New York City Department of Environmental Protection
Bureau of Water Supply

Stream Management Program
Upper Esopus Creek Watershed Turbidity/Suspended Sediment Monitoring Study: Biennial Status Report

March 2021

Prepared in accordance with Section 4.6 of the NYSDOH
2017 Filtration Avoidance Determination

Prepared by: DEP, Bureau of Water Supply

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1. Introduction

1.1 Background

The 2017 Filtration Avoidance Determination (FAD) requires the New York City Department of Environmental Protection (DEP) Stream Management Program (SMP) to continue data collection and analysis for the Esopus Creek Watershed Turbidity/Suspended Sediment Study ("the Study") initiated in 2016. The 2017 FAD further requires DEP to submit biennial reports on the status of this research every other March, along with a five-year summary report of research findings due in November 2022 and a final report due in November 2027.

DEP's first biennial status report in March 2019 covered the study period from United States Geological Survey (USGS) water years 2017 through 2018. This is the second biennial status report and covers the monitoring period through USGS water year 2020 with some reporting on hydrology and geomorphology covering the remainder of calendar year 2020. USGS water years begin on October 1 of a given year and continue through to September 30 of the following year. The water year is numbered based on the concluding year. Thus, water year 2020 ends on September 30, 2020.

On December 25, 2020, a flood occurred in the Ashokan Reservoir basin that measurably impacted turbidity dynamics and also impacted the research monitoring infrastructure. The flow occurred during winter conditions, thereby limiting field investigation, and subsequent hydrological and water quality monitoring data is still under review. While this report cannot adequately cover the impact of that flood on the research given the timing of the event near the very end of the reporting period, its significance merits some brief discussion in this report.

1.2 Study Overview

DEP is collaborating with USGS on this 10-year research project to potentially answer the following New York City water supply resource management questions:

- What are the primary sub-basin sources and causal factors influencing turbidity delivered to the Ashokan Reservoir?
- Can stream management practices reduce stream turbidity and suspended sediment delivered to the Ashokan Reservoir?

The Upper Esopus Creek drainage basin (UEC basin) is the principal source of water to the Ashokan Reservoir and is the focus of this research effort. The monitoring-based research uses streamflow, turbidity and suspended sediment monitoring, source investigation methods, and stream restoration projects to inform turbidity reduction management strategies and evaluate stream turbidity reduction efficacy across a range of spatial, temporal and hydrologic scales. The Study monitoring started in water year 2017 and will continue through water year 2026 before DEP submits a final research report per the FAD in November 2027.

DEP funds the Ashokan Watershed Stream Management Program (AWSMP) to develop and implement stream management strategies and practices in the UEC basin, in large part to reduce stream-sourced turbidity which is a priority water quality parameter for DEP. In Catskill streams, turbidity is a function of the concentration of suspended sediment (SS) in streamflow. The primary means for stream turbidity reduction is through stream restoration projects, referred to in the Study as sediment turbidity reduction projects (STRPs). Esopus Creek serves as a representative model fluvial system to investigate SS and turbidity source dynamics at the basin to sub-basin scale because of its extensive glacially derived sources of clay and silt which generate turbidity disproportionately in the Ashokan Basin. Stony Clove Creek is the largest tributary to Esopus Creek and serves as an experimental sub-basin system to investigate SS and turbidity source dynamics as well as STRP efficacy at the reach to sub-basin scale.

In July 2016, DEP entered into a five-year agreement with USGS to initiate this Study, although work toward this research goes back to at least 2001. USGS is responsible for: (1) monitoring and analyzing streamflow (Q), SS concentration (SSC), and turbidity; (2) evaluating STRP impacts on monitored turbidity and SS flux (SSC*Q); and (3) testing SS fingerprinting as a source sediment characterization technique in the Study area. DEP is responsible for: (1) research project coordination and FAD reporting; (2) geologic and geomorphologic investigations; and (3) funding design, construction and monitoring of STRPs in the Stony Clove sub-basin through an agreement with Ulster County Soil and Water Conservation District (UCSWCD). The AWSMP further supports this Study through research grants administered by Cornell Cooperative Extension of Ulster County (CCEUC).

The Study design addresses three areas that will inform DEP's long-term efforts to protect and improve source water quality:

- Characterize how primary UEC sub-basins vary in terms of turbidity, SS flux (sediment transport rate) and yield (sediment transported per unit area). How do observed differences between sub-basins change under a range of flow and sediment source conditions and over time? How can characterization of this variability inform stream management strategies?
- Using the Stony Clove as a model sub-basin, characterize how different stream segments (monitoring reaches) vary in terms of turbidity, SS flux and yield within the same sub-basin. What are the reach-scale conditions and processes that lead to heterogeneous yields, and how can understanding of these inform STRP siting and design?
- Using the Stony Clove sub-basin SS and turbidity monitoring data, evaluate the effectiveness of existing and future STRPs on reducing turbidity, SS flux and yield from the monitoring reach to sub-basin scale across a range of flows. To what extent can SS and turbidity associated with different sediment sources, channel conditions and processes be sustainably managed within the stream system? By changing sediment connectivity source conditions (e.g., separating a channel from a hillslope SS source) can the functional connectivity (e.g., SS flux) be measurably changed?

Most of the water quality parameters monitored in this Study have been introduced and defined above. To ensure clarity of terminology, DEP has defined the key parameters discussed throughout this report as follows:

- **Streamflow (Q)**: the velocity and volume of water flowing in a stream channel; sometimes referred to as channel runoff, stream discharge. Units are expressed in volume/time. In this report, the units are cubic feet per second (cfs).
- **Turbidity**: an optical property that is the measure of relative clarity of a liquid and is affected by solids suspended in the water scattering light. In Catskill streams, the suspended solids are typically fine sediment. Units used in this report are formazin nephelometric units (FNUs) based on the monitoring equipment.
- **Suspended sediment (SS)**: the sediment transported by water that is fine enough for fluid dynamics to keep the particles from settling. This is typically silt and clay, but can include sand during high velocity streamflow.
- **Suspended sediment concentration (SSC)**: the sampled mass of SS in a unit volume of water. This will be a function of available sediment grain size and velocity or capacity of flowing water to transport sediment. Units used in this report are USGS standard units of mg/L.
- **Suspended sediment load (SS load)**: the mass of sediment that the streamflow transfers downstream over some specified range in time, typically days or years. Units of sediment load are generally expressed in volume/time (e.g., tons/year).
- **Suspended sediment flux (SS flux)**: the transfer of a mass (or volume) of sediment through the fluvial system; it is sometimes referred to as sediment discharge (Qs) and can be expressed in the same units as sediment load. SS flux is used in this report as a process-based term when referring to the transfer of sediment through the stream system.
- **Suspended sediment yield (SS yield)**: refers to the quantity of sediment that reaches an observation point from stream reach to basin outlet scale. It is often computed as sediment load divided by the drainage area upstream of the observation point. Units are often expressed in mass/area. Yield is discussed but no data is presented in this report.

1.3 Study Area

Upper Esopus Creek is the section of Esopus Creek above the Ashokan Reservoir in the south-central Catskill Mountains of New York State, draining 192 mi^2 of mostly forested high relief terrain (Figures 1.1 and 1.2). Elevation in the UEC basin ranges from 4,180 feet above sea level (asl) at Slide Mountain to 585 feet asl at the Ashokan Reservoir. There are 21 mountain peaks in the basin with elevations greater than 3,000 feet asl, creating a high topographic relief catchment basin.

The stream network that drains this mountainous terrain is a high gradient/high energy mountain stream system. Streams are coarse-bedded, predominantly composed of gravel- to boulder-sized sediment, and range in stream type from pool-riffle in the lower gradient reaches to step-pool and cascade in the higher gradient reaches. The network includes 10 primary sub-basin streams that contribute to Esopus Creek (Table 1.1; Figure 1.1). The Study monitoring network includes eight of the 10 sub-basin streams, excluding Fox Hollow and Peck Hollow. Several headwater sub-basins in the upper portion of the UEC basin are grouped into the "Esopus Headwaters" sub-basin. There are three Study monitoring stations on Esopus Creek, including the long-term station in Boiceville, just upstream of the Ashokan Reservoir.

Historical annual precipitation rates in the Catskill Mountain region range between 39 and 63 inches (Frei and Kelly-Voicu 2017). The higher range is associated with the south-central and eastern Catskills due to orographic effects and the southeastern track of many high precipitation storms. The mountainous and rocky terrain magnifies flooding from heavy precipitation events, enhancing precipitation and maximizing runoff amount and velocity (Matonse and Frei 2013). The primary disturbance regime that influences turbidity dynamics in the fluvial system is storm event flood hydrology. On a seasonal basis, rainfall-induced snowmelt streamflow has produced some of the biggest floods in the UEC basin.

Catskill mountain bedrock in the study area is sedimentary, composed of a repeating sequence of Devonian-aged fluvial sandstones, mudstones and conglomerates (Ver Straeten 2013). The typically reddish mudstone is the principal source rock for the silts and clays that comprise Catskill stream turbidity. The stream drainage network that has formed over geologic time is structurally influenced by the bedrock lithology and orientation of bedrock fractures.

Like many mountainous regions in the northeastern U.S., the Catskills experienced repeated glaciation during the Pleistocene, leaving a glacially conditioned landscape enriched in SS source sediment (Rich 1935; Cadwell 1986; Nagle et al. 2007; Yellen et al. 2014). In the UEC basin, Pleistocene glaciation mantled the bedrock with fine-grained sediment in glacial till and glacial lake meltwater deposits. Catskill streams are still processing this legacy sediment, eroding into and entraining glacial deposits in both confined river corridors and glacially formed valley bottoms, yielding very turbid streamflow during and following hydrologic disturbances.

Most of the human population in the UEC basin resides in the valley bottoms and lower slopes of the mountains. This co-existence between streams and people - and associated infrastructure - in the limited real estate of the valley bottoms imposes limitations on the streams' ability to respond to high flow events. Most streams in the UEC basin are not pristine wild streams; they have instead been shaped by historic and ongoing land use/land cover conditions as well as direct and indirect stream management practices. The AWSMP has produced several stream management plans for UEC basin streams that include more detail on the human impacts to the stream system and on Study area physiography, hydrology, geology and geomorphology (www.ashokanstreams.org).

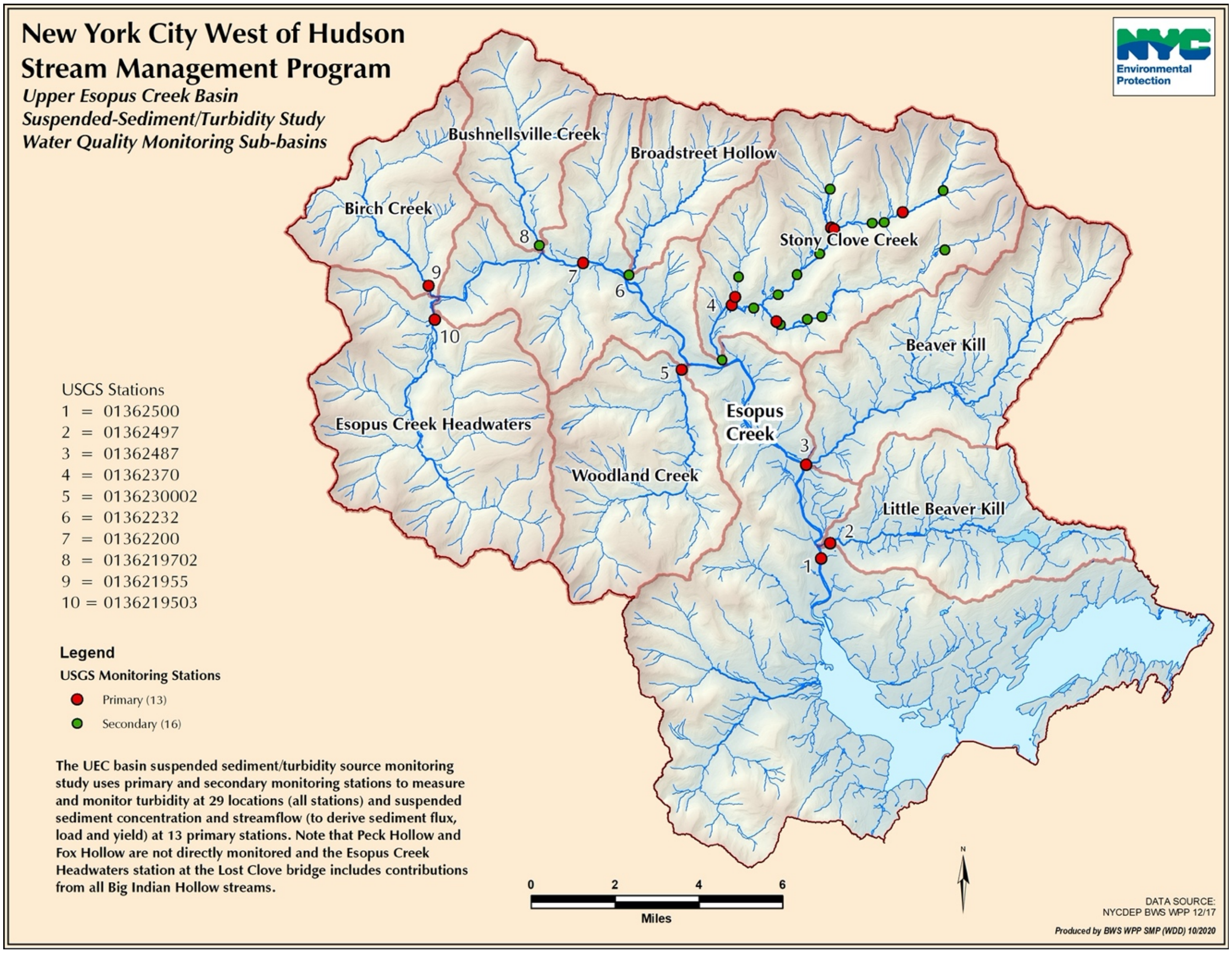


Figure 1.1 UEC basin study area with USGS water quality monitoring stations.

Figure 1.2 The UEC basin looking north from the Esopus Headwaters and Woodland Valley Creek drainage divide toward the Stony Clove sub-basin.

Table 1.1 Upper Esopus Creek and primary contributing streams listed from upstream to downstream.

Stream name	Drainage area (mi^2)	Stream length (mi)
Esopus Creek Headwaters (above Big Indian, NY)[1]	30	42
Birch Creek	13	16
Bushnellsville Creek	11	14
Fox Hollow Creek	4	6
Peck Hollow Creek	5	7
Broadstreet Hollow Creek	9	12
Woodland Creek	21	25
Stony Clove Creek	32	39
Beaver Kill	25	29
Little Beaver Kill	17	21
Esopus Creek (above the Ashokan Reservoir)	192	330

[1] Esopus Creek headwaters includes streams ranging in drainage area from < 2 mi^2 to 5 mi^2.

2. Study Goals and Objectives

The Study goals are listed below in bold font, followed by related objectives in italic font and a brief description of progress toward each objective during the current reporting period.

Goal 1: In the Upper Esopus Creek basin, monitor streamflow and water quality, and characterize suspended sediment sources.

Objective 1: Monitor Q, SSC and turbidity at three Esopus Creek locations and five tributary sub-basins, and monitor turbidity only at an additional two tributary sub-basins.

- Ten monitoring stations in the UEC basin are installed and operational (Figure 1.1). These locations include pre-existing stations and new stations.
- *Primary* monitoring stations are those where Q, SSC, and turbidity are measured (Figure 2.1a). *Secondary* monitoring stations are those where only turbidity is measured (Figure 2.1b).
- SSC sampling, 15-minute interval turbidity and Q monitoring cover most of USGS water years 2017 through 2020 (October 1, 2016 to September 30, 2020) and include some moderate flood events.

Objective 2: Develop SSC and/or turbidity-Q rating curves for each monitoring location.

- USGS successfully monitored turbidity and sampled SSC at primary stations, collecting samples through the range of turbidity levels measured at each station to develop SSC-turbidity relationships.
- A minimum of two years of data collection is typically recommended to develop turbidity-SSC regression equations. Further review of the data indicated a third year of monitoring would greatly improve the quality of the equations, delaying the development of the updated equations.
- Turbidity-SSC regression equations have been developed using data from water years 2017 through 2019. A USGS Open File Report and associated Data Release documenting the methods and data used to develop the regression equations are in the final stages of USGS review.

Objective 3: Estimate SS loads and yields at eight locations within the UEC basin

- Upon approval of the Open File Report, anticipated in 2021, the USGS National Water Information System will make available turbidity-derived SSC at a 15-minute timestep, and daily mean SSC and loads. This data will be used to compute yields for each primary sub-basin.

