are based on 30 or more data points at Coldbrook, Little Beaver Kill, and Stony Clove Creek, but are based on fewer than 20 data points for Hollow Tree Brook, Woodland Creek, and Birch Creek (table 2). Results from all monitoring sites are included, but results from sites with fewer than 20 data points should be considered cautiously. In fact, these regressions should be considered preliminary for all of the stations because of the short period of record (table 1). Loss of power was also a frequent problem at the sites, especially during large storms; therefore, the SS7s did not always record measurements during the largest storms. Because the samples that correspond with in situ turbidity measurements represent a shorter time period, these samples do not cover the range of discharge measured at each monitoring site; therefore, the regression models are only valid for the range in flow accounted for by these samples (table 3).

Turb15 and laboratory turbidity were strongly related at all sites except Little Beaver Kill (table 2); however, the Little Beaver Kill regression is heavily leveraged by one data point (appendix 1, figs. 1–7—1–15). When that outlier is removed from the dataset, the r^2 value increases from 0.40 to 0.89. In contrast, Hollow Tree Brook and Birch Creek show strong relations between Turb15 and laboratory turbidity, but those regressions are also heavily leveraged by one or two points (appendix 1, figs. 1–7—1–15). For example, the regression calculated for Birch Creek is deceptively strong, with an r^2 of 0.99; however, the relation is heavily leveraged by one high-concentration sample. When the one high-concentration sample is removed from the dataset, the r^2 decreases to 0.66. Although the high concentrations of the few samples from Hollow Tree Brook and Birch Creek are believed to be accurate, more data are required to develop less leveraged models. Turb15 was a strong predictor of laboratory turbidity for the Coldbrook site but less so at Stony Clove Creek (table 2). Turb15 was also a good predictor of laboratory turbidity for the Woodland Creek site for the 17 available data points.

Turb15 was not as good a predictor of SSC as it was for laboratory turbidity at any of the stations (table 2). For Hollow Tree Brook the weak relation between Turb15 and SSC is probably caused by the low concentrations measured at the site and the small dataset available. For Stony Clove Creek the cause of the weak relation between Turb15 and SSC might be the high turbidity values measured at low flow as well as the disturbance from stream stabilization work in the watershed that caused increases in turbidity that were not related to increases in flow. At four of the six sites, Turb15 turbidity is a good predictor of SSC, but additional data are required at all sites to define those relations throughout the full range in flow conditions.

In general, the in situ probes provided a much more robust dataset than the discrete grab and storm samples. The data from the in situ probes were strong predictors of laboratory turbidity at most of the stations although less so for SSC. More data are needed to fully evaluate these relations, but the results of this study suggest that the use of in situ probes works well as a measure of turbidity levels and a predictor of SSC in the upper Esopus Creek watershed. Although evaluating the performance of the two in situ probe types was not an objective of this study, it appears that the Hach Surface Scatter 7 underestimated turbidity levels at the Stony Clove sites as compared with the DTS–12 probe (fig. 3). This was likely caused by the low flow rate required by the SS7 and the need to use a bubble trap, which appeared to allow some suspended sediment to drop out of the water, rather than any shortcoming with the instrument itself. In this region, where power outages frequently occur during large storms, the need for AC power is a disadvantage of the SS7.

Table 3. The range in discharge measured at each U.S. Geological Survey streamgaging station during the study period and the range in discharge accounted for by the samples used in the regression model for suspended-sediment and turbidity analyzed in the laboratory and in the regression model for suspended-sediment and in situ turbidity.

[See figure 2 for streamgaging-station locations. USGS, U.S. Geological Survey; ft^3/s, cubic feet per second; SSC, suspended-sediment concentration, in milligrams per liter; LabTurb, turbidity analyzed in the laboratory; Turb15, turbidity from in situ probes, measured every 15 minutes]

USGS station name	Range in discharge, in ft^3/s		
	During study period	Accounted for by SSC and LabTurb samples	Accounted for by SSC and Turb15 samples
Birch Creek	1.8–1,460	2–1,072	3–267
Woodland Creek at Phoenicia	2.5–6,460	3–4,179	8.5–854
Hollow Tree Brook	0.42–487	0.6–295	0.6–406
Stony Clove Creek at Chichester	4.2–14,300	7–4,428	7–9,562
Little Beaver Kill at Beechford	0.59–2,530	1–1,935	1.5–1,935
Esopus Creek at Coldbrook	135–75,800	187–43,450	240–4,891

Summary

The U.S. Geological Survey, in cooperation with the New York City Department of Environmental Protection, New York State Department of Environmental Conservation, and Cornell Cooperative Extension of Ulster County, investigated spatial and temporal patterns of suspended-sediment concentration (SSC) and turbidity in the upper Esopus Creek watershed in the Catskill Mountains of New York State, estimated suspended-sediment loads at 14 monitoring sites throughout the watershed, and investigated the relations between SSC and turbidity in the watershed. Continuous turbidity monitoring (measuring turbidity every 15 minutes) was used to evaluate patterns in turbidity at six sites and to compare to laboratory turbidity measurements. The flow conditions varied widely among the 3 years of the study, so temporal patterns were difficult to discern at all of the sites. Data from this study were combined with data collected during a 7-year water-quality-monitoring study that included the Hollow Tree Brook and Stony Clove Creek sites. The combined datasets showed that, during this most recent study period (2010 to 2012), flows were generally higher than in the past and resulted in higher SSC and turbidity values. Stony Clove Creek had the highest SSC and turbidity values of any of the tributaries in the upper Esopus Creek watershed, and these values were in fact higher than the values measured at Coldbrook, the watershed outlet. Beaver Kill, Birch Creek, and Woodland Creek also had high SSC and turbidity values, but they were only a fraction (15 to 50 percent) of those measured at Stony Clove Creek. Still, concentrations at those tributaries were often as high as those measured at the Allaben site on the main stem of the Esopus Creek. High SSC and turbidity levels were measured at Beaver Kill, Birch Creek, and Woodland Creek during the study, but the high concentrations were of short duration. Turbidity values and SSCs were rarely high at the headwater site on the Esopus main channel at Oliverea, Hollow Tree Brook, and Little Beaver Kill.

Stony Clove Creek produced the largest suspended-sediment loads of any of the Esopus Creek tributaries; it accounted for 30 to 57 percent of the annual suspended-sediment load at the upper Esopus Creek watershed outlet at Coldbrook. Woodland Creek, Beaver Kill, and, to a lesser extent, Birch Creek also contributed substantial amounts of sediment to the upper Esopus Creek. Annual sediment yields (load per unit area) were higher for Stony Clove Creek than any other site in the upper Esopus Creek watershed, including the outlet at Coldbrook. Annual sediment yields were also consistently high at Woodland Creek compared to yields from tributaries other than Stony Clove Creek. Birch Creek, Bushnellsville Creek, Broadstreet Hollow, and Beaver Kill all had sediment yields that were fairly comparable to one another during the study.

The relations among SSC, laboratory turbidity, and discharge varied among the monitoring sites; the strongest were calculated for the watershed outlet at Coldbrook. The relations between discharge and SSC and between discharge and laboratory turbidity were not as strong as the relations between SSC and laboratory turbidity for any of the sites except Coldbrook, for which the relation between SSC and discharge was very strong (coefficient of determination (r^2) of 0.91). The regressions between SSC and in situ turbidity were not as strong as those between SSC and laboratory turbidity partly because there were fewer in situ samples to compare. Data from in situ probes measuring turbidity at 15-minute intervals were strongly related to laboratory turbidity levels although less strongly to SSC. The in situ probes provided much more detailed data about the relation between discharge and turbidity at each station than did grab samples and samples collected using automated samplers. As a result, the relations between discharge and in situ turbidity were not as strong as those between discharge and laboratory turbidity for any of the sites. This difference was caused by hysteresis that is apparent in the more plentiful in situ data but not as obvious in data from discrete samples. Consequently, the linear models developed for the relations between discharge and in situ turbidity are not reliable predictors of turbidity levels. Additional data and more complex models are required to reliably predict turbidity from discharge measurements at theses monitoring sites. More data are also required, throughout the range in flow conditions, before SSC can be reliably predicted from turbidity data collected at 15-minute intervals by in situ turbidity probes. Nonetheless, the probes hold great promise in this watershed where most of the turbidity is caused by inorganic particles.