Objective 4: Examine the influence of hydrology and sub-basin SS source geologic and geomorphic conditions on SSC/turbidity levels.

- USGS continued to provide continuous Q monitoring at 13 primary monitoring stations.
- UCSWCD and DEP advanced geologic and geomorphic mapping using stream feature inventory (SFI) methods for four streams from 2017 to 2018 and seven streams from 2019 to 2020.
- DEP and USGS will evaluate potential correlations between Q, the set of monitored water quality parameters, and geologic and geomorphic conditions after the completion and USGS approval of five complete water years of monitoring and completion of at least one round of Stony Clove sub-basin SFI mapping. Work on this is anticipated in early 2022.

Goal 2: Streamflow and water quality monitoring, suspended sediment source characterization, and STRP efficacy at the reach to basin-scale in the Stony Clove sub-basin.

Objective 1. Monitor Q, SSC and turbidity at two Stony Clove Creek locations and four tributary sub-basins, and monitor turbidity only for multiple stream reaches within the Stony Clove sub-basin.

- Six primary and 14 secondary monitoring stations in the Stony Clove sub-basin are installed and operational. One station location and station ID was changed during the reporting period. On Warner Creek, headwater station #01362354 was discontinued in November 2018 due to repeated problems of turbidity probe burial by streambed sediment and extended periods of no streamflow at the monitoring location. The turbidity probe was relocated downstream in December 2018 to serve as a future Warner Creek STRP monitoring station (#0136235585).
- Sediment sampling, turbidity and Q monitoring covered most of USGS water year 2017, and all of water years 2018 through 2020. This monitoring period included two moderate flood events with Q between a 1.5 to 2-year recurrence interval. A large flood event (Q ~ 11-year recurrence interval) was monitored at the end of December 2020.

Objective 2. Assess, monitor and characterize the geomorphic and geologic SS source conditions at the monitoring reach to sub-basin scale.

- DEP continued multiple GIS-based analyses for SS source characterization using remotely sensed data and field data.
- In 2018, DEP developed a SS source characterization protocol that was used to map Stony Clove sub-basin sediment sources. DEP mapped Stony Clove Creek in 2018, Warner Creek in 2019, and Ox Clove Creek and Myrtle Brook in 2020. Hollow Tree Brook has yet to be mapped due to difficulties in obtaining written landowner permission to access private property. DEP plans to resume mapping efforts in Hollow Tree Brook in 2021.
- DEP established eight reach-scale bank erosion monitoring study sites (BEMS) between 2016 and 2018 for recurring topographic surveys. Four of the eight sites

were repeatedly surveyed during 2019 and 2020. Investigation at these sites also includes geomorphic evaluation, stream bank sediment sampling, and hydraulic modeling.
- With support from DEP and the AWSMP, USGS initiated a pilot SS fingerprinting study in 2017 that was extended through 2020 and will be renewed as an integral part of the Study in 2022.

Objective 3. Select future STRPs in the Stony Clove sub-basin using the reach-level SSC and turbidity monitoring and geomorphic characterization data.

- In January 2019, DEP nominated three prioritized stream reaches that had measurable reach-scale turbidity contributions (DEP, 2019a). Projects addressing those sites (two on Warner Creek and one on Stony Clove Creek) have advanced into design and are planned for 2021 construction by UCSWCD.

Objective 4. Evaluate the effectiveness of individual and combined Stony Clove sub-basin STRPs from the reach scale to the sub-basin scale in the Stony Clove sub-basin, and the basin scale in the UEC basin at station #01362500.

- USGS and DEP will provide the status of this objective in the five-year report, since it requires multiple years of monitoring data representing as broad a range of hydrologic conditions as possible.
- USGS annually updates turbidity-Q and/or SSC-Q regression plots to compare, to the extent feasible, before/after conditions associated with STRP implementation in the Stony Clove Creek sub-basin, and the Stony Clove Creek tributary Warner Creek sub-basin.
- Limited pre-construction monitoring for individual STRPs constructed prior to the start of the Study limits reach scale evaluation of those projects. With the establishment of station #0136235585, the current monitoring network includes upstream/downstream monitoring station placement sufficient to capture before/after water quality data for the three proposed STRPs planned for construction in 2021.

Figure 2.1 (a) Primary water quality monitoring station #01362322 for Myrtle Brook in the Stony Clove sub-basin. (b) Secondary water quality monitoring station #01362365 on Ox Clove Creek.

3. Streamflow and Water Quality Monitoring

3.1 Monitoring Network

Tables 3.1 and 3.2 provide details on the primary and secondary monitoring stations established for the Study area and in operation for most of the Study period. Results from the first four water years (October 2016 – September 2020) suggest the monitoring design has been successful in measuring SSC and turbidity for the flows observed during that period.

The Stony Clove sub-basin monitoring stations delineate water quality monitoring reaches for five streams: Stony Clove Creek, Ox Clove Creek, Warner Creek, Hollow Tree Brook, and Myrtle Brook (Figure 3.1). The water quality monitoring reaches segment the monitored streams into distinct SS loading and turbidity production sections. SS source characterization investigations in the Stony Clove sub-basin will be used to interpret variations in water quality monitoring reach turbidity dynamics.

Table 3.1 UEC basin USGS monitoring stations listed from upstream to downstream.

Station Name	USGS Station ID	Drainage Area (mi^2)	Station Type	Measurements
Esopus Cr blw Lost Clove @ Big Indian	0136219503	29.6	Primary	Q, SSC, Turbidity
Birch Cr @ Big Indian[1]	013621955	12.5	Primary	Q, SSC, Turbidity
Bushnellsville Creek @ Shandaken	0136219702	11.1	Secondary	Est. Q, Turbidity
Esopus Cr @ Allaben[1]	01362200	63.7	Primary	Q, SSC, Turbidity
Broadstreet Hollow Brook at Allaben	01362232	9.2	Secondary	Est. Q, Turbidity
Woodland Cr abv mouth @ Phonecia[1]	0136230002	20.6	Primary	Q, SSC, Turbidity
Stony Clove Cr blw Ox Clove @ Chichester[1]	01362370	30.9	Primary	Q, SSC, Turbidity
Beaver Kill @ Mt Tremper	01362487	25.0	Primary	Q, SSC, Turbidity
Little Beaver Kill at Beechford nr Mt Tremper[1]	01362497	16.5	Primary	Q, SSC, Turbidity
Esopus Cr at Coldbrook[1]	01362500	192	Primary	Q, SSC, Turbidity

[1] Existing monitoring station funded through separate DEP-USGS agreement. Note that Stony Clove Creek blw Ox Clove @ Chichester (01362370) is included in both the UEC basin monitoring count and the Stony Clove sub-basin monitoring count.

Table 3.2 Stony Clove sub-basin USGS monitoring stations listed from upstream to downstream.

Station Name	USGS Station ID	Drainage Area (mi^2)	Station Type	Measurements
Stony Clove Cr @ Edgewood	01362312	2.3	Secondary	Est. Q, Turbidity
Myrtle Br @ SR 214 @ Edgewood	01362322	1.8	Primary	Q, SSC, Turbidity
Stony Clove Cr nr Lanesville	01362330	7.5	Secondary	Est. Q, Turbidity
Stony Clove Cr @ Wright Rd nr Lanesville	01362332	8.1	Secondary	Est. Q, Turbidity
Stony Clove Cr @ Jansen Rd @ Lanesville	01362336	9.3	Primary	Q, SSC, Turbidity
Hollow Tree Br @ SR 214 @ Lanesville	01362345	4.6	Primary	Est. Q, SSC, Turbidity
Hollow Tree Br @ Lanesville[1]	01362342	2.0	Secondary	Q, Turbidity
Stony Clove Cr @ Lanesville	01362347	15.4	Secondary	Est. Q, Turbidity
Stony Clove Cr abv Moggre Rd nr Chichester	01362349	16.4	Secondary	Est. Q, Turbidity
Stony Clove Cr @ Chichester	01362350	17.5	Secondary	Est. Q, Turbidity
Warner Cr blw Silver Hollow Notch nr Edgewood	01362354	2.3	Secondary	Est. Q, Turbidity; Discontinued Nov 2018
Warner Cr nr Carl Mountain nr Chichester	0136235575	7.1	Secondary	Est. Q, Turbidity
Warner Cr in Silver Hollow nr Chichester	0136235580	7.3	Secondary	Est. Q, Turbidity
Warner Cr in Silver Hollow nr Phoenicia	0136235585	7.4	Secondary	Est. Q, Turbidity; Established Dec 2018
Warner Cr @ Silver Hollow Rd nr Chichester	01362356	8.6	Secondary	Est. Q, Turbidity
Warner Cr nr Chichester	01362357	8.9	Primary	Q, SSC, Turbidity
Stony Clove Cr @ Silver Hollow Rd, Chichester	01362359	26.6	Secondary	Est. Q, Turbidity
Ox Clove @ Chichester	01362365	3.1	Secondary	Est. Q, Turbidity
Ox Clove nr mouth @ Chichester	01362368	3.8	Primary	Q, SSC, Turbidity
Stony Clove Cr blw Ox Clove @ Chichester[1]	01362370	30.9	Primary	Q, SSC, Turbidity
Stony Clove Cr abv SR 214 @ Phoenicia	01362398	32.4	Secondary	Est. Q, Turbidity

[1] Existing monitoring station funded through separate DEP-USGS agreement.

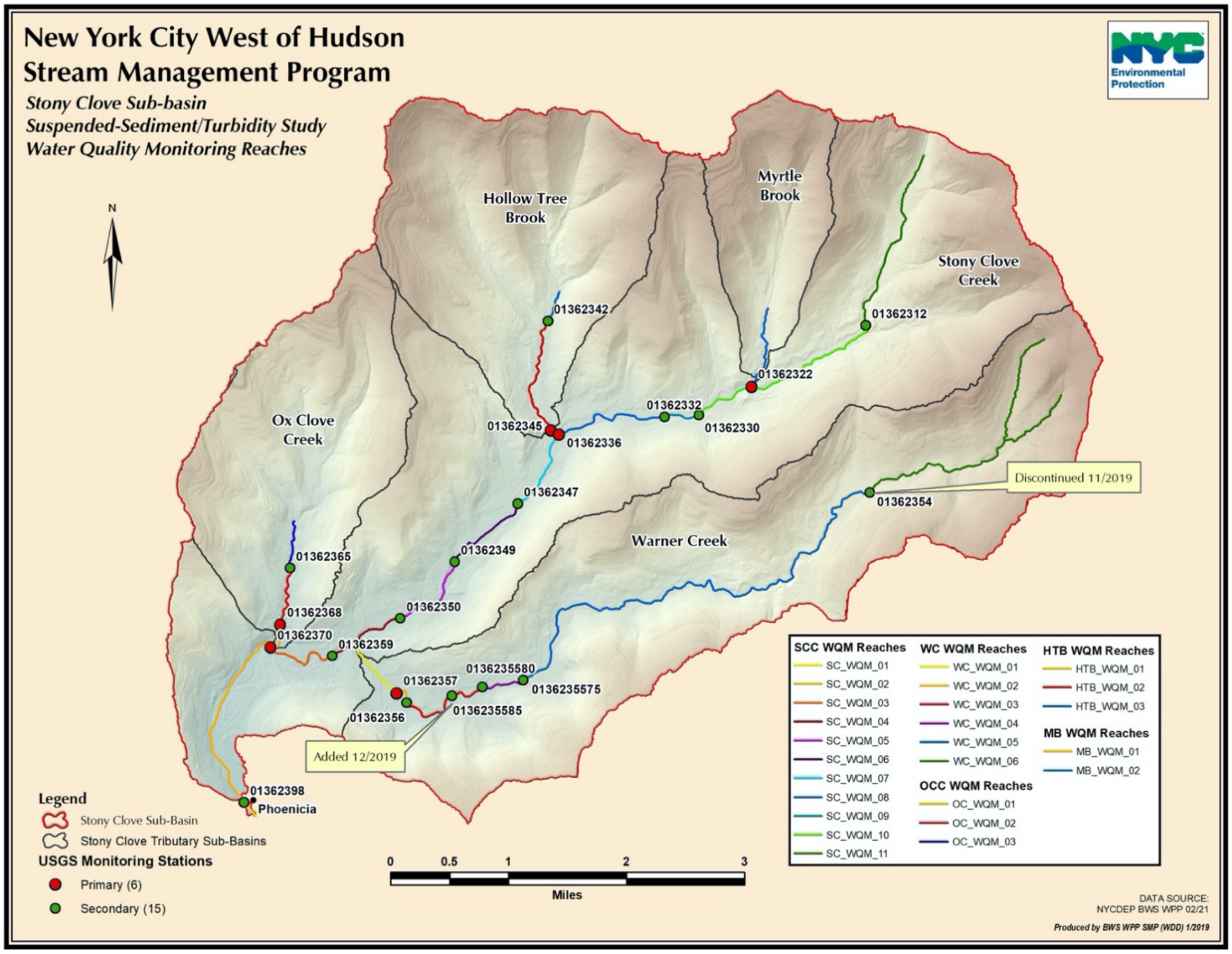


Figure 3.1 Stony Clove sub-basin USGS water quality monitoring stations and water quality monitoring reaches.

3.2 Streamflow Monitoring

Streamflow measurement and stage-Q rating curve development by USGS are ongoing at all primary stations. USGS also measures streamflow at three of the secondary stations (#01362312, #0136235575, and #01362365) to calibrate estimates at these stations. These measurements are made under stable streamflow conditions.

Streamflow is energy applied to the landscape that powers fluvial processes (Castro and Thorne 2019; Figure 3.2). The magnitude, timing, duration and flow energy of discrete flood events directly influence the geomorphic process-response relationship that produces stream turbidity and SS load. DEP provides a preliminary review of the available hydrology data examining the role of relative flood magnitude on observed geomorphic response. Figures 3.3

and 3.4 show the continuous streamflow hydrographs for Esopus Creek and Stony Clove Creek, covering a 21-year period from water year 2000 through calendar year 2020. The Study monitoring period is marked on the hydrographs. The depicted 21-year record places the monitoring period in a temporal and hydrologic context.

Figure 3.2 Flood runoff in Woodland Creek on December 25, 2020. The high energy streamflow entrains and transports fine sediment (SS flux) producing turbidity.

The scale of a flood's "geomorphic effectiveness" is relative to the flood magnitude-frequency, the geomorphic resistance of the stream channel, and the recovery process period (Fryirs and Brierley 2013; Dethier, et al 2016). Flood magnitude-frequency is readily estimated using the available USGS streamflow monitoring stations in the Study area. Estimates of geomorphic resistance and recovery period in the Study area are much more complicated and currently beyond the reach of this report. For this analysis, DEP assumes there are streamflow event magnitudes that represent lower and upper geomorphic effectiveness thresholds. The lower threshold represents a frequently recurring flood capable of geomorphic work and the upper threshold represents a less frequently recurring flood that is capable of "excess" geomorphic work resulting in a disturbance to the stream network. Disturbance in this context refers to a process resulting in an adjustment that requires a period of recovery, or initiating a new geomorphic condition (Wohl 2019). Floods capable of geomorphic disturbance can lead to the acute and chronic turbidity conditions observed in the Study area. It is important to note these threshold flows are estimates and used solely for this preliminary discussion on streamflow as a principal driver of fluvial geomorphology process and turbidity.

Three reference streamflow magnitudes are depicted as horizontal lines on the hydrographs in Figures 3.3 and 3.4. The 1.5-year recurrence interval streamflow ($Q_{1.5}$) approximately represents the bankfull flow, which over decadal time scales performs most of the fluvial geomorphic work in shaping the stream channel and conveying sediment. This frequently recurring event is set as the lower threshold, as it is generally not associated with a stream network scale channel "disturbance" but is capable of performing work. The 10-year recurrence interval streamflow (Q_{10}) is an event capable of geomorphic work that has the potential to cause disruptive disturbance at the stream network scale. Flood events at or exceeding this threshold may result in potential systemic geomorphic responses including chronic elevated turbidity triggered by reach-to-network scale bank erosion, headcut initiation and migration, channel avulsions, planform changes, and mass wasting at channel-hillslope coupled reaches. Not all Q_{10} floods will have this effect, though observations of similar magnitude events in the Study area demonstrate its potential for geomorphic response. An intermediate 5-year recurrence interval streamflow (Q_5) is also depicted. These reference streamflows represent theoretical geomorphic thresholds and are used in this report as indicators for potential geomorphic response in the monitored UEC basin. Table 3.3 summarizes the counts of recorded peak streamflows that occur in three categories: $Q_{1.5} < Q_5$, $Q_5 < Q_{10}$ and $\geq Q_{10}$.