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Appendix 1. Suspended-Sediment Concentration, Turbidity, and Discharge

Time Series

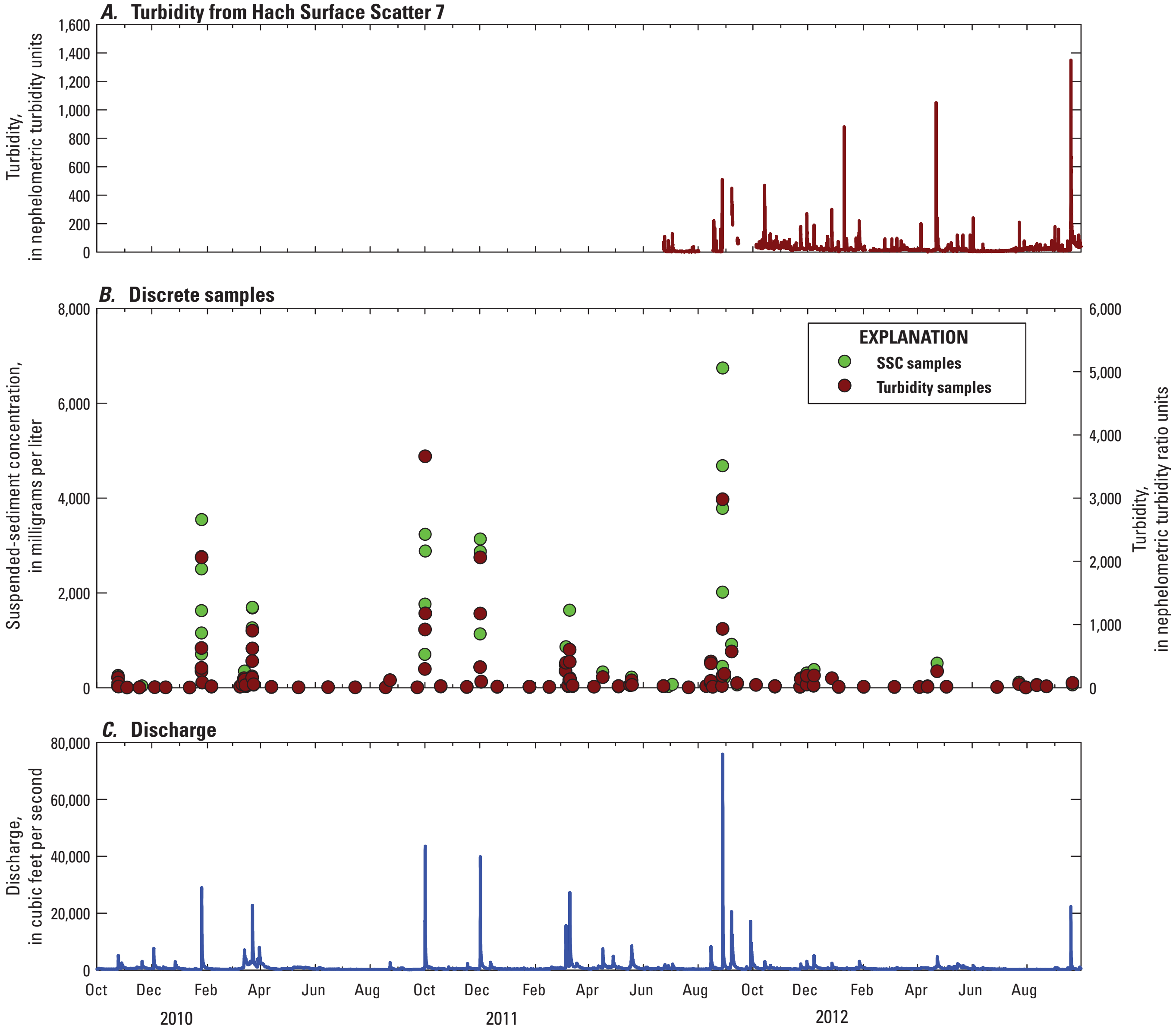

Figure 1–1. *A*, Continuous turbidity (measured by the Hach Surface Scatter 7 flow-through system), *B*, discrete samples of suspended-sediment concentration (SSC) and turbidity, and *C*, daily mean flow for the Coldbrook monitoring site (U.S. Geological Survey streamgaging station 01362500). See figure 2 for site location.

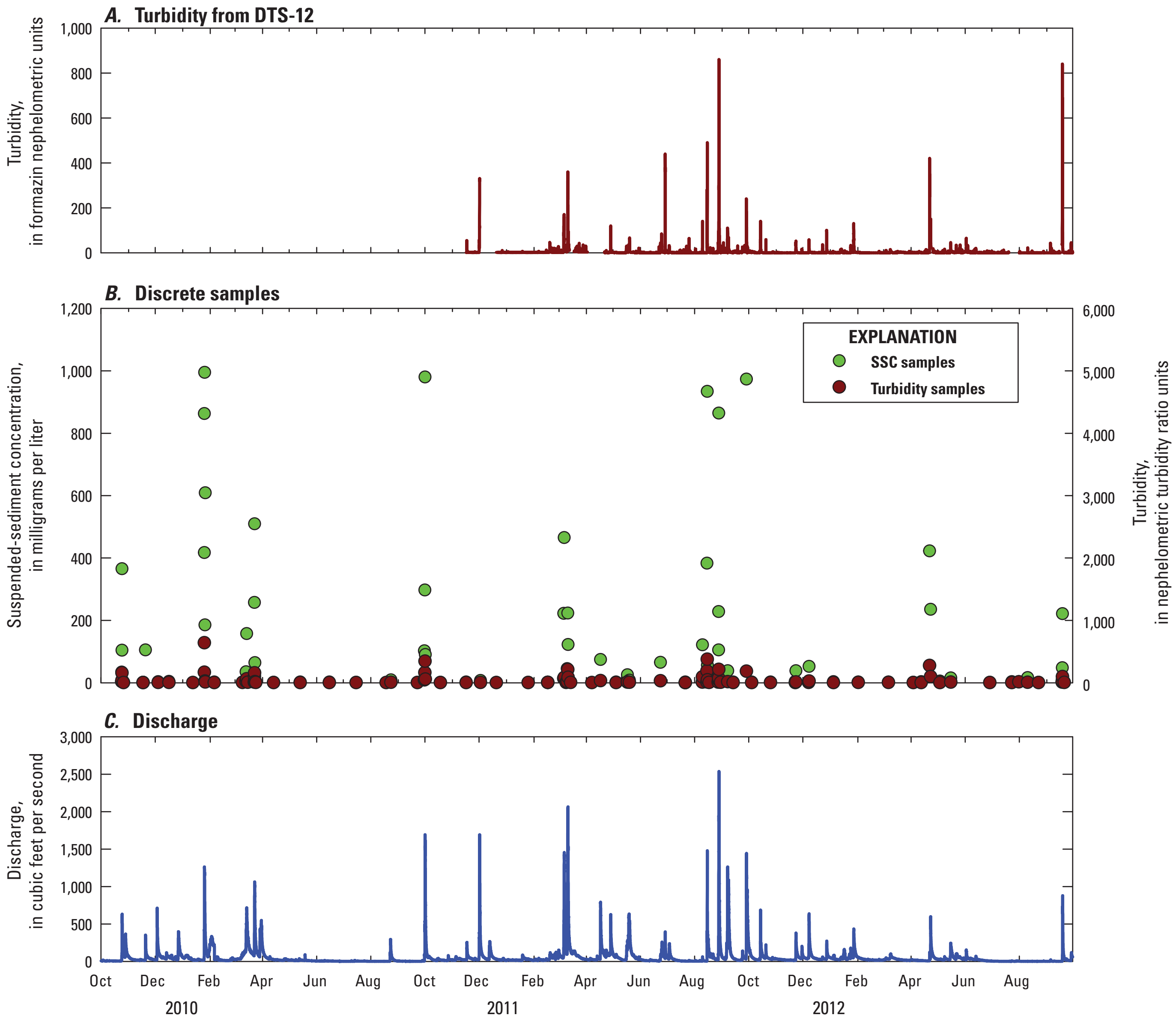

Figure 1–2. *A*, Continuous turbidity (measured by the DTS–12 in situ probe), *B*, discrete samples of suspended-sediment concentration (SSC) and turbidity, and *C*, daily mean flow for the Little Beaver Kill monitoring site (U.S. Geological Survey Station Number: 01362497). See figure 2 for site location.

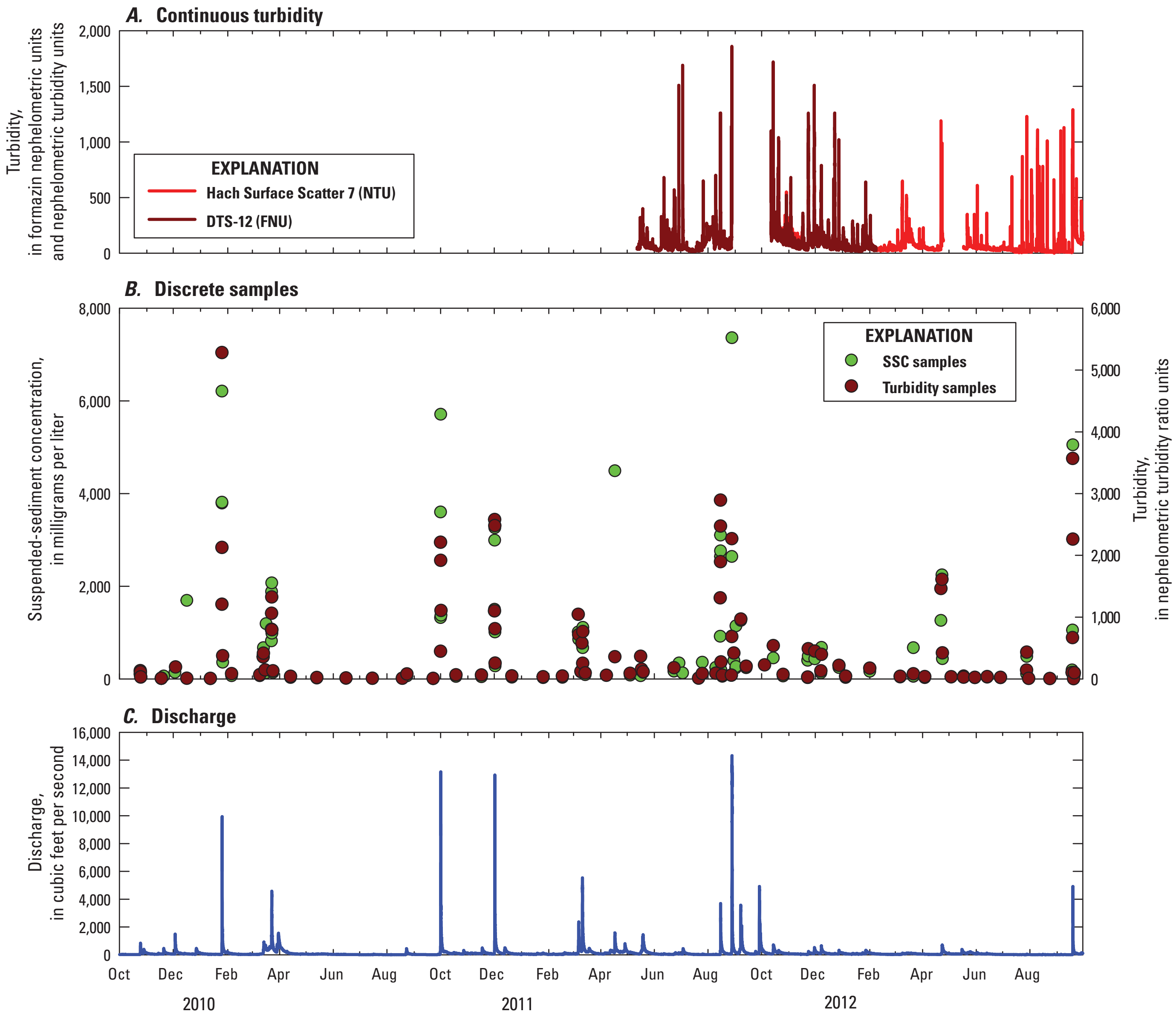

Figure 1–3. *A*, Continuous turbidity (measured by the Hach Surface Scatter 7 flow-through system and DTS–12 in situ probe), *B*, discrete samples of suspended-sediment concentration (SSC) and turbidity, and *C*, daily mean flow for the Stony Clove Creek monitoring site (U.S. Geological Survey Station Number: 01362370). See figure 2 for site location.