The frequency distribution of flood events in these three categories is similar. For the 21-year period there were 25 and 27 events between $Q_{1.5}$ and Q_5 for Stony Clove Creek and Esopus Creek, respectively. The events in this category are not evenly distributed through the 21-year period. In both streams, 21 of the events occur in a 10-year period from 2003 to 2012, representing a geomorphically active decade. Between 2013 to 2020, there are only three events in this category in Stony Clove Creek and six similar magnitude events at the Esopus Creek station. Thus, the Study period corresponds to a less geomorphically active period.

The flood events that meet or exceed the upper magnitude-frequency threshold are similarly clustered. At both stream stations there are five events (counting the December 25, 2020 flood) that exceed the Q_{10} threshold during the 21-year period. Three of the five events occur within an 11-month period (October 2010 to August 2011). This would correspond to a period of geomorphic disturbance. The prolonged elevated monitored turbidity levels in the UEC basin during this time period support this point (McHale and Siemion 2014).

The nearly two-year period from January 2010 to September 2011 included a high number of streamflow events capable of reach and network-scale channel morphology adjustment and elevated SS flux/turbidity. During that 21-month period there were nine and eight events that exceeded $Q_{1.5}$ in Stony Clove Creek and Esopus Creek, respectively. Three of those events exceeded the Q_{10} threshold. This was a period of extreme hydrologic disturbance to the fluvial system. Many of the STRPs constructed in the Stony Clove sub-basin from 2012 to 2016 were intended to treat stream instabilities caused or exacerbated by the high magnitude events during this period. From October 2012 to November 2020, there were no events recorded at either station that would typically cause network-scale geomorphic impacts. This prolonged period without hydrologic disturbance allowed the fluvial geomorphic system time to recover some geomorphic stability. During 2018 and 2019 field mapping, DEP observed examples of geomorphic recovery including re-vegetation on eroded banks and depositional features, re-sorting of in-stream deposits at bankfull flows to achieve more stable channel dimensions, and bank toe protection by in-stream large wood or colluvial deposits from mass failures.

The fluvial geomorphic system was in an extended recovery period from the disruptive disturbance of the 2010-2011 hydrology until the December 25, 2020 flood. The preliminary observed geomorphic response to that flood through changes in channel morphology (e.g., channel erosion) and monitored turbidity confirm that a flood of this magnitude (Q_{11}) yields a system-scale geomorphic disturbance that can substantively alter geomorphic connectivity with SS sources in the Study area. Due to its late year occurrence, the impact of this flood will be analyzed in the five-year summary report to be submitted in November 2022.

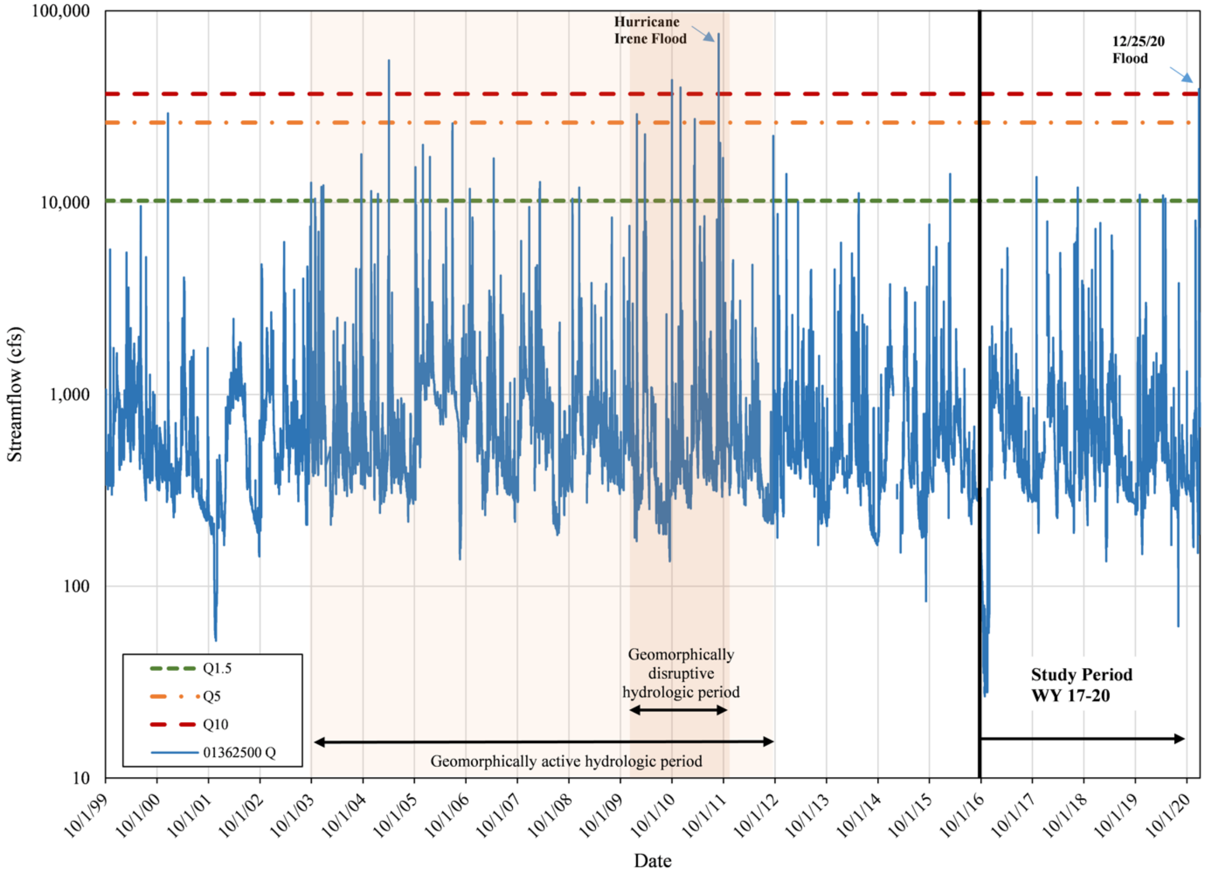


Figure 3.3 Continuous streamflow hydrograph for Esopus Creek monitoring station #01362500 with reference recurrence interval streamflows. The start of the Study period on October 1, 2016 is noted.

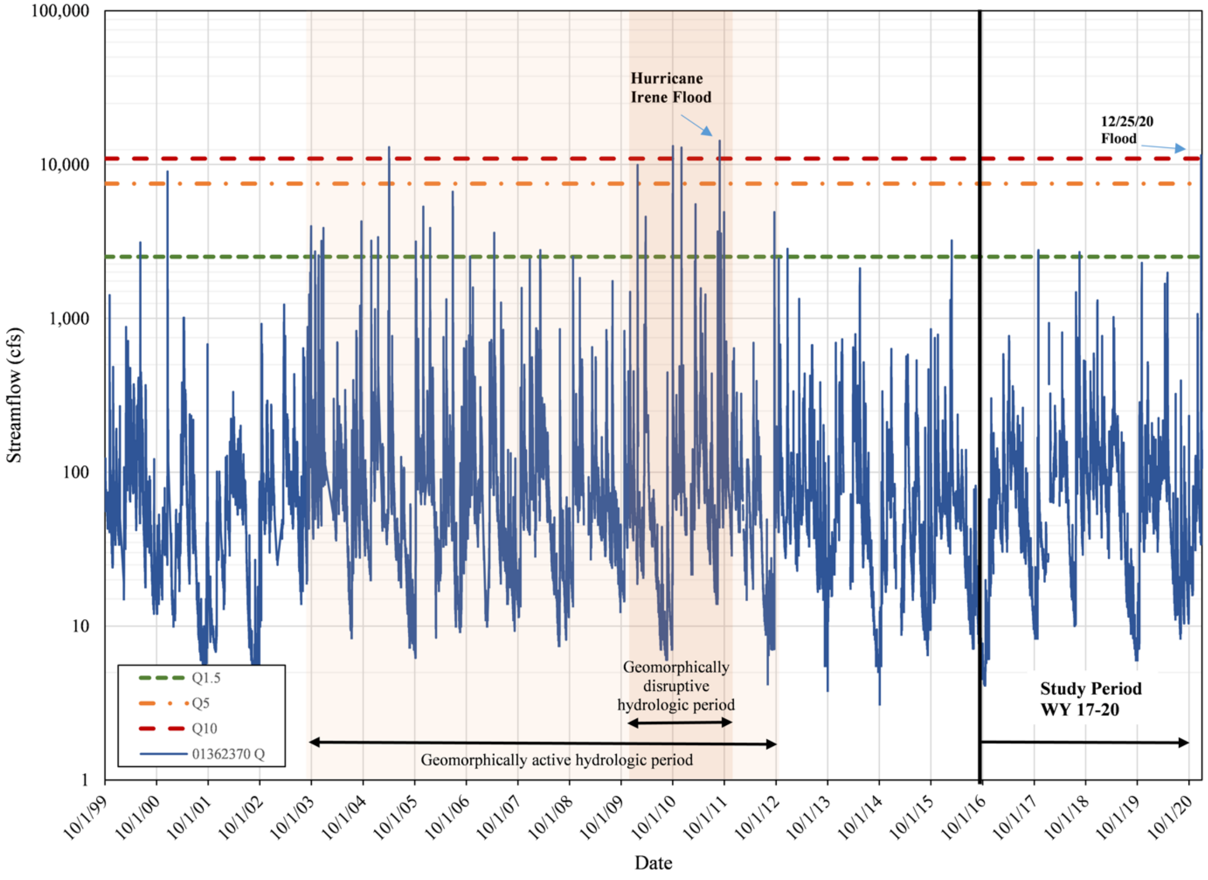


Figure 3.4 Continuous streamflow hydrograph for Stony Clove Creek monitoring station #01362370 with reference recurrence interval streamflows. The start of the Study period on October 1, 2016 is noted.

Table 3.3 Number of peak streamflows in magnitude-frequency categories for Stony Clove Creek and Esopus Creek monitoring stations for a 21-year period of record from October 1, 1999 to December 31, 2020.

Stream (USGS Station ID)	$Q_{1.5} – Q_5$	$Q_5 – Q_{10}$	$\geq Q_{10}$
Stony Clove Creek (01362370)	25	2	5
Esopus Creek (01362500)	27	3	5

3.3 Suspended Sediment Monitoring

USGS continued to implement SS sampling through the reporting period. USGS collected water samples for analysis of SSC using standard USGS methods (Edwards and Glysson 1999). An automated sampler was used to collect discrete point samples during storms at predetermined changes in stream stage. Cross-section samples were collected using the equal-width depth-integrated method by either wading at the measurement section or from a nearby bridge using isokinetic samplers. USGS analyzed cross-section and point samples for SSC using methods, as described in Guy (1969), at either the USGS Ohio Kentucky Indiana Water Science Center or the Cascade Volcano Observatory sediment laboratories.

USGS uses the cross-section samples to calibrate and ensure the representativeness of the point samples. Sample collection occurs throughout the range in streamflow and turbidity values. Periods of high streamflow and turbidity are targeted for more frequent sampling because this is when most suspended sediment is transported. The total number of point samples collected during the first four years of the study averaged more than 100 per primary station and were representative of the range of monitored streamflow. USGS also collected 9-12 cross-section samples at each primary station. Particle size is measured on a subset of suspended sediment samples from each primary station, generally when turbidity values exceed 200 FNU. USGS will provide SSC data analysis and interpretation for the five-year summary report.

Esopus Creek Basin Monitoring

Table 3.4 summarizes the point sample SSC for each sub-basin monitoring site for water years 2017 through 2019 and partial water year 2020 data. Laboratory SSC results are typically available within a few months of sample collection. However, the COVID-19 pandemic has caused extensive delays in data delivery due to limited staffing capacity at the laboratories as part of following federal social distancing guidelines.

Table 3.4 Summary of SSC in point samples for each sub-basin monitoring site.

Station Name	USGS Station ID	Number of Samples	Minimum (mg/L)	Median (mg/L)	Maximum (mg/L)
Esopus Cr blw Lost Clove @ Big Indian	0136219503	98	<1	46	2,120
Birch Cr @ Big Indian	013621955	114	1	108	2,710
Esopus Cr @ Allaben	01362200	106	<1	69	1,920
Woodland Cr abv mouth @ Phoenicia	0136230002	91	<1	89	3,200
Stony Clove Cr blw Ox Clove @ Chichester	01362370	97	2	65	2,770
Beaver Kill @ Mt Tremper	01362487	114	1	143	2,560
Little Beaver Kill at Beechford nr Mt Tremper	01362497	100	1	85	1,110
Esopus Cr at Coldbrook	01362500	104	2	75	1,700

Stony Clove Sub-basin Monitoring

Table 3.5 summarizes the point sample SSC for each sub-basin monitoring site for water years 2017 through 2019 and partial water year 2020. Stony Clove sub-basin SSC sampling analysis has also experienced extensive COVID-19 pandemic related delays.

Table 3.5 Summary of SSC in point samples for each sub-basin monitoring site.

Station Name	USGS Station ID	Number of Samples	Minimum (mg/L)	Median (mg/L)	Maximum (mg/L)
Myrtle Br @ SR 214 @ Edgewood	0136219503	92	1	23	920
Stony Clove Cr @ Jansen Rd @ Lanesville	013621955	108	<1	82	1,750
Hollow Tree Br @ SR 214 @ Lanesville	01362200	89	1	22	2,400
Warner Cr nr Chichester	0136230002	99	<1	63	1,080
Ox Clove nr mouth @ Chichester	01362370	90	1	72	1,780
Stony Clove Cr blw Ox Clove @ Chichester	01362487	97	2	65	2,770

3.4 Turbidity Monitoring

Turbidity was measured with Forest Technology Systems DTS12 turbidity probes at a 15-minute interval using methods described in Wagner and others (2006). The DTS12 probes were checked with a calibrated field probe and cleaned during routine site visits at least every six weeks. The DTS12 turbidity probes were removed and returned to the manufacturer approximately annually for calibration and factory service checks. Calibration and fouling corrections were completed following methods described in Wagner and others (2006). Erroneous data caused by fouling of the probes, ice cover, or equipment malfunction were deleted from the record. All primary and secondary monitoring stations measure turbidity at 15-minute time intervals. Turbidity data from all stations is finalized through the 2019 water year. USGS will provide turbidity data analysis and interpretation for the five-year summary report.

Esopus Creek Basin Monitoring

Daily mean turbidity exceeded 100 FNU at all Esopus watershed monitoring stations except for Little Beaver Kill (Figure 3.5). Woodland Creek had the greatest daily mean turbidity of the sub-basins. Greater frequency and duration of moderate turbidity values may indicate chronic sources of turbidity in sub-basins. Woodland Creek, Broadstreet Hollow Brook, Birch Creek, Stony Clove Creek, and Beaver Kill sub-basins all had more frequent and longer lasting moderate turbidity values.

Maximum 15-minute turbidity values at Esopus Creek stations were all greater than 900 FNU except for Broadstreet Hollow (868 FNU) and Little Beaver Kill (657 FNU). These results suggest that Beaver Kill, Birch Creek, and Woodland Creek were the greatest sources of turbidity from tributaries to the upper Esopus Creek during water years 2017 through 2020 (Table 3.6). Stony Clove Creek had turbidity values lower than Beaver Kill, Birch Creek, and Woodland Creek, but higher than the other tributaries and the mainstem station located furthest upstream (Esopus Creek below Lost Clove at Big Indian). Little Beaver Kill and Bushnellsville Creek had the lowest turbidity values of the tributaries. Turbidity values increased in a downstream direction along the mainstem of Esopus Creek.

These results represent the combined finalized monitoring data for the Study period and do not present inter-annual variations among the monitored sub-basins, or potential trends (given the limited sampling period). DEP's five-year summary report will include a more detailed analysis of the first five years of the monitoring data.

Stony Clove Sub-basin Monitoring

Daily mean turbidity exceeded 100 FNU at the Stony Clove Creek at Jansen Road at Lanesville station, Warner Creek near Chichester, Ox Clove near mouth Chichester, and Stony Clove Creek below Ox Clove at Chichester monitoring stations (Figure 3.6). Warner Creek near Chichester had the greatest daily mean turbidity. Warner Creek near Chichester and Ox Clove at mouth near Chichester had more frequent and longer lasting moderate turbidity values than other primary monitoring stations.

Maximum 15-minute turbidity values at the Stony Clove basin primary stations ranged from 256 FNU at Hollow Tree Brook to 1,090 FNU at Stony Clove Creek at the Jansen Road station. Turbidity exceedance percentage is the percent of time a turbidity level was equaled or exceeded. For example, the 1% exceedance is the turbidity level that is equaled or exceeded one percent of the time. The turbidity exceedance results suggest that Warner Creek was the greatest tributary source of turbidity to Stony Clove Creek during water years 2017 through 2020 (Table 3.7). Ox Clove was a secondary tributary source; Hollow Tree Brook and Myrtle Brook produced little turbidity.

Daily mean turbidity generally increased in a downstream direction in Stony Clove Creek and exceeded 100 FNU at all Stony Clove Creek monitoring sites downstream of the Wright Road monitoring station (#013632332, Figure 3.7). The Stony Clove Lane monitoring site had the greatest daily mean turbidity, though this site is not well mixed and may be biased high by runoff from a hillslope a short distance upstream of the site. The Stony Clove Creek monitoring sites downstream of the confluence with Warner Creek had more frequent and longer lasting moderate turbidity values than other primary monitoring stations.

Daily mean turbidity generally increased in a downstream direction in Warner Creek and exceeded 100 FNU at the Warner Creek monitoring sites downstream of the 0136235580 monitoring station (Figure 3.8). Daily mean turbidity increased from the upstream to downstream monitoring sites in Ox Clove and Hollow Tree Brook (Figure 3.9).

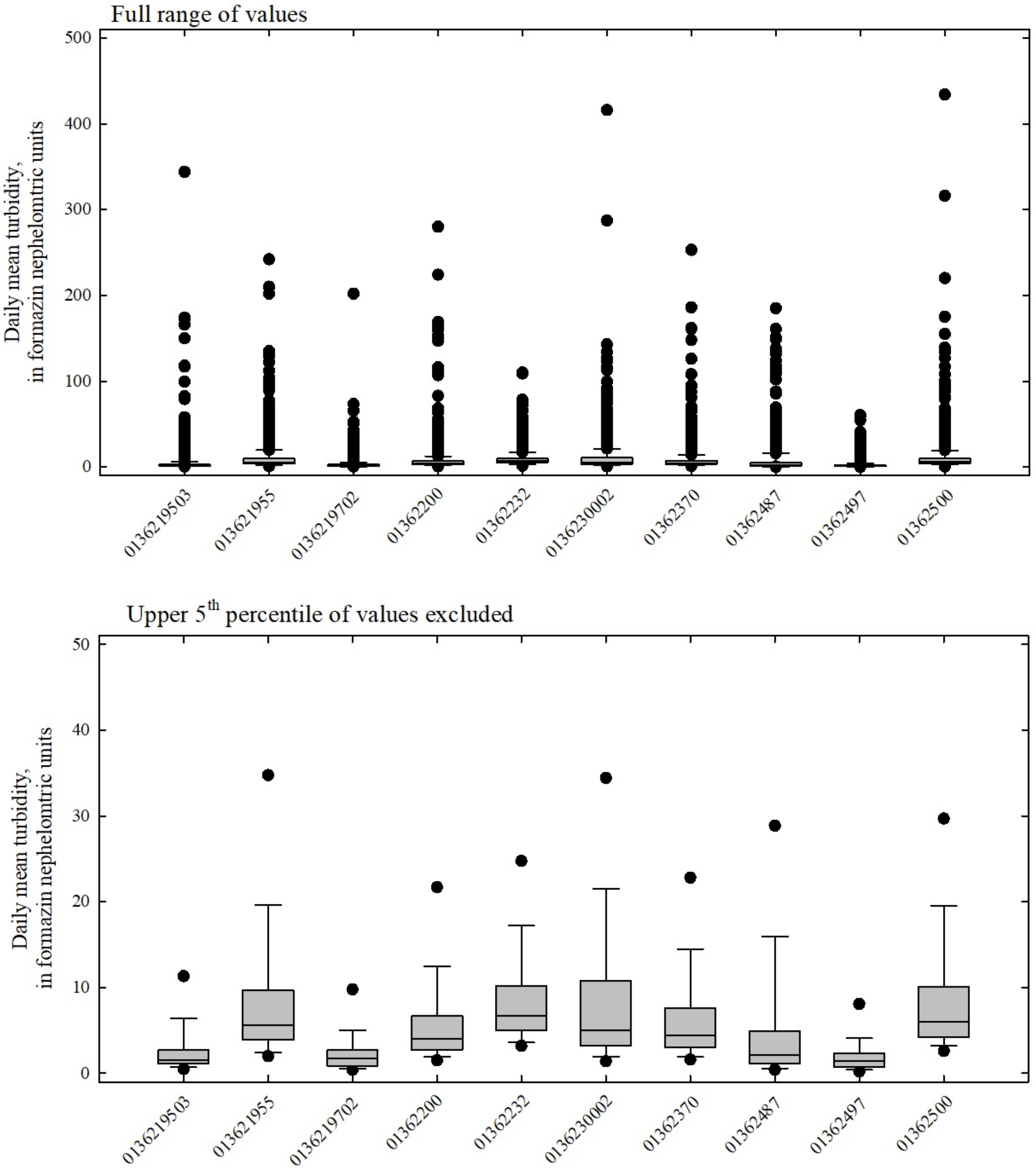


Figure 3.5 Plot provided by USGS. Upper panel, box plots of the full range in daily mean turbidity at Esopus sub-basin monitoring stations and lower panel, box plots of daily mean turbidity at Esopus sub-basin monitoring stations excluding the upper 5th percentile of values for the period October 1, 2016 through September 30, 2020. USGS station numbers along the x-axis; refer to Table 3.1 for station stream names.

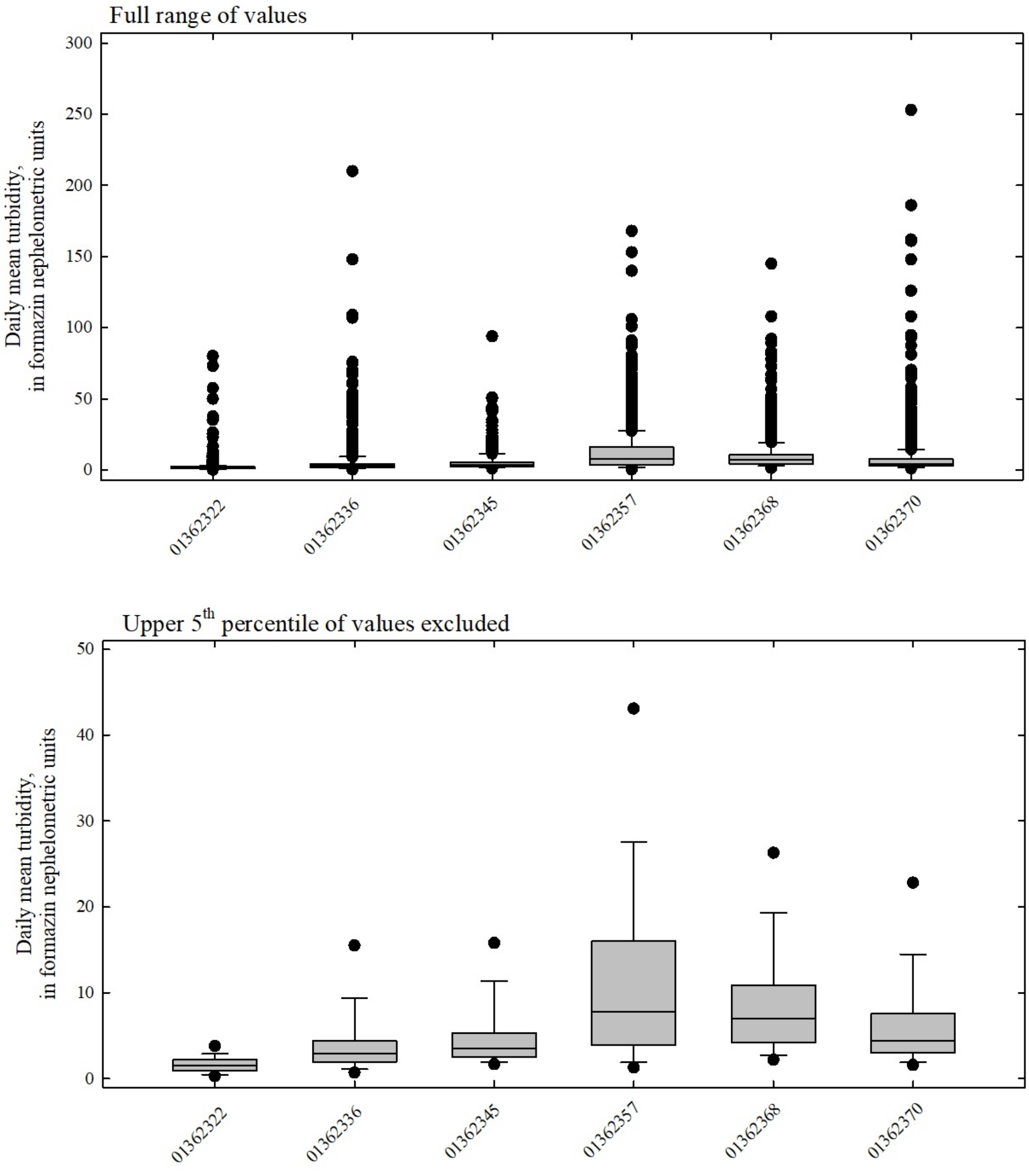


Figure 3.6 Plot provided by USGS. Upper panel, box plots of the full range in daily mean turbidity at Stony Clove sub-basin monitoring stations and lower panel, box plots of daily mean turbidity at Stony Clove sub-basin monitoring stations excluding the upper 5th percentile of values for the period October 1, 2016 through September 30, 2020. USGS station numbers along the x-axis; refer to Table 3.2 for station stream names.

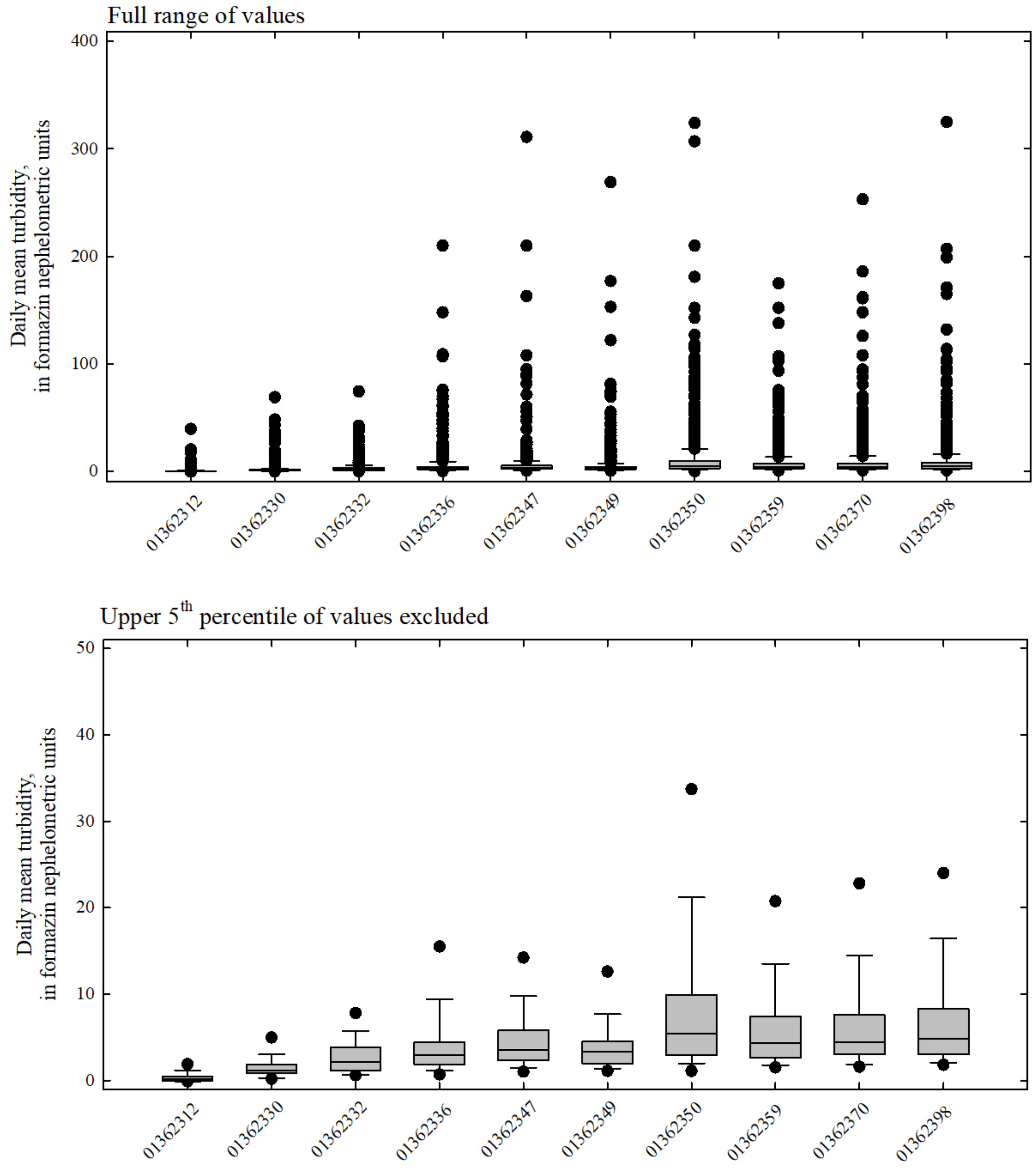


Figure 3.7 Plot provided by USGS. Upper panel, box plots of the full range in daily mean turbidity at Stony Clove Creek reach monitoring stations and lower panel, box plots of daily mean turbidity at Stony Clove Creek reach monitoring stations excluding the upper 5th percentile of values for the period October 1, 2016 through September 30, 2020. USGS station numbers along the x-axis; refer to Table 3.2 for station stream names.