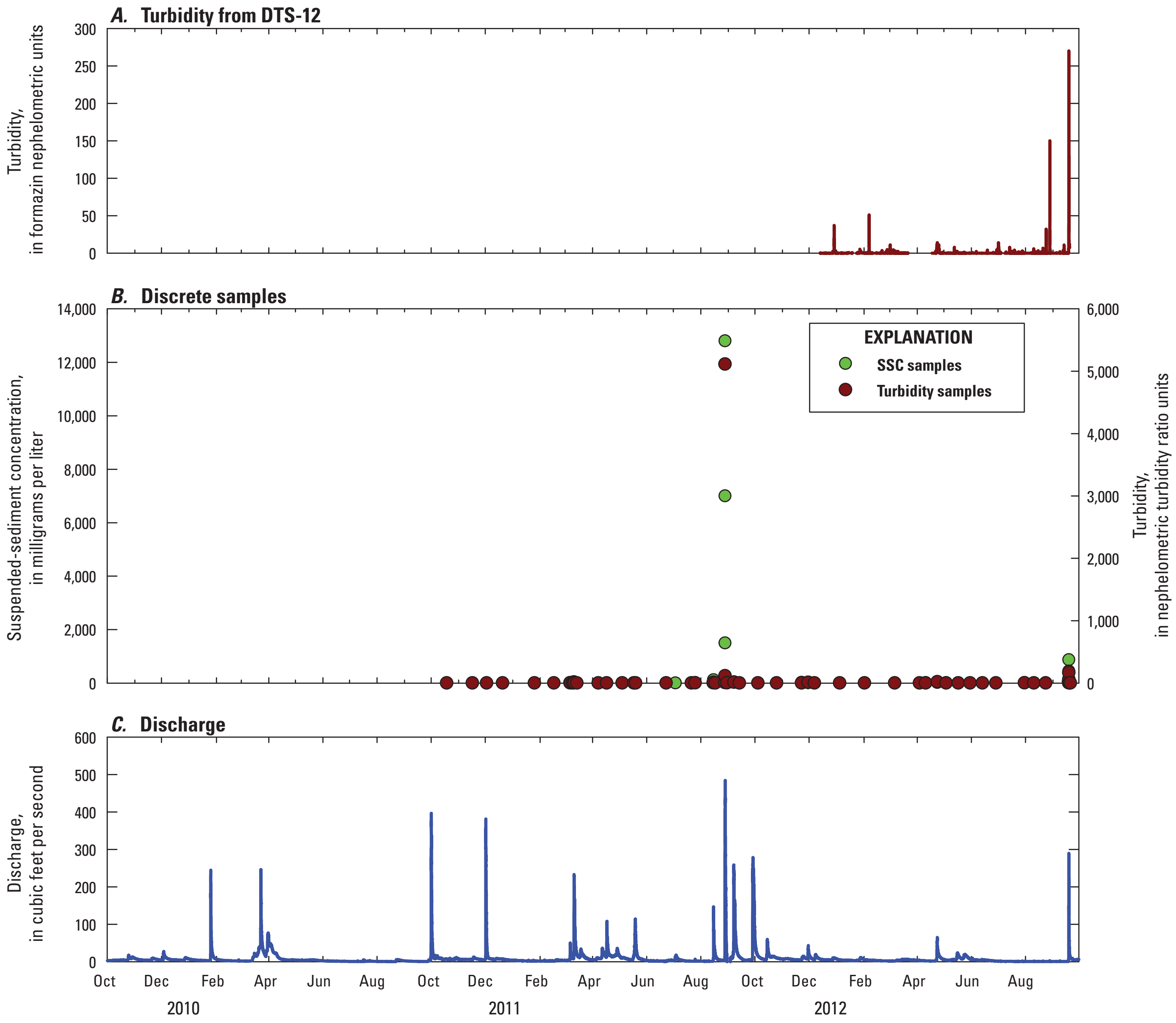

Figure 1–4. *A*, Continuous turbidity (measured by the DTS–12 in situ probe), *B*, discrete samples of suspended-sediment concentration (SSC) and turbidity, and *C*, daily mean flow for the Hollow Tree Brook monitoring site (U.S. Geological Survey streamgaging station 01362342). See figure 2 for site location.

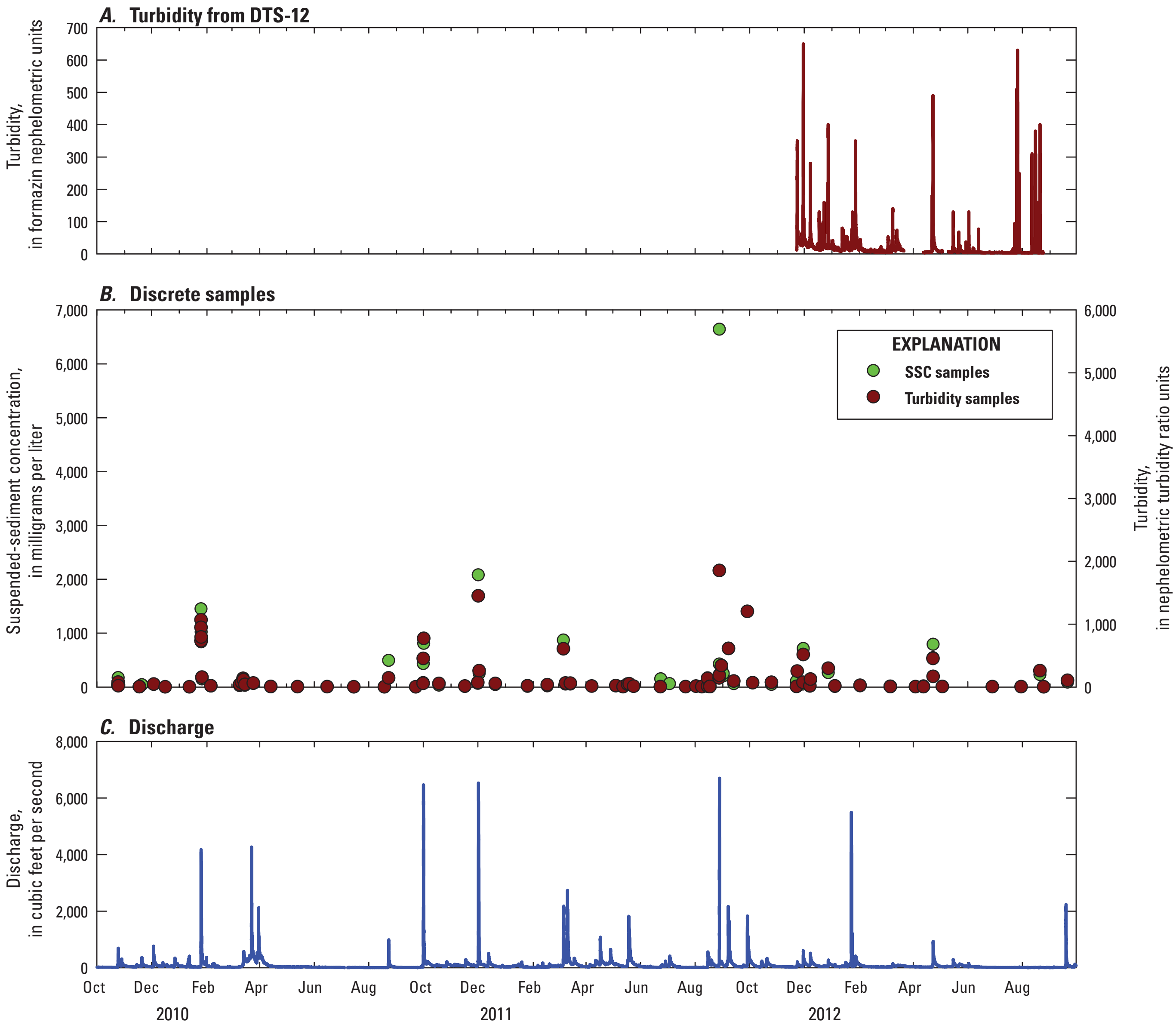

Figure 1–5. *A*, Continuous turbidity (measured by the DTS–12 in situ probe), *B*, discrete samples of suspended-sediment concentration (SSC) and turbidity, and *C*, daily mean flow for the Woodland Creek monitoring site (U.S. Geological Survey streamgaging station 0136230002). See figure 2 for site location.

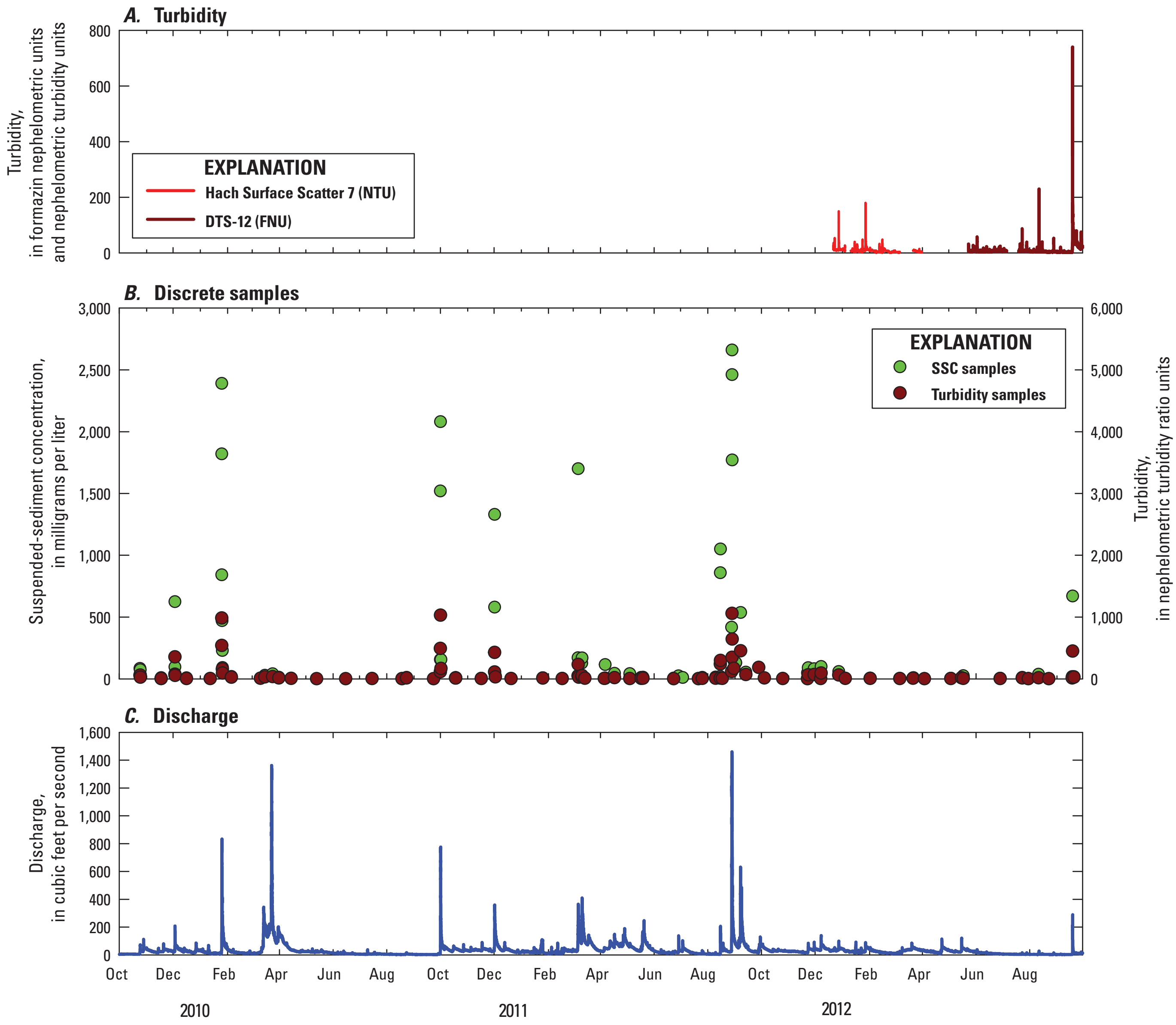

Figure 1–6. *A*, Continuous turbidity (measured by the Hach Surface Scatter 7 flow-through system and DTS–12 in situ probe), *B*, discrete samples of suspended-sediment concentration (SSC) and turbidity, and *C*, daily mean flow for the Birch Creek monitoring site (U.S. Geological Survey streamgaging station 013621955). See figure 2 for site location.

Linear Regressions

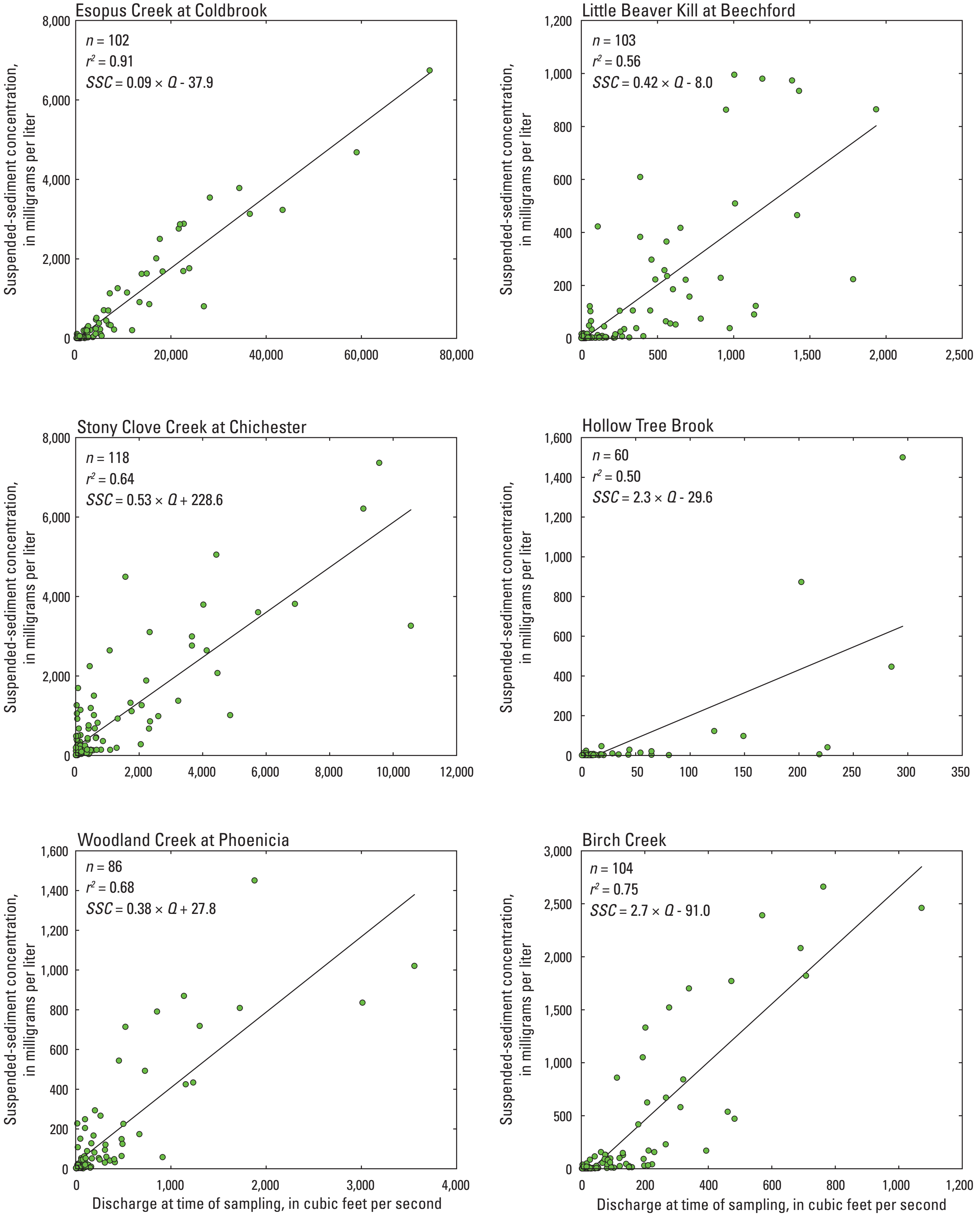

Figure 1–7. Relations between suspended-sediment concentration (SSC) and discharge (Q) at U.S. Geological Survey monitoring sites in the upper Esopus Creek watershed for water years 2010 to 2012. n, number of samples; r^2, coefficient of determination.