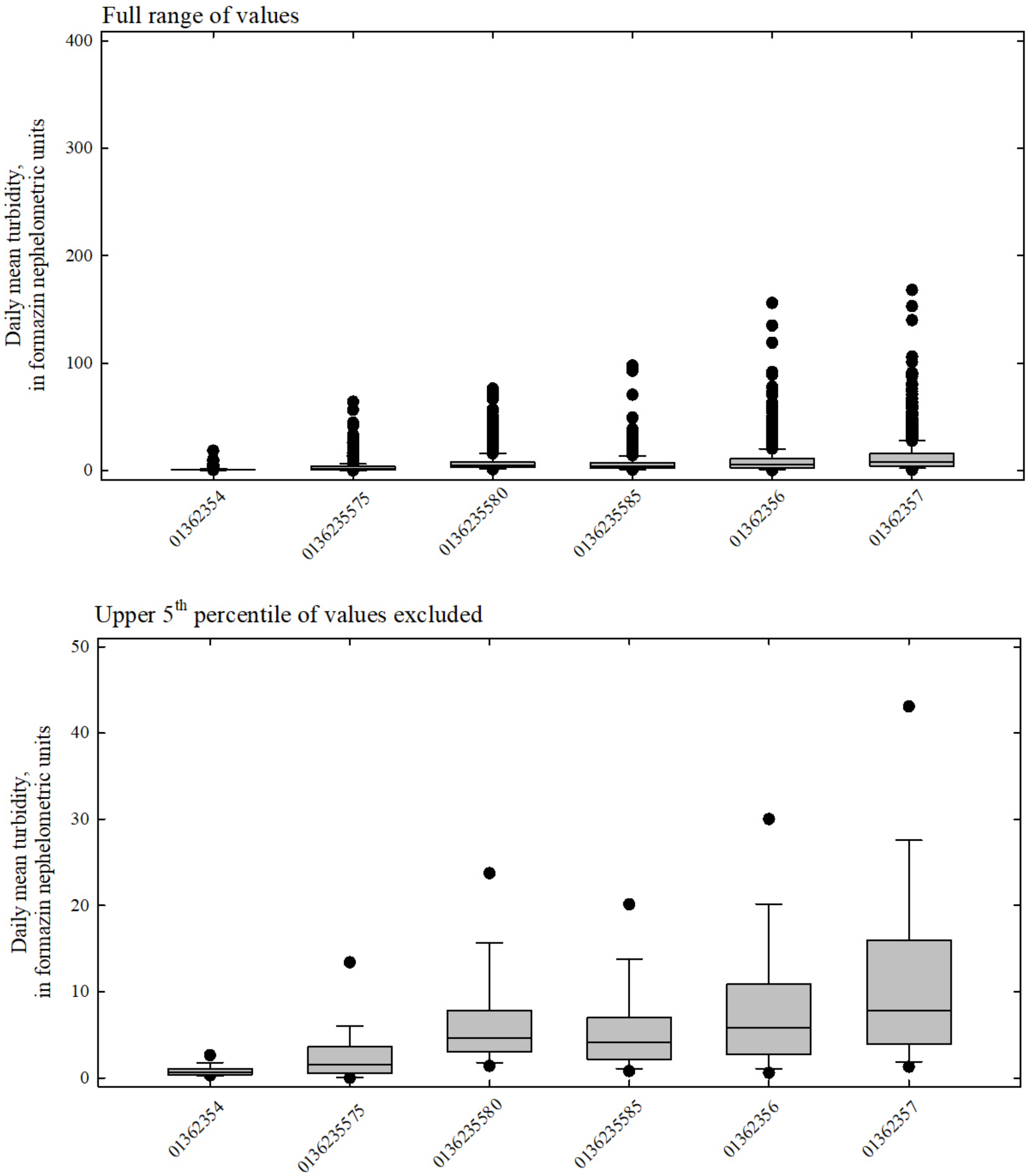
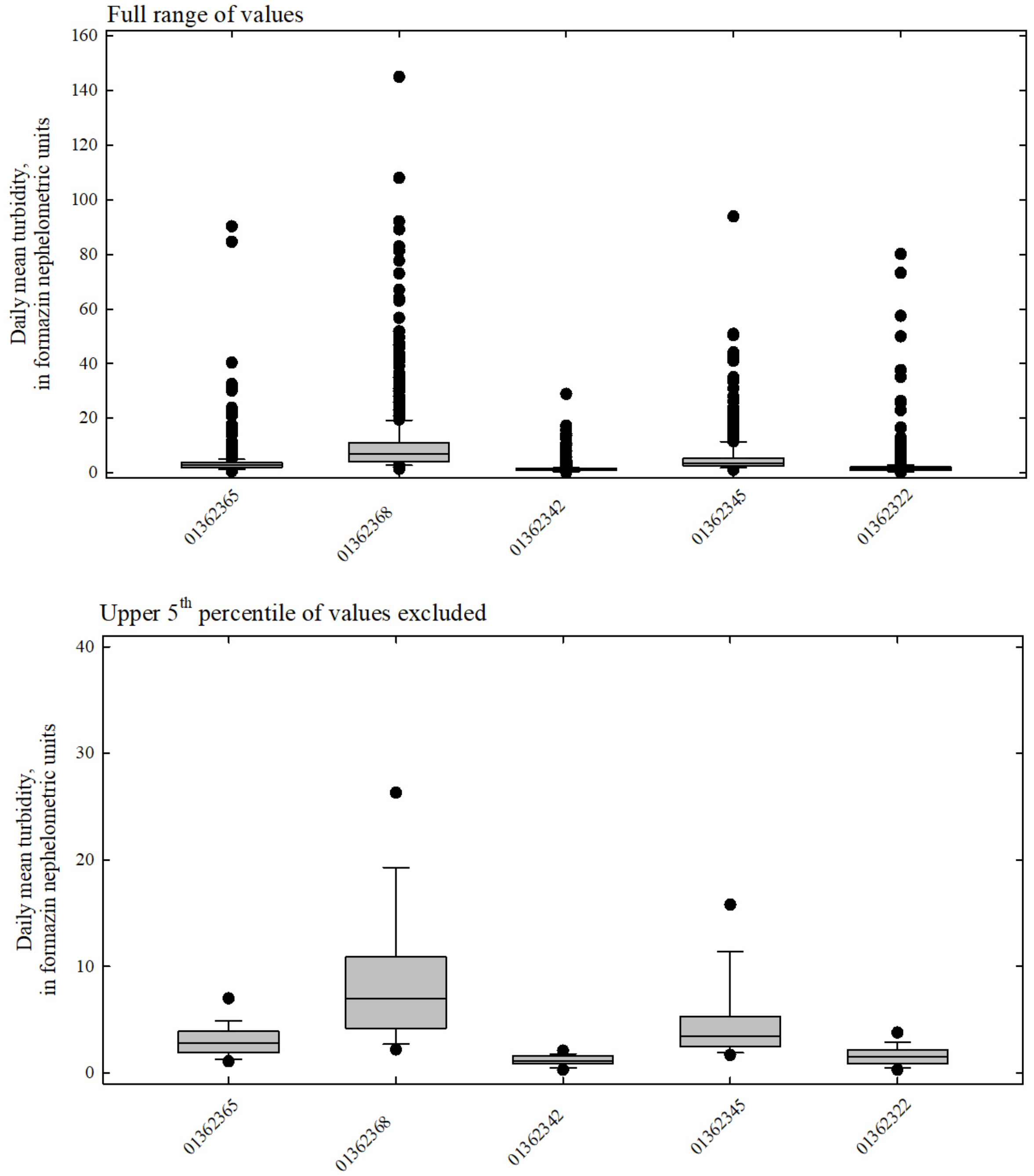


Figure 3.8 Plot provided by USGS. Upper panel, box plots of the full range in daily mean turbidity at Warner Creek reach monitoring stations and lower panel, box plots of daily mean turbidity at Warner Creek reach monitoring stations excluding the upper 5th percentile of values for the period October 1, 2016 through September 30, 2020. USGS station numbers along the x-axis; refer to Table 3.2 for station stream names. Monitoring station 01362354 was active from February 21, 2017 through November 14, 2018. Monitoring station #0136235585 began operation on December 19, 2018.


Full range of values

Upper 5th percentile of values excluded

Figure 3.9 Plot provided by USGS. Upper panel, box plots of the full range in daily mean turbidity at Ox Clove, Hollow Tree Brook and Myrtle Brook reach monitoring stations and lower panel, box plots of daily mean turbidity at the same reach monitoring stations excluding the upper 5th percentile of values for the period October 1, 2016 through September 30, 2020. USGS station numbers along the x-axis; refer to Table 3.2 for station stream names.

Table 3.6 Summary of 15-minute turbidity values from Esopus Creek sub-basin monitoring stations listed from upstream to downstream for water years 2017-2020 for most sites. Water year 2020 turbidity is provisional and subject to revision.

Stream	USGS Station ID	Maximum	1% Exceedance	5% Exceedance	10% Exceedance	Median
Esopus Creek	0136219503	>1,600	37	10	6	2
Birch Creek	013621955	1,240	101	30	18	5
Bushnellsville Creek	0136219702	1,050	37	8	4	2
Esopus Creek	01362200	1,370	58	19	12	4
Broadstreet Hollow Brook	01362232	868	54	22	16	7
Woodland Creek	0136230002	>1,600	93	32	20	5
Stony Clove Creek	01362370	985	69	22	14	4
Beaver Kill	01362487	1,160	98	29	13	2
Little Beaver Kill	01362497	657	24	6	4	1
Esopus Creek	01362500	1,410	90	27	16	5.7

Table 3.7 Summary of 15-minute turbidity values from Stony Clove monitoring stations listed from upstream to downstream for water years 2017-2020 for most sites. Water year 2020 turbidity is provisional and subject to revision.

Stream	USGS Station ID	Maximum	1% Exceedance	5% Exceedance	10% Exceedance	Median
Stony Clove Creek	01362312	950	5.8	2	1	<1
Myrtle Brook	01362322	709	11	3	3	2
Stony Clove Creek	01362330	649	16	4	3	1
Stony Clove Creek	01362332	539	21	7	5	2
Stony Clove Creek	01362336	1,090	48	14	9	3
Hollow Tree Brook	01362342	801	5	2	2	1
Hollow Tree Brook	01362345	466	25	15	11	3
Stony Clove Creek	01362347	1,440	60	16	10	4
Stony Clove Creek	01362349	1,130	47	13	7	3
Stony Clove Creek	01362350	>1,600	106	29	17	5
Warner Creek	01362354	98.4	7	3	2	<1
Warner Creek	0136235575	380	27	11	5	2
Warner Creek	0136235580	>1,600	57	22	14	4
Warner Creek	0136235585	770	51	21	12	4
Warner Creek	01362356	1050	63	29	20	5
Warner Creek	01362357	957	85	43	30	7
Stony Clove Creek	01362359	878	61	20	13	4
Ox Clove Creek	01362365	945	18	6	5	3
Ox Clove Creek	01362368	1,600	71	24	17	7
Stony Clove Creek	01362370	985	69	22	14	4
Stony Clove Creek	01362398	>1,600	89	23	14	4

4. Suspended Sediment Source Characterization

4.1 Source Characterization Framework

The conceptual framework for this Study is founded in the science of geomorphology, specifically employing the concept of connectivity in fluvial geomorphology (Yellen 2014; Wohl et al. 2019; Cienciala et al., 2020). Connectivity in this context can refer to structural connections between SS/turbidity sources in the fluvial system (e.g., linkages between channels and valley bottom features such as hillslopes) and functional connections such as SS flux. The turbidity and SS flux regime in the UEC basin is driven by hydrology and sourced by three primary types of fine sediment (silt and clay) input: fine sediment stored in streambed alluvium during bed mobilizing streamflows, lateral fine sediment inputs from channel margins and connected terrain, and channel incision into and entrainment of fine sediment in glacial legacy deposits exposed in the streambed (Figure 4.1). The Study assumes that a significant part of the observed variability in turbidity and SS flux and yield in the UEC basin is associated with spatially variable stream erosional contact with glacial legacy sediments. The SS source characterization part of the Study aims to qualify and quantify these controlling source conditions through use of a range of GIS and field investigations.

The stored streambed fine sediment along the stream network is equivalent to SS flux in temporary stasis, having been deposited during the waning stage of a prior streambed mobilizing flood. Resuspension of this fine sediment during subsequent streambed sediment transporting flows is likely a high portion of the SS flux during the rising and peak stages of a flood as the sediment is transferred downstream. Lateral and channel incision SS inputs in this fluvial system account for the sediment recruitment component of SS flux. Lateral inputs are principally supplied through stream bank erosion, avulsions and mass wasting into alluvial and glacial legacy sediment. Channel incision inputs are principally from headcuts and scour into glacial legacy sediment.

Some SS flux is supplied by other sources including road drainage entraining fine sediment from ditch networks, unpaved roads and from sediment applied to paved roads for traction in winter. Upland gully erosion in forested mountain slopes is another lateral input source that can episodically supply fine sediment into the fluvial network. An additional atypical source in the UEC basin is the inter-basin transfer of water from the Schoharie Reservoir to Esopus Creek via the Shandaken Tunnel, the volume of which is, in turn, similarly sourced in the Schoharie Watershed from channel incision, eroding margins and landscape inputs.

Figure 4.1 SS input conditions: (a) stored in streambed alluvium, (b) bank erosion, (c) mass wasting, (d) channel incision.

The current SS source assessment focus is on the lateral and incision inputs from channel and adjacent hillslope erosion as these are the input source conditions treated by STRPs. Stored fine sediment in streambed alluvium has yet to be quantitatively assessed in the Study but there are plans for future assessment as described in Section 4.4.

The Study uses multiple methods to account for the primary SS recruitment source conditions and processes. These methods include (1) terrain and process interpretation using remote-sensing data in GIS; (2) baseline and repeat mapping of spatial and temporal erosional connectivity with sediment sources; (3) repeat geomorphic assessment, topographic monitoring, sediment sampling, and hydraulic modeling at select stream erosion sites; (4) geologic sediment source investigation and interpretation (including sediment fingerprinting techniques); and (5) starting in 2019, use of computer mechanistic modeling of stream process and sediment flux. The modeling work is an ancillary effort led by Cornell University using data obtained during this Study. During the course of the 10-year Study, DEP and USGS (and potentially others) will use these methods to derive and test potential predictive geomorphic metrics to help explain SS flux through the system and the potential for reduction through stream management practices.

4.2 GIS Analysis

GIS is an ideal computer-based set of tools and georeferenced data for performing spatial analysis of all aspects of this turbidity monitoring and source characterization research. DEP is fortunate to have an extensive GIS data library for this purpose along with data collected in this study. DEP uses a variety of GIS-based analyses to obtain watershed and stream channel characteristics for geomorphic metric development. This section describes the status of each of the ongoing analyses and identifies if geomorphic metrics have been produced or planned as being either categorical (e.g., high/medium/low), quantitative (e.g., indices, percentages) or logical (true, false). If a task was reported as completed in the 2019 biennial status report it is not updated in this report. Some methods have been dropped as they are replaced by others or proven not useful to achieve the research objectives. Each biennial status report may include different sets of GIS tasks as the Study advances.

Historic Channel Alignment Analysis

Stream channel planform (the ‘bird’s eye” view of the channel geometry) often changes through time as the channel erodes banks and deposits eroded sediment. Tracking changes in channel planform through time is one measure of assessing channel erodibility and potential erosive contact with SS sources. DEP currently uses two GIS-based approaches to analyze observed stream channel planform adjustment through time using aerial imagery and other available planform data. Stream channel centerlines and active channel margins are delineated in GIS to provide information on stream channel planform. If there are at least two time periods of observable planform data, then a channel planform time series can be used to measure and assess channel adjustment.

The first method uses stream channel centerlines digitized in GIS using available orthorectified or georeferenced aerial photos (orthoimagery) spanning at least two time periods. The stream centerline time series is plotted and qualitatively and/or quantitatively analyzed to identify or measure observed adjustments in channel planform based on changes in centerline position and curvature. An advantage of this method is that it is a relatively quick process to digitize and attribute a line feature. This approach is used throughout the SMP across the Catskills as part of the standard geomorphic assessment for stream management plan development. All of the UEC basin SFI-mapped streams have a stream centerline time series that can be used in this Study. Work to date in the Stony Clove sub-basin includes digitizing stream channel centerlines for several years (1959 to 2016) for Stony Clove Creek and partially for

Warner Creek. Low resolution on aerial imagery prior to 2009 limits digitized multi-year centerlines for the remaining monitored smaller Stony Clove sub-basins to 2009 and 2016. Currently only the 2009 centerline has been digitized for these three streams. Possible metrics that can be developed from this data include categorical metrics such as potential for reach-scale lateral adjustment (high/medium/low); and quantitative metrics such as braiding indices and bank erosion indices.

The second method includes digitizing active channel margins (ACM) observed in orthoimagery, digital elevation models, hydraulic modeling, and field observations. DEP initiated this method in 2018 for the Stony Clove sub-basin confinement assessment (described below) and has since expanded the method into potential use for quantifying channel width and planform adjustment. The ACM feature is a digitized polygon that represents the lateral limits of the channel subjected to regularly recurring flows, and is approximately coincident with, or marginally greater than the bankfull streamflow channel. Advantages of this method include a potentially more accurate measure of channel planform adjustment, accounting for spatial and temporal changes in channel width, explicit inclusion of in-stream sediment storage and multiple channels, and obtaining estimates of eroded area between time series.

By the end of 2020, DEP produced a 2009 ACM network for all monitored streams in the UEC basin using the 2009 orthoimagery, the 2009 1-meter digital elevation model (DEM), available FEMA hydraulic modeling depth grids, and field observations. DEP will produce a 2016 ACM network in 2021 to measure channel margin adjustment between the two time periods that bracket the geomorphically significant hydrology in 2010 to 2011. In the Stony Clove sub-basin, DEP produced ACMs for 2001, 2009, 2013 and 2016 using available orthoimagery for Stony Clove Creek and Warner Creek (Figure 4.2a). DEP digitized the 2009 ACM boundaries for the remaining monitored Stony Clove tributaries and the 2016 ACM boundaries will be digitized in 2021. DEP will perform an overlay analysis in the Stony Clove sub-basin to measure channel margin adjustment, and the results translated into categorical and quantitative metrics to be included in the set of predictive water quality monitoring reach attributes.