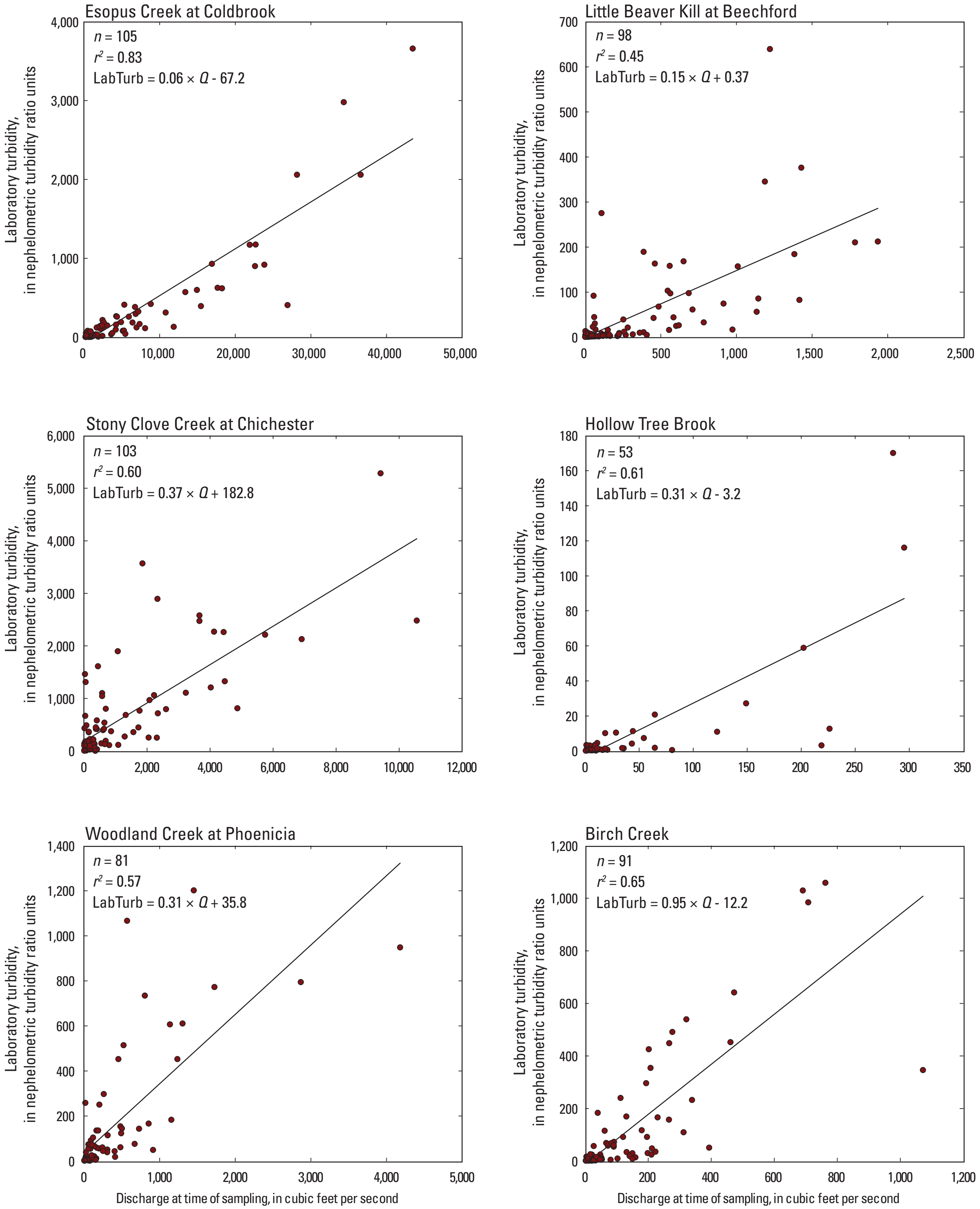

Figure 1–8. Relations between laboratory turbidity measured with a Hach 2100AN Turbidimeter (LabTurb) and discharge (Q) at U.S. Geological Survey monitoring sites in the upper Esopus Creek watershed for water years 2010 to 2012. n, number of samples; r^2, coefficient of determination.

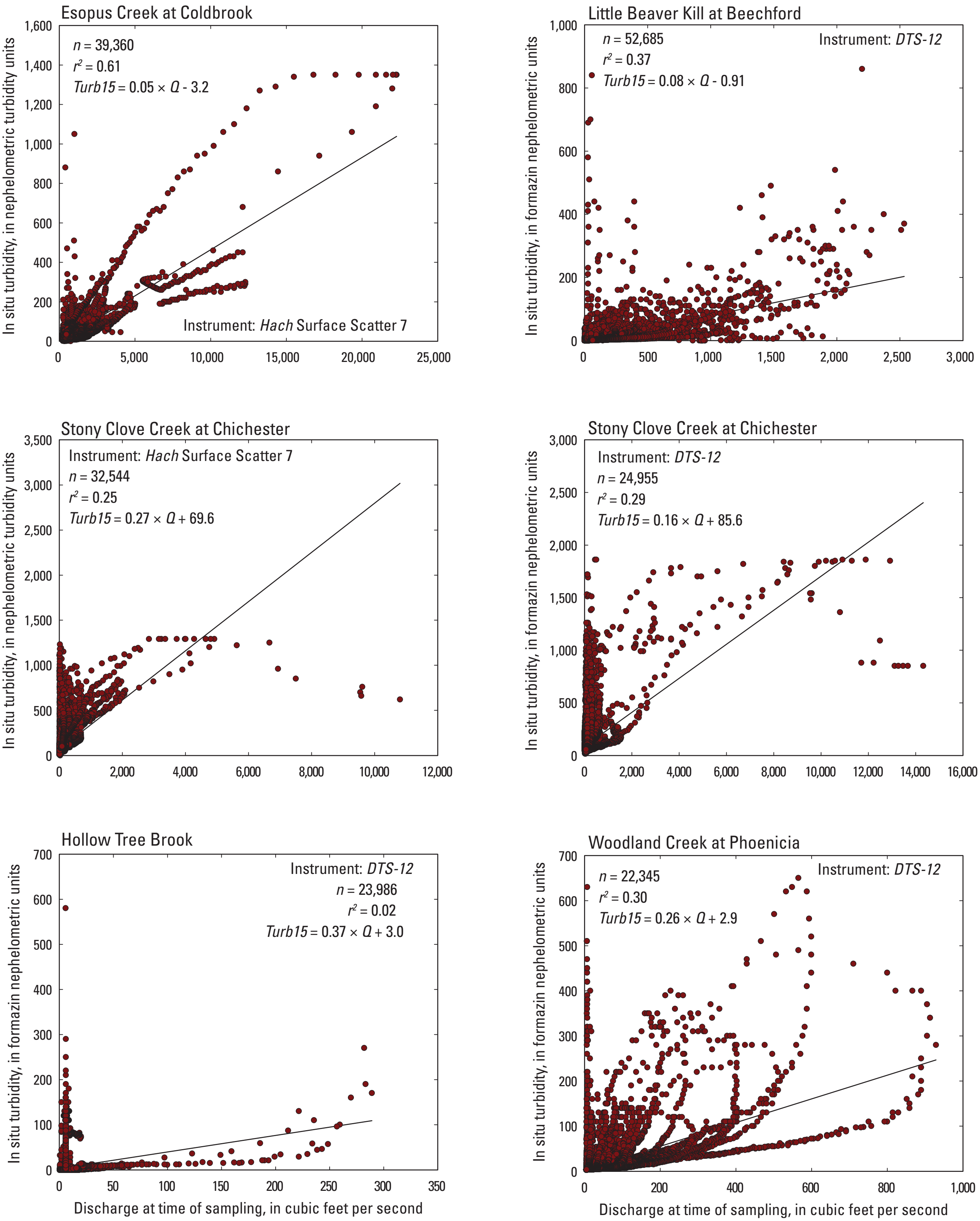

Figure 1–9. Relations between turbidity measured with DTS–12 or Hach Surface Scatter 7 in situ probes (Turb15) and discharge (Q) at U.S. Geological Survey monitoring sites in the upper Esopus Creek watershed. Instrument type is specified for each plot. n, number of samples; r^2, coefficient of determination.

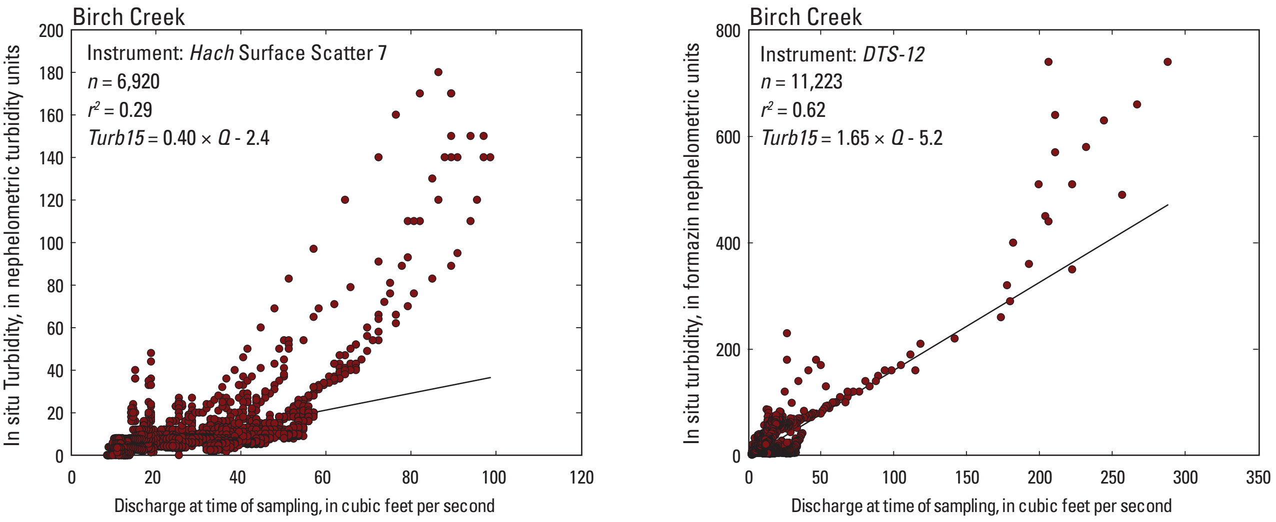

Figure 1–9. Relations between turbidity measured with DTS–12 or Hach Surface Scatter 7 in situ probes (Turb15) and discharge (Q) at U.S. Geological Survey monitoring sites in the upper Esopus Creek watershed. Instrument type is specified for each plot. n, number of samples; r^2, coefficient of determination.—Continued

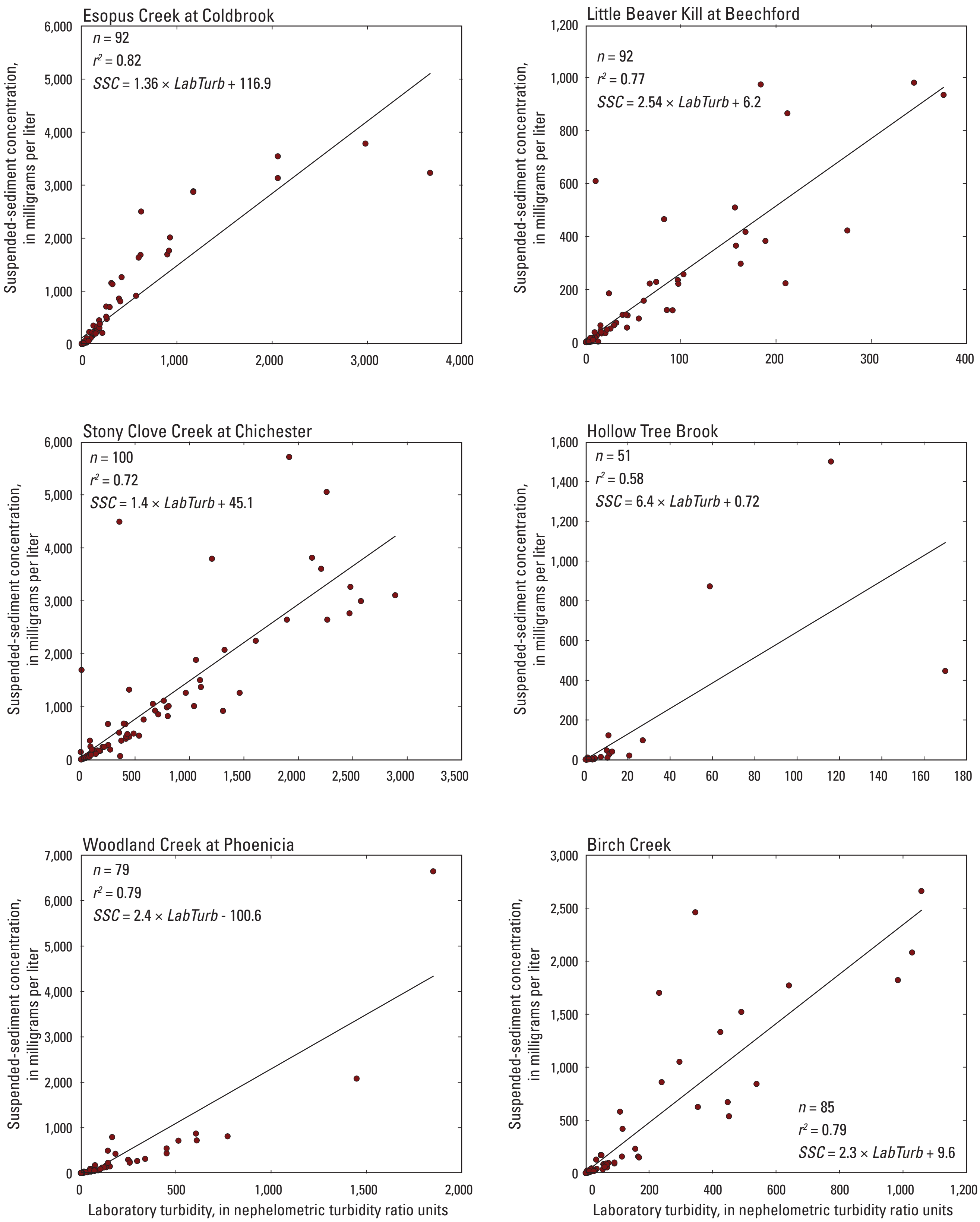

Figure 1–10. Relations between laboratory turbidity measured with a Hach 2100AN Turbidimeter (LabTurb) and suspended-sediment concentration (SSC) at U.S. Geological Survey monitoring sites in the upper Esopus Creek watershed for water years 2010 to 2012. n, number of samples; r^2, coefficient of determination.

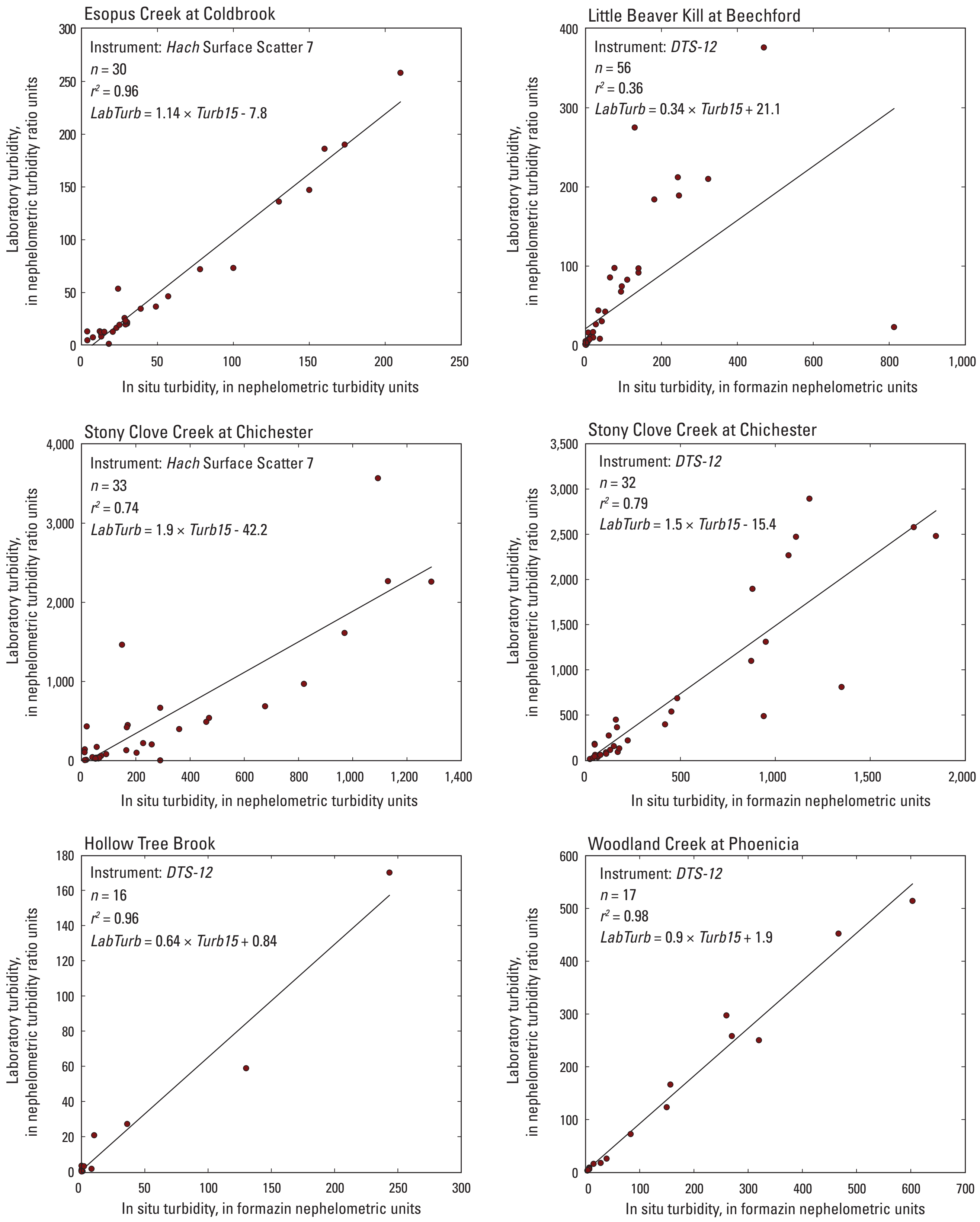

Figure 1–11. Relations between turbidity measured with DTS–12 or Hach Surface Scatter 7 in situ probes (Turb15) and laboratory turbidity measured with a Hach 2100AN (LabTurb) at U.S. Geological Survey monitoring sites in the upper Esopus Creek watershed. Instrument type is specified for each plot. n, number of samples; r^2, coefficient of determination.