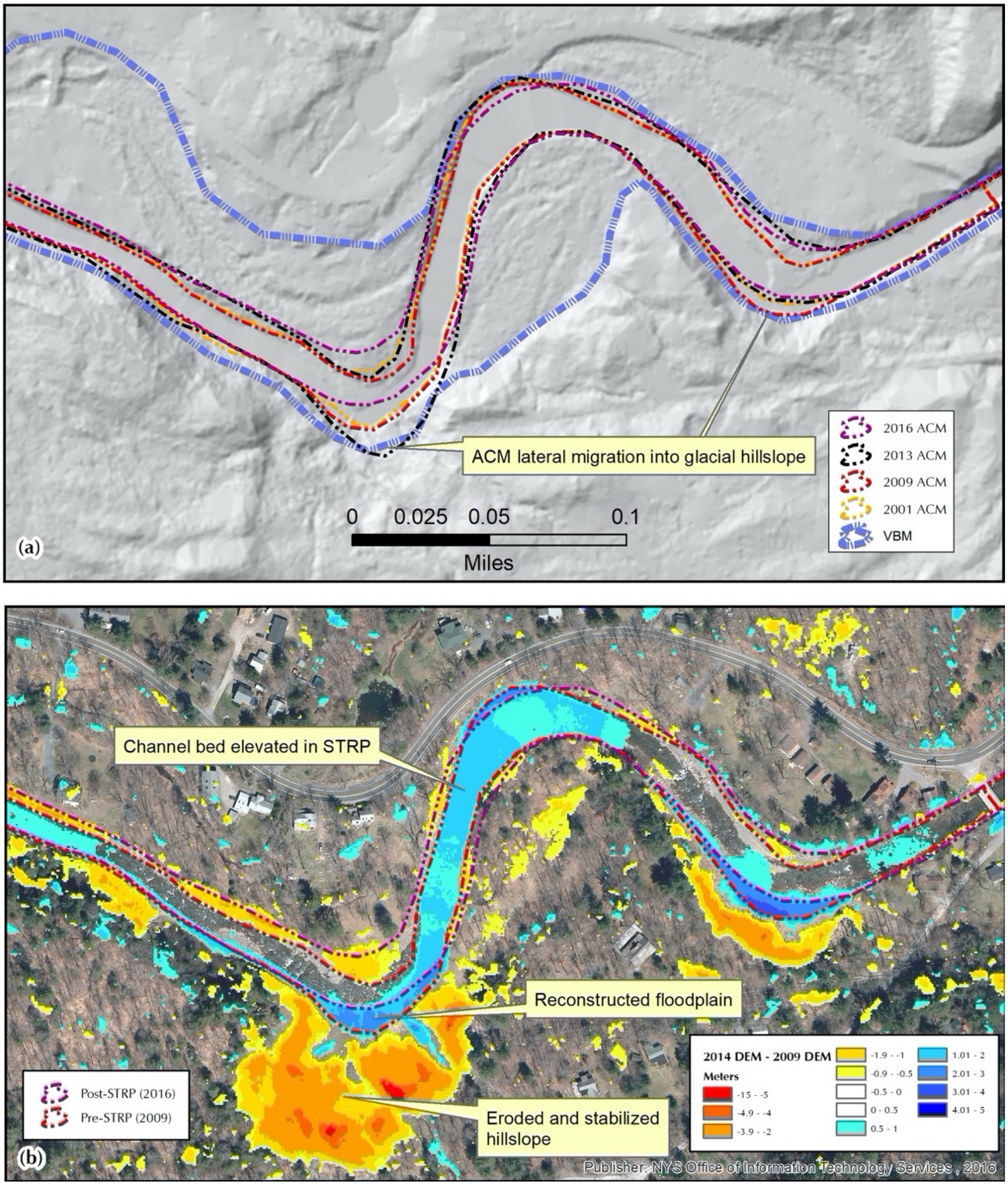


Figure 4.2 Utilizing remotely sensed data for geomorphic analysis: (a) ACM time series with a confining valley bottom margin (VBM) polygon for Stony Clove Creek at Chichester STRP sites overlain on 2009 DEM hillshade, (b) same reach with a DEM of difference analysis comparing the 2014 DEM with the 2009 DEM. Yellow to red color range represents a lowered surface; blue color range represents a raised surface. Background is 2016 orthoimagery.

Stream Channel Confinement Assessment

DEP investigated this GIS-based analysis in 2018 and 2019 as a potential new method for geomorphic metric development. Stream channel confinement, as used in this research, is a measure of a stream's ability to adjust its margins; as such, it can be a potential metric for lateral sediment connectivity and entrainment potential in the stream system. Typically, a confined channel is assumed to have less ability to laterally recruit sediment through bank erosion compared to an unconfined stream that can migrate across the valley floor. Conversely, in the Study area confinement by valley bottom features that are composed of glacial legacy sediment can be sites of SS recruitment where stream channel erosion triggers confining hillslope mass wasting. DEP is still investigating use of this method by reviewing its applications in other research presented in scientific literature. Updates will be provided in future reporting.

Stream Channel Slope and Stream Power Assessment

This planned assessment is currently limited to the Stony Clove sub-basin. DEP computes stream channel slope and stream power (product of slope and streamflow) using the 2009 1-meter DEM and streamflow estimated based on the Stony Clove Creek primary monitoring station #01362370 and bankfull streamflow regional curves. DEP plans further work on this analysis will update the status in future reporting.

DEM of Difference Assessment

DEP introduced this new GIS-based Study analysis in 2018 to detect geomorphic change in the stream corridor using DEM differencing methods (the subtraction of one DEM from another). Fluvial geomorphologic investigations increasingly use this method when at least two DEMs representing different periods of the same terrain and resolution are available to quantitatively measure changes in elevation at each DEM cell (Wheaton et. al 2010; Hinshaw et. al 2020). Subtracting the more recent DEM from a prior DEM can yield a DEM of difference (DoD) that can represent erosion (negative values) and deposition (positive values). Preliminary testing finds this method is useful in depicting zones of erosion (sediment entrainment) and deposition at the reach and sub-basin scales for **part** of the UEC basin. Unfortunately, it's application is currently limited in the Stony Clove sub-basin. There are two 1-meter DEMs currently available for the Study area:

- 2009 1-meter DEM derived from the April 2009 LiDAR data covers the entire UEC basin. This is the DEM that was processed to produce the 2009 National Hydrography Data (NHD) and supplement FEMA flood modeling;
- "2014" 1-meter DEM derived from LiDAR data obtained between November 2013 and June 2014 for the Ulster County portion of the UEC basin.

DEP produced a DoD for the portion of the UEC basin that has both the 2009 and 2014 DEMs. Only about one third of the Stony Clove sub-basin is in Ulster County so this analysis cannot be completed at this time for the primary research sub-basin where most GIS analysis is focused. However, the results of the analysis seem useful where available (Figure 4.2b). This work is on hold until new DEM data is available for the Stony Clove sub-basin.

4.3 Mapping Sediment Source Distribution

DEP uses field-based mapping of erosional sediment sources as the primary method to quantify their spatial distribution from stream channel erosion and channel-hillslope mass wasting. This field mapping is based on the SFI approach used for many years by the SMP in the development of stream management plans in the UEC basin and throughout the Catskills. Figure 4.3 depicts the extent of SFI mapping in the UEC basin for the period 2001-2019.

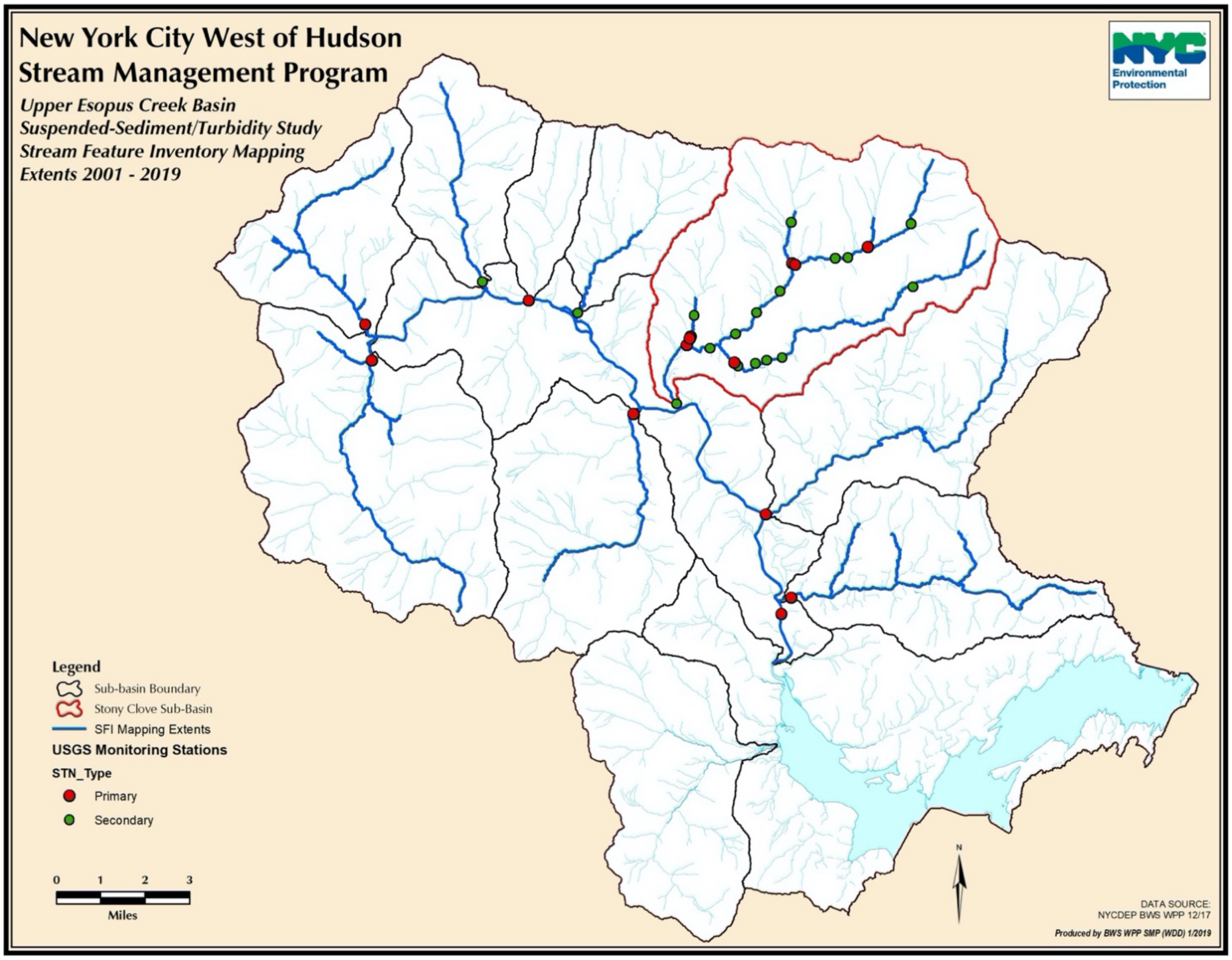


Figure 4.3 Extent of SFI mapping in the UEC basin from 2001 to 2019. All USGS monitored streams have been assessed at least once.

Mapping the spatial distribution and relative magnitudes of erosional sediment sources (bank erosion, headcuts, bed scour, avulsions, and hillslope erosion) can help explain the basin, sub-basin, and reach scale variations in measured turbidity and SS across the monitored sub-basins. The method uses high-resolution GPS devices with a digital data form (data dictionary) that records details such as the geology of the eroding feature, bank failure mechanics, feature dimensions, and other potentially useful attributes that can inform metric development. SFI-based metrics can include several quantitative measures of erosional contact with SS sources (e.g., bank erosion length and area indices, channel-hillslope erosion indices; geologic source erosional contact indices). Work over the next two years will explore the predictive power of these metrics.

During the 10-year Study period, UCSWCD will continue to perform SFI mapping in the UEC basin with the exception of the Stony Clove sub-basin, where DEP will continue to perform SFI mapping using the Study-specific SFI data dictionary designed to support development of geomorphic metrics predictive of reach scale turbidity monitoring. In 2018, DEP developed a GPS mapping protocol specifically for the Stony Clove sub-basin SFI effort to minimize user bias that can occur during field mapping. DEP supervises all Stony Clove sub-basin SFI teams; UCSWCD has supervised all other UEC basin SFI teams with the exception of the original Esopus Creek assessment.

Upper Esopus Creek Basin Mapping

UCSWCD completed baseline SFI mapping for Esopus Creek from the headwater reaches in Oliverea downstream to the confluence with Bushnellsville Creek in 2019 and for three tributary streams to the Esopus headwaters reaches (McKenley Hollow, Elk Bushkill, and Little Peck Hollow) in 2020. The 2020 data is still undergoing processing for inclusion in the DEP-maintained SFI geodatabase. Table 4.1 presents a summary of SFI bank erosion mapping results for the UEC basin streams through 2019.

It is important to note that the SFI data for the UEC basin spans nearly 20 years covering a period that includes three different data dictionaries (pre-2008, 2008 to 2018, and 2019 to present), different SFI teams, and improving GPS technology. One limitation with the pre-2008 data is that the data dictionary did not include a geology field for bank erosion so use of that data requires some interpretation of the available data to deduce the probable SS source geology. Repeat SFIs of UEC sub-basin streams mapped prior to 2008, while not part of the Study design would be beneficial for associating source conditions with monitored turbidity and SS flux. UCSWCD remapped Esopus Creek from the Esopus Headwaters reaches down to Bushnellsville Creek in 2019 and that data can be used to compare with the pre-2008 data.

An additional significant limitation of the SFI data for geomorphic metric development is that SFIs are seasonal “snapshots” of channel condition and reflect the occurrence or absence of geomorphic disturbance events such as high magnitude floods and management actions. The conditions mapped in Broadstreet Hollow in 2001 reflect the hydrology and management intervention of the previous years; it is reasonable to assume they do not necessarily reflect the current conditions. This is so for all the SFI results prior to the start of the Study in 2016. For example, streams assessed just after the repeat high magnitude flooding of 2010 through 2011, such as Beaver Kill and Bushnellsville Creek, would possibly have more active bank erosion than if those streams were mapped in 2019, following multiple years of natural or managed recovery. Given these limitations, DEP is not relying on the broader UEC sub-basin SFI mapping for source attribution in the Study; the data will be considered when interpreting the turbidity and SS flux monitoring.

Stony Clove Sub-basin Mapping

Table 4.1 includes the pre-Study SFIs completed for Stony Clove sub-basin streams in 2010 through 2015. DEP has four pre-Study years of repeat SFI mapping for Warner Creek covering the lower ~2 miles of stream channel. National Science Foundation-funded college students with DEP supervision collected the first three years of data (2010–2012). A private engineering consultant with some DEP supervision collected the 2015 data for all Stony Clove sub-basin streams.

The Study methods include completing at least two SFIs for each monitored stream in the Stony Clove sub-basin during the Study period. Each SFI is to be separated by approximately five years or following a geomorphic disturbance scale flood to obtain information on the temporal variation in source conditions. As discussed below, this might be difficult to achieve for some streams.

The Study SFIs use the mapping protocol developed in 2018 to generate improved quantitative SS source metrics in the Stony Clove sub-basin. Newly mapped features include bed erosion into SS source sediment, mass failure scarps of mass wasting sources of SS, and increasing detail in mapping whether an eroding bank is active, recently dormant (could be reactivated during a flow greater than bankfull streamflow) or recovering (would take a high magnitude streamflow to reactivate the erosion). More attributes on SS sources, valley setting, and potential causal factors are also recorded.

DEP completed the first Study SFI on Stony Clove Creek in 2018. Figure 4.4 presents a portion of the 2018 sediment source mapping results for Stony Clove Creek classified by primary SS source (alluvium, lacustrine sediment, glacial till, colluvium and stratified combinations; see Section 4.5 for sediment descriptions). Table 4.2 presents the pre-Study 2013 and Study 2018 bank erosion index (bank erosion length/reach bank length) results attributed to each water quality monitoring (WQM) reach. There are a few observations to note in this comparison between the two mapping years:

- All 2013 mapped bank erosion is assumed to be active and is more temporally proximal to the 2010-2011 disturbance hydrology. The 2018 mapped bank erosion is seven years after the disturbance hydrology and includes all implemented STRPs in addition to other stream protection projects implemented by landowners and highway departments.
- The 2013 data did not include mapping WQM reach 11.
- Four of the 10 reaches mapped in both years have a higher **total** bank erosion length in 2018 than 2013; however, in no instance did the 2018 mapped **active** bank erosion exceed the 2013 mapped bank erosion. Many of the 2013 mapped active eroding banks were mapped as dormant or recovering in 2018. Some previously mapped eroding banks were not identified in the field in 2018.

- It is clear in the WQM reaches with STRPs (3, 4, 5, 6, 9) that STRPs removed much of the previously mapped active bank erosion.
- The WQM reaches with STRPs also had an expected substantial reduction in the erosional contact with SS non-alluvial sources, with the exception of WQM reach 6 which includes the Stony Clove at Lanesville STRP first constructed in 2006 and reconstructed in 2015.

These preliminary findings in Stony Clove Creek support the supposition that the post-2012 hydrology allowed for significant geomorphic recovery through vegetation on previously eroding surfaces, stabilized colluvial slopes, bank toe protection through colluvial deposition of boulders and large wood deposited during the high streamflow events. Table 4.2 also demonstrates that the STRPs have successfully tested the management practice of disconnecting stream reaches from non-alluvial SS sources.

There are several other geomorphic metrics that can be explored with these SFI data including percent erosional contact with hillslopes, percent contact with specific geologic SS sources, and percent area of erosion/reach. Once all Stony Clove sub-basin streams are mapped with the Study mapping protocol, DEP will pursue more thorough analysis of the SFI data to develop predictive metrics.

DEP initiated an additional use of the Study SFI data in 2020. The 2018 SFI data and DEM analysis informed development of a stream channel geology map for Stony Clove Creek (Figure 4.5) that can be used for estimating whether any given section of stream has the potential to supply fine sediment based on probable geologic composition.

SFI investigations for the four water quality-monitored tributaries to Stony Clove Creek were planned for 2019; however, only Warner Creek mapping was completed in 2019. The lower 2-mile stretch of Warner Creek was mapped consistent with previous mapping in 2011, 2012 and 2015. The full length of the stream was mapped in 2010. Ox Clove Creek mapping started in 2019 and completed in 2020. Myrtle Brook was also mapped in 2020. DEP has not yet mapped Hollow Tree Brook pending additional written permission to access private land. In 2020, only 30% of the Hollow Tree Brook landowners, representing about 50% of the needed SFI stream length, provided DEP permission to access their lands. DEP continues to seek landowner permissions so that this tributary can be mapped and included in the geomorphic SFI analysis.

The December 25, 2020 flood caused significant incision into glacial lacustrine sediment in the lower third of Hollow Tree Brook, resulting in a chronic source of very elevated turbidity in the Stony Clove sub-basin. Prior to the flood, the Hollow Tree Brook turbidity monitoring data (Figure 3.8 and Table 3.7) suggested this sub-basin had much less contact with SS source geology than Stony Clove Creek, Warner Creek and Ox Clove Creek during the monitoring period. That has changed, and DEP will prioritize efforts to map SS source conditions in this sub-basin.

Data analysis and computation of SFI-based geomorphic SS connectivity metrics will continue in 2021 and 2022 and will be presented in the five-year summary report.

Table 4.1. UEC basin and Stony Clove sub-basin SFI-mapped stream bank erosional sediment source analysis. Sediment sources are lumped into two categories for percentage computation – alluvial (AL) and non-alluvial (N-AL). N-AL comprises two primary sources: glacial till (GT) and lacustrine sediment (LS).

Stream Name	SFI Year	SFI Stream Length (ft)	Bank Erosion Length (ft)	Bank Erosion (%)[1]	Erosional Contact AL (%)	Erosional Contact N-AL (%)	Dominant SS Source (1st/2nd)
UEC Sub-basin SFI Results (2001–2019)							
Esopus Creek[2]	2005-06	144,974	25,003	9	78	22	GT/LS
Birch Creek	2011	49,662	8,940	9	91	9	LS/GT
Bushnellsville	2013	28,858	8,658	15	75	25	LS/GT
Broadstreet Hollow[2]	2001	17,992	4,678	13	86	14	LS/GT
Woodland Creek	2015	33,100	9,508	14	66	34	GT/LS
Beaver Kill	2009	50,338	26,175	26	71	29	GT/LS
Little Beaver Kill	2017	50,338	26,650	26	85	15	GT/LS
Lost Clove	2018	8,424	2,112	13	93	7	LS/GT
Hatchery Hollow	2018	9,105	4,520	25	85	15	GT/LS
Esopus Creek: Lost Clove to Bushnellsville Cr	2019	21,019	5,897	14	79	21	LS/GT
Esopus Creek upstream of Lost Clove	2019	51,298	9,553	9	77	23	LS/GT
Stony Clove Sub-basin SFI Results (2010–2015)							
Stony Clove Creek	2013	54,459	12,129	11	45	55	LS/GT
Ox Clove Creek	2015	6,696	1,161	9	70	30	GT/LS
Warner Creek[3]	2010	50,144	11,056	11	82	17	GT/LS
Hollow Tree Brook	2015	7,684	1,529	10	89	11	GT/LS
Myrtle Brook	2015	4,281	1,070	11	100	0	None

[1] % bank erosion = bank erosion length / 2(SFI stream length)

[2] Esopus Creek and Broadstreet Hollow data are from use of a SFI data dictionary that did not include bank geology as an attribute; other fields were used to interpret geology. As repeat SFIs occur, this data will be replaced.

[3] Warner Creek also has SFI data for 2011, 2012 and 2015. 2010 data is for full stream.

Table 4.2 Comparison of 2013 and 2018 SFI bank erosion data for Stony Clove Creek. The non-alluvial (N-AL) category includes erosional contact with lacustrine sediment, glacial till, colluvium and mapped mixes with alluvium. Reaches with STRPs are in italic font.

WQM Reach	WQM Reach Bank Length (ft)	2013 Bank Erosion[1] (%)	2018 total Bank Erosion (%)	2018 Active Bank Erosion (%)	2018 Dormant Bank Erosion (%)	2018 Recovered Bank Erosion (%)	2013 Erosional Contact N-AL (%)	2018 Erosional Contact N-AL (%)
1	1,679	0	4	0	4	0	0	0
2	17,708	9	9	5	1	3	71	70
3	*7,177*	*29*	*2*	*0*	*1*	*1*	*79*	*0*
4	*7,747*	*8*	*12*	*4*	*6*	*3*	*100*	*53*
5	*8,002*	*18*	*10*	*1*	*4*	*4*	*20*	*4*
6	*8,240*	*11*	*9*	*6*	*3*	*0*	*33*	*34*
7	7,785	7	10	7	3	0	36	17
8	10,837	18	12	7	4	1	52	28
9	*3,218*	*51*	*3*	*3*	*0*	*0*	*39*	*0*
10	18,995	7	9	6	3	0	37	36
11[2]	17,528	NA	4	2	2	0	NA	36

[1] % bank erosion = bank erosion length / 2(SFI stream length)

[2] WQM reach 11 was not mapped in 2013.

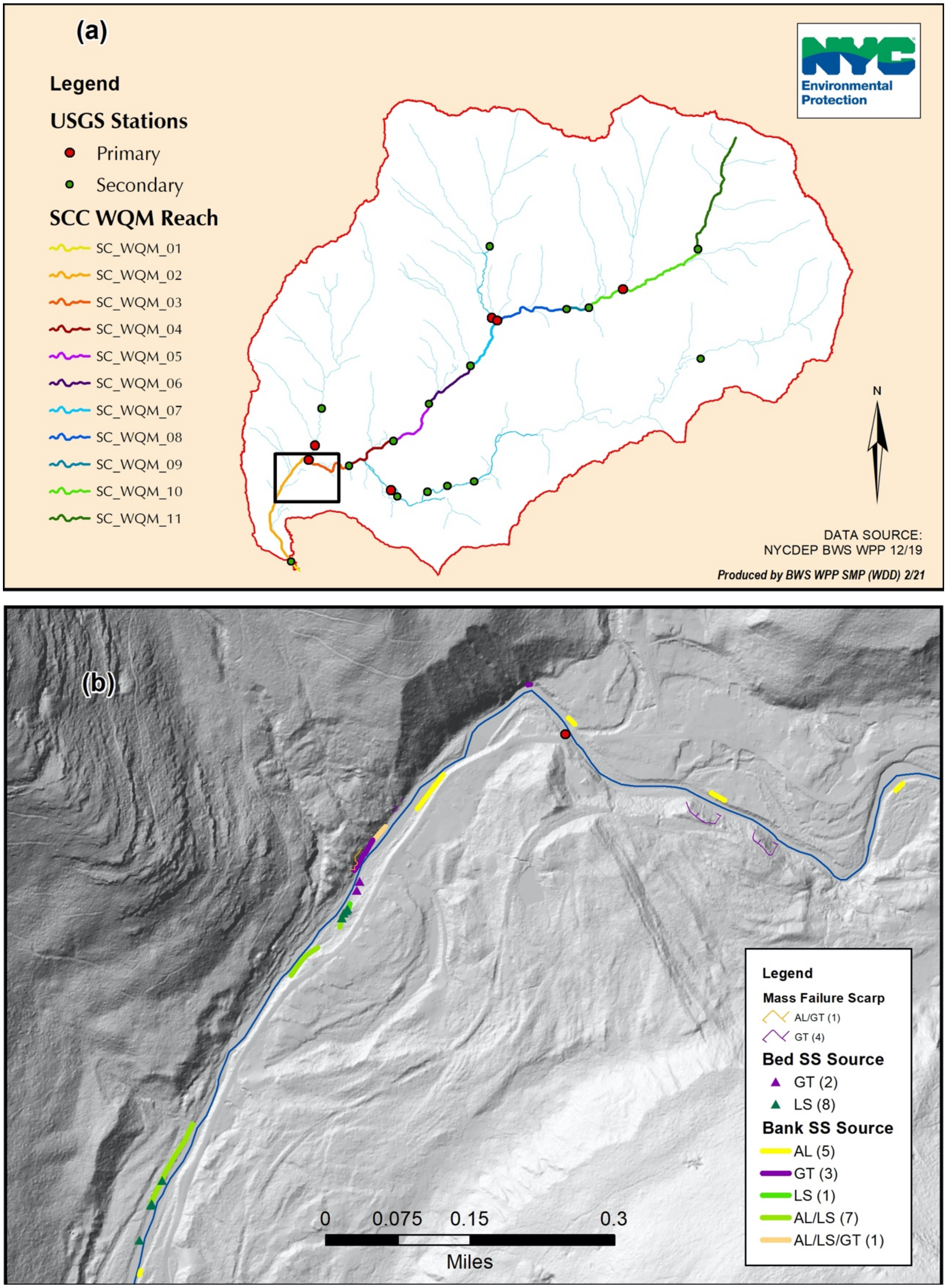


Figure 4.4 SFI mapping of SS sources in Stony Clove Creek as completed in 2018. Panel (a) shows the sub-basin and WQM Reaches. Panel (b) depicts the mapped streambed and bank SS sources classified by geology for the rectangular area shown in panel (a).

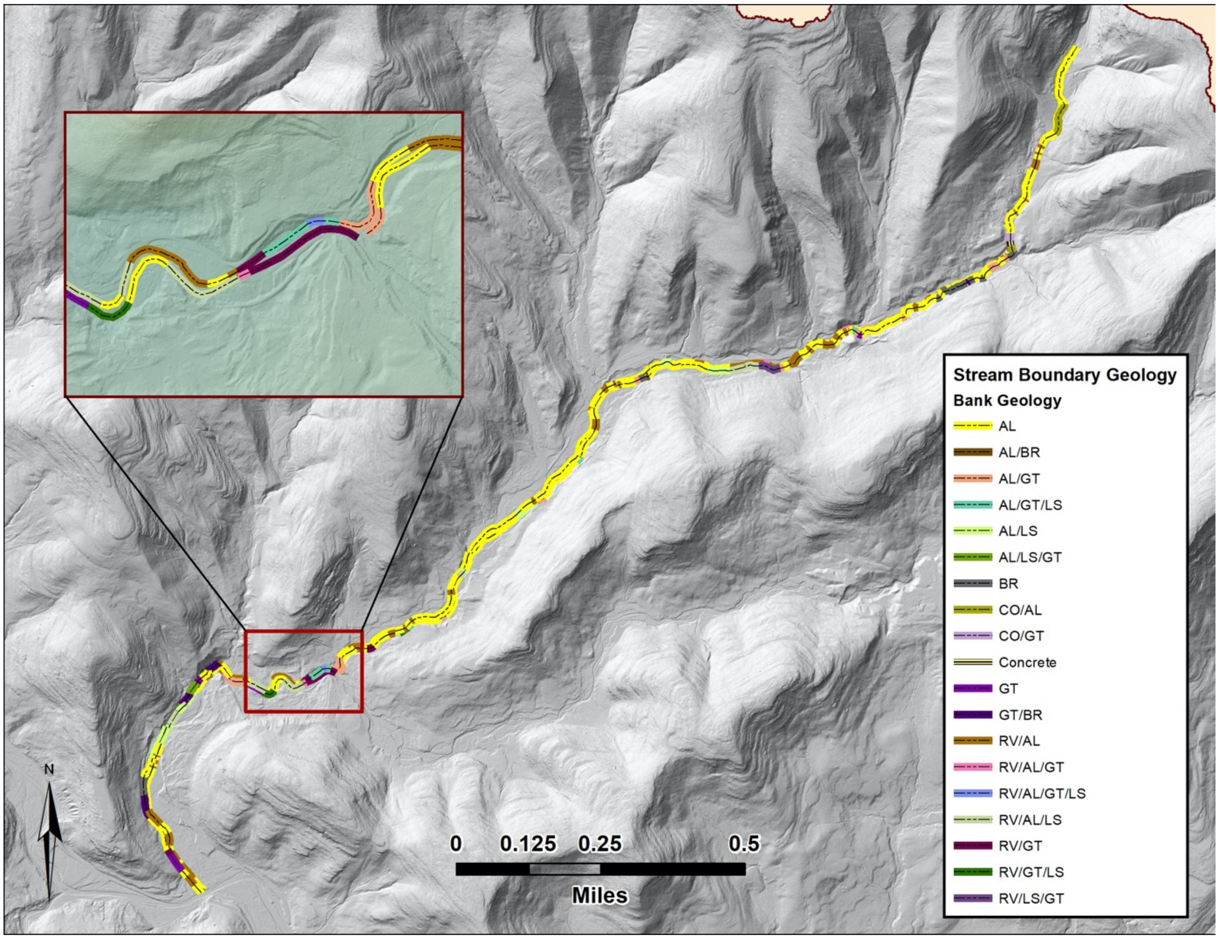


Figure 4.5 Stream channel geology map for estimating SS source potential. Symbol key: AL = alluvium, BR = bedrock, CO = colluvium, GT = glacial till, LS = lacustrine sediment, RV = revetment.

4.4 Stream Erosion Monitoring

The Study includes monitoring of site-to reach-scale bank erosion at a set of sites in the Stony Clove sub-basin. DEP established eight BEMS sites during the period 2016 to 2018, selected from previously mapped SS sources (Table 4.4 and Figure 4.6). This monitoring is performed by a private engineering firm (SLR, formerly MMI) under contract to DEP. SLR submitted an initial report in May 2019; a second report is planned for 2021. The results of both reports will be presented in the five-year report.

DEP presents examples of BEMS methods and results in this report. Monitoring includes topographic surveys, hydraulic modeling, geomorphic characterization, and stream bank sediment sampling for grain size analysis. Selected sites represent erosional SS source conditions expected to contribute measurable levels of SS and turbidity that can potentially be accounted for at downstream monitoring stations. Stream channel-hillslope connectivity with eroding glacial legacy sediment is present at all sites and channel bed incision into glacial legacy sediment is present at six sites.

The BEMS has three objectives: (1) to inform development of geomorphic metrics to help explain turbidity and SS flux dynamics, (2) to inform future STRP site selection, and (3) to monitor untreated sites as reference for comparison with treated sites. The first objective has been scaled back as a result of contracting delays with SLR as well as a need to compare alternative survey methods. SLR was able to survey some but not all of the sites in 2019 and 2020, resulting in a scaling back of DEP expectations in meeting the first objective. Three of the BEMS sites were approved as future STRPs moving to construction in 2021 (see Section 5.2). Additional BEMS sites will be added in 2021 to replace the three new STRP sites. At least two of the current BEMS sites are on New York State land and are not eligible for STRP status – these sites will be used to monitor untreated condition through the course of the Study.