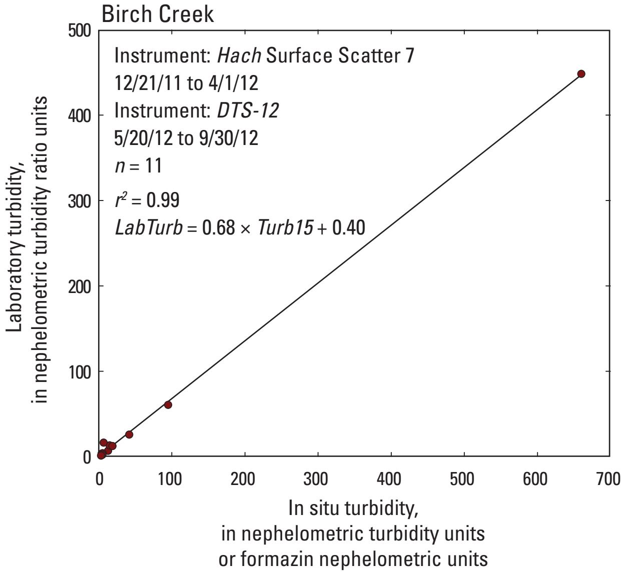

Figure 1–11. Relations between turbidity measured with DTS–12 or Hach Surface Scatter 7 in situ probes (Turb15) and laboratory turbidity measured with a Hach 2100AN (LabTurb) at U.S. Geological Survey monitoring sites in the upper Esopus Creek watershed. Instrument type is specified for each plot. n, number of samples; r^2, coefficient of determination.—Continued

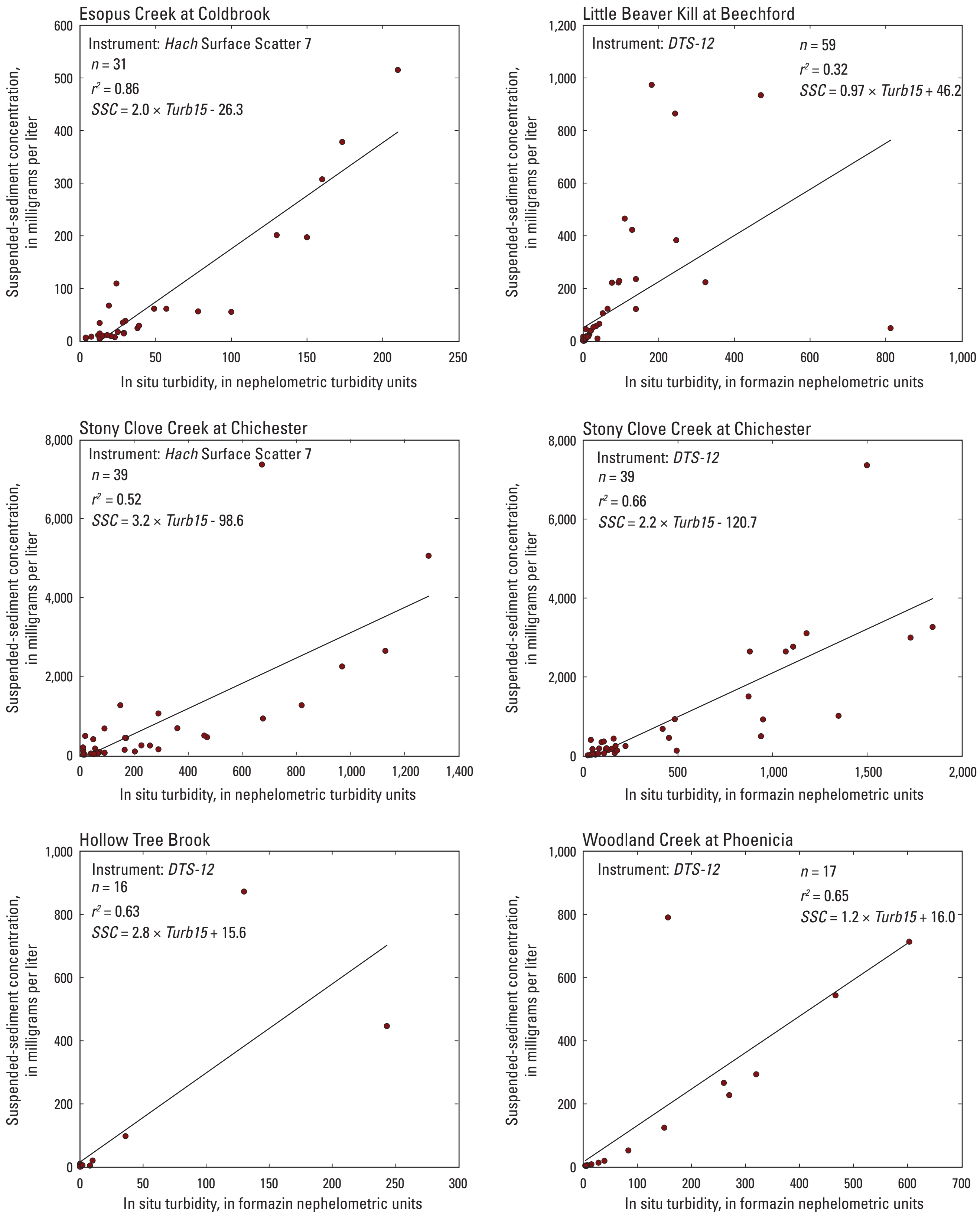

Figure 1–12. Relations between turbidity measured with DTS–12 or Hach Surface Scatter 7 in situ probes (Turb15) and suspended-sediment concentration (SSC) at U.S. Geological Survey monitoring sites in the upper Esopus Creek watershed. Instrument type is specified for each plot. n, number of samples; r^2, coefficient of determination.

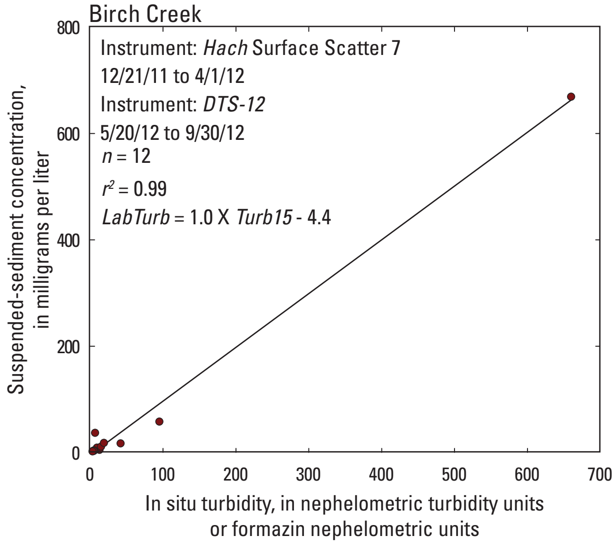

Figure 1–12. Relations between turbidity measured with DTS–12 or Hach Surface Scatter 7 in situ probes (Turb15) and suspended-sediment concentration (SSC) at U.S. Geological Survey monitoring sites in the upper Esopus Creek watershed. Instrument type is specified for each plot. n, number of samples; r^2, coefficient of determination.—Continued

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