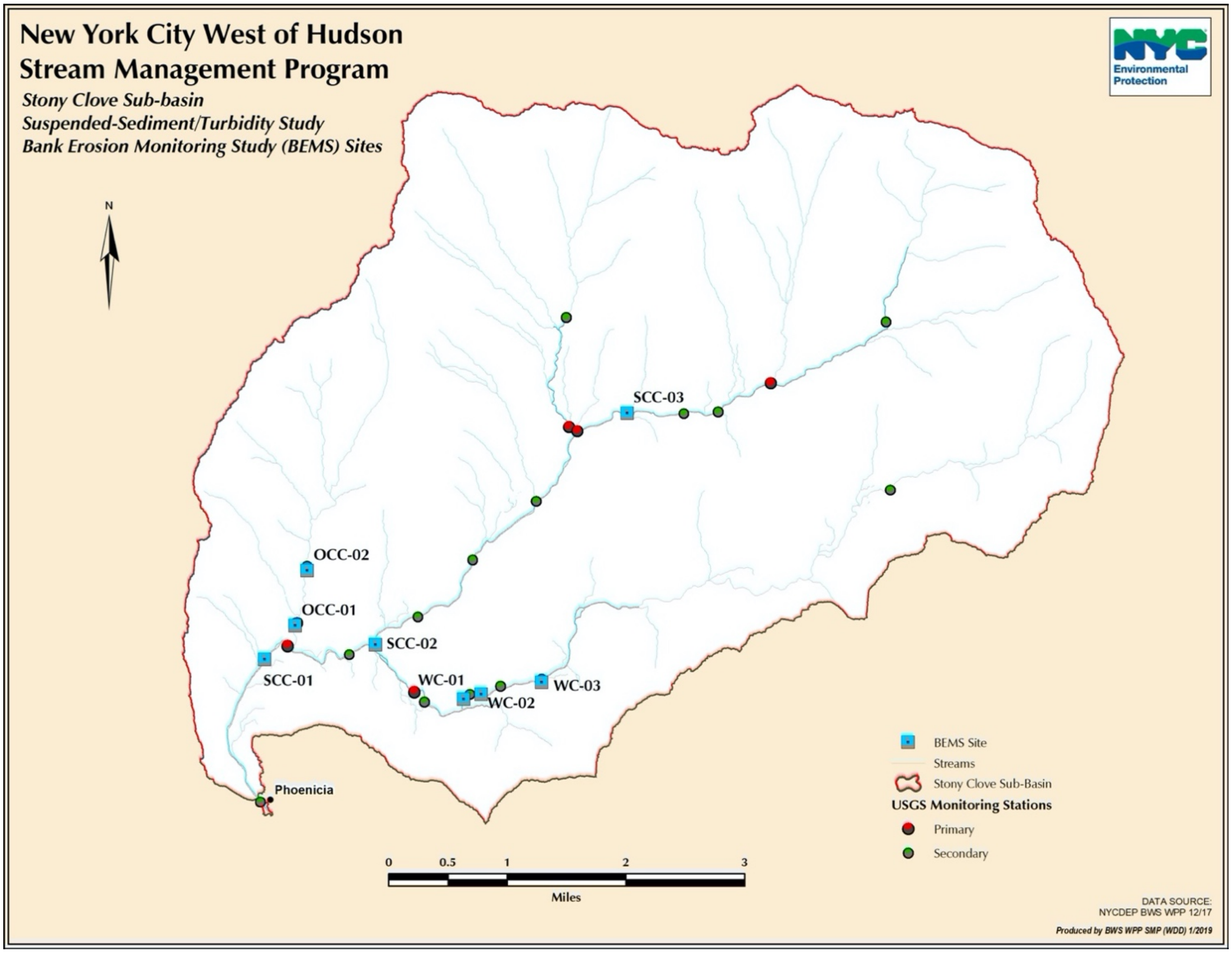


Figure 4.6 Stony Clove sub-basin BEMS locations and USGS monitoring stations.

Topographic Survey

The original Study methods detailed use of standard fluvial geomorphic survey methods comprising longitudinal profile and cross-section surveys using self-leveling laser levels. DEP has worked with SLR to adopt more advanced methods. Modified methods now include use of total station equipment to survey the stream channel, banks and adjacent terrain to produce topographic maps rather than just cross-sections and longitudinal stream profiles. In 2017, SLR pilot-tested use of Unmanned Aerial System (UAS) technology (drones) to develop higher resolution topographic surfaces using Structure-from-Motion (SfM) techniques at two of the BEMS locations (OCC-01 and WC-02). From 2018 to 2020, the SfM technique was incorporated into surveys at the three Warner Creek BEMS sites and the Stony Clove Creek SCC-03 BEMS site.

SfM is the process of estimating 3-D structure (e.g., topography) from a set of 2-D images. The process reconstructs 3-D scenes from SfM algorithms based on the derived positions of multiple photographs in 3-D space. The final product includes both high-resolution imagery and a dense georeferenced point cloud, which can be used to create a variety of digital elevation products (e.g., DEMs). SLR compared the SfM-derived topographic surfaces with the land-based survey surfaces and concluded the SfM method was more representative of actual surfaces and could yield better estimates of geomorphic change. Discrete profile surveys (cross-sections) can only provide estimates of bank retreat/sediment loss at one discrete location, whereas topographic surveys covering the entire eroding bank can provide more accurate estimates of aerial retreat and volumetric sediment loss. A limitation with this method is vegetation or snow cover obscuring terrain, which is primarily controlled for by having all surveys occur during leaf-off conditions with no (or minimal) snow cover. Table 4.4 summarizes the status of topographic surveys for all current BEMS sites through 2020. Figure 4.7 presents provisional SfM survey results and a high resolution UAS-based ortho photo composite at SCC-03. BEMS SCC-03 represents a future STRP SCC3.

Several sites received multiple re-surveys while others only had one or two (Table 4.4). This is largely due to two factors: (1) priority for STRP site selection (WC-01, WC-02, and SCC-03), and (2) DEP contractual delays with SLR. DEP initiated a new BEMS scope of work with SLR in December 2020 that will continue through 2022. This scope now includes fixed frequency surveys for each BEMS site in addition to the other work described below.

Hydraulic Modeling

The BEMS methods include developing hydraulic models with HEC-RAS using the topographic survey data and the existing FEMA flood study models available for the Stony Clove sub-basin. The hydraulic modeling simulates flood hydrology/hydraulics through the BEMS reaches. The modeling can be used to simulate sediment transport and bank failure as well as inform conceptual and final STRP designs. Calibrated hydraulic models for SCC-03, WC-01 and WC-02 are complete. These models are also being used to inform STRP design.

Hydraulic models will be developed for the additional BEMS sites by SLR starting in 2021. Figure 4.5 presents an example of 2-D hydraulic modeling results for SCC-03.

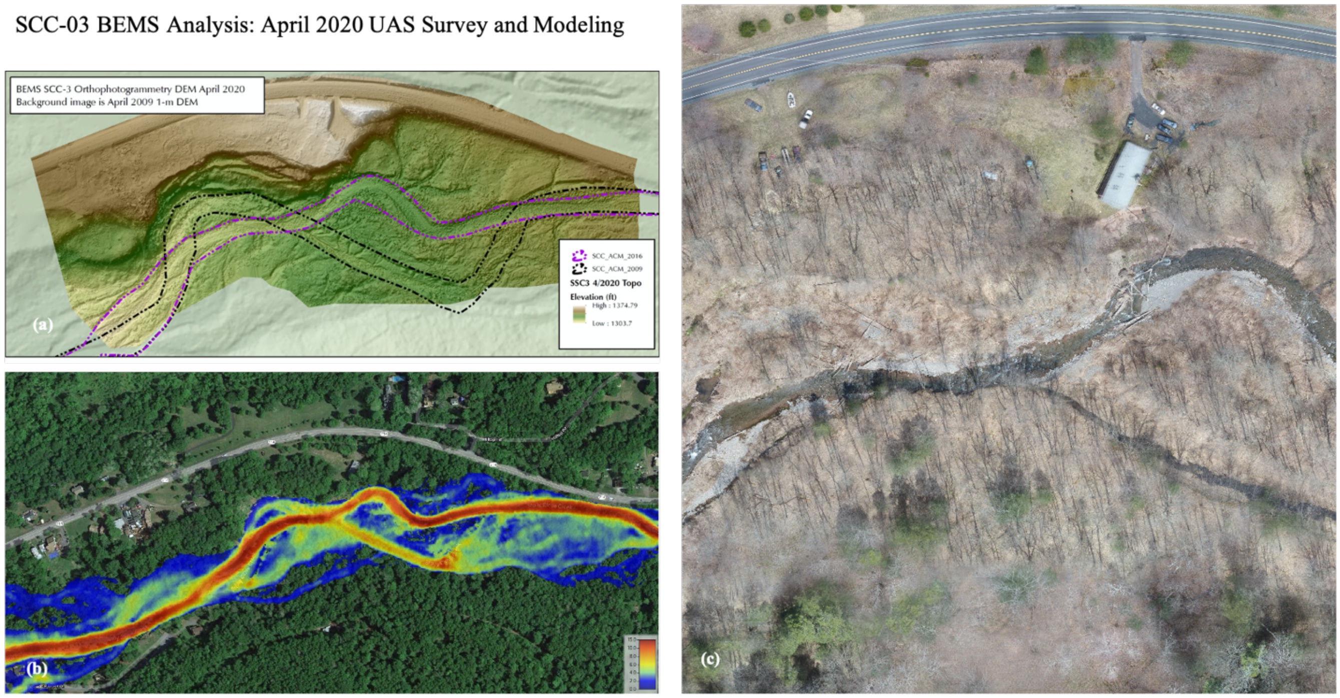


Figure 4.7 Examples of BEMS UAS survey results and hydraulic modeling at SCC-03: (a) high resolution DEM derived from orthoimagery, (b) 2-D hydraulic model depicting velocity gradients for a simulated 50-year flood, (c) high resolution orthoimagery used to develop topography data.

Geomorphic Characterization

Geomorphic characterization at each site includes an initial Rosgen stream type classification, Rosgen bank erosion hazard index (BEHI) and near bank stress (NBS) ranking, and repeat Wolman pebble counts for streambed surface grain size frequency distribution. DEP provides interpretation of stream channel/corridor geology. DEP's five-year summary report will include details on each BEMS site's geomorphic characterization.

Stream Bank Sediment Sampling

DEP assesses stream bank stratigraphy for each BEMS site to identify SS source sediment types. SS source sediment types are categorized into groups based on depositional process: alluvial and non-alluvial sediment. The alluvial sediment comprises stream sediment exposed in eroding banks. The non-alluvial sediment includes pro-glacial lake (lacustrine) sediment, glacial till, and colluvial sediment. Descriptions are covered in Section 4.5. Representative samples of each sediment type at most of the BEMS sites have been collected and analyzed for grain size distribution. A summary of the results is presented in Table 4.5.

Table 4.4 Stony Clove sub-basin BEMS status table.

Site	Started	Survey Dates	Survey Method[1]	Sediment Analysis[2]	Description[3]
SCC-01	2017	12/2017	TS	Yes	Mass wasting of AL/GT in right VM; Bank erosion in LS on left ACM.
SCC-02	2017	12/2017	TS	No	Mass wasting of GT in left VBM (moraine); Channel incision in GT.
SCC-03	2018	04/2018 01/2019 04/2020 11/2020	SfM	No	Mass wasting of AL/LS in right VBM (delta terrace); Channel incision in LS. Bank erosion in AL/LS in left ACM.
WC-01	2016	11/2016 07/2017 04/2018 12/2018 04/2020 11/2020	TS SfM	Yes	Mass wasting of AL/LS in right VBM (terrace); Channel incision in LS.
WC -02	2016	11/2016 07/2017 11/2017 12/2018 04/2020 11/2020	TS SfM	Yes	Mass wasting of AL/LS in left VBM (terraces); Channel incision in LS; Former avulsion
WC-03	2016	07/2017 05/2018 04/2020 11/2020	TS SfM	Yes	Mass wasting of AL/GT?/LS in left VM; Channel incision in LS.
OC-01	2016	11/2016 11/2017	TS SfM	Yes	Mass wasting of GT in right VBM (moraine).
OC-02	2017	7/2017	TS	Yes	Mass wasting of AL/LS/GT? in left VBM (glacial terrace); Channel incision in LS

[1] Survey methods included land-based topographic surveys with total station (TS) and UAS-based Structure from Motion (SfM) surveys.

[2] Sediment grain-size distribution analyses were completed for several sites to get representative ranges of fine sediment content (clay-silt) in the sampled sedimentologic units.

[3] Symbol key: AL = alluvium; GT = glacial till; LS = lacustrine sediment; VM = valley margin; VBM = valley bottom feature margin; ACM = active channel margin. If a “?” follows a geologic unit, its presence is not certain.

4.5 Source Sediment Analysis

Distinct geologic sediment sources (sedimentologic units) exposed in the streambed, stream banks and channel-connected hillslopes can supply SS through the process of stream, erosion and mass wasting. DEP defines a sedimentologic unit as a mappable geologic source of sediment that is identifiable in the field. Each has distinct sediment size distribution and erodibility characteristics. As described in Section 4.3, there are two general categories for SS source sediment analyzed in this Study: alluvial and non-alluvial sediment. DEP and UCSWCD currently map four distinct sedimentologic units exposed in eroding stream channels and mass wasting hillslopes:

Holocene and Pleistocene alluvium – stream-sorted unconsolidated alluvium composed principally of sand to small boulder size material with interstitial finer grained sediment. Alluvium present in some high terraces along the valley margins are possibly from Pleistocene glacial meltwater streams and may have a higher fine sediment content. Holocene (post-glacial to present) streams deposited alluvium now stored in stream banks and low to moderately high fluvial terraces. This is the typical and most abundant material exposed in the active eroding valley bottom. Examples of Holocene and Pleistocene alluvium are included in Figure 4.8a and 4.1c,d.

Glacial Till – unsorted and typically over-consolidated aggregation of sediment ranging in size from clay to boulders. Coarser sediment is embedded in a dense silty-clay matrix. It was deposited sub-glacially as lodgement till or supra-glacial as moraines. Glacial till is typically connected to streams via valley wall slopes or glacial moraine/terrace hillslopes. It can also be exposed in streambed headcuts and channels that have incised below the stream alluvium. An example of glacial till exposed in an eroding stream bank is included in Figure 4.8b.

Lacustrine sediment (pro-glacial lake deposits) – stratified and cohesive layers of clay, silt and some sand deposited subaqueously in impounded glacial meltwater. Lacustrine sediment in the Study area is a complex distribution of fine sediment representing a range of lake setting (facies) deposits, from near shore, shallow depth deposits with higher sand content to deeper basin deposits with no sand. Valley-filling pro-glacial lakes formed as continental ice sheet lobes advanced and retreated in the Esopus basin from the Hudson River valley, with ice margins preventing glacial meltwater from draining out of the ice-blocked basin. Some of these lakes are hypothesized to have occupied much of the UEC basin below about 1,850 ft asl (Rich 1935). Other "lakes" were smaller impoundments during the chaotic deglaciation period. The result is a heterogeneous distribution of lacustrine facies deposits ranging in thickness from less than a few feet to tens of feet as measured in exploratory drilling. In the fluvial system, this unit is commonly exposed along the toe of eroding stream banks and as distinct layers in mass wasting hillslopes. It can also be exposed in streambed headcuts and channels that have incised below the stream alluvium. Examples of layered glacial lacustrine sediment exposed in an eroding stream channel is included in Figure 4.8c and 4.1d.

Colluvium – unsorted and variably consolidated aggregation of sediment ranging in size from clay to boulders. Terrestrial erosional processes such as mass wasting on hillslopes deposit colluvium downslope. This is the most common sedimentologic unit present at the toe of dormant or recovering stream channel-hillslope coupled stream banks. It is often a mix of two or more of the other sedimentologic units and can be very variable in sediment composition. An example of colluvium exposed in a mass wasting hillslope composed of alluvium, glacial till and lacustrine sediment is included in Figure 4.8d.

DEP used Stony Clove sub-basin SFI mapping and DEM analysis to produce a stream channel geologic map depicting the probable lateral and longitudinal distribution of sedimentologic units with some connectivity to the stream network (Figure 4.5). The mapped data also includes the presence of bedrock and revetment. This spatial data can be used in conjunction with sediment connectivity mapping to predict potential SS supply. DEP plans to expand the mapping to the other Stony Clove monitored streams.

In 2017, DEP and USGS introduced SS source fingerprinting as a source sediment characterization Study method. The AWSMP funded this pilot study, led by the USGS Maryland Water Science Center, to test the hypothesis that sedimentologic units are detectable as source material in sampled SS. DEP's 2019 biennial status report provided some preliminary results of the pilot effort. For example, the one complete storm hydrograph sampled in Woodland Creek confirmed an assumption that stream connectivity to lacustrine sediment is a primary source for chronic SS load following storm events. Based on the promising preliminary results of the pilot, USGS and DEP have integrated this methodology into the Study. Sediment fingerprinting will resume following registration of the successor USGS contract in 2022; publication of the results will follow.

DEP, USGS and SLR advanced geologic source sediment characterization through grain size analysis of bulk samples representing the different sedimentologic units exposed in eroding stream banks and hillslopes at BEMS locations and at sampling sites for the SS source fingerprinting pilot study. Results of the initial round of sampling are summarized in Table 4.5.

Figure 4.8 Examples of the four primary sedimentologic units mapped using SFI methodology: (a) unconsolidated alluvium, (b) consolidated glacial till, (c) cohesive lacustrine sediment, (d) unconsolidated colluvium from mass wasting of alluvium, glacial till and lacustrine sediment.

Table 4.5 SS source sediment grain size distribution analysis using samples from Stony Clove sub-basin BEMS sites.

Sample	Sediment Unit[1]	% Clay	% Silt	% Sand	% > Sand	% Fines
SC1-LS1	LS	22.3	15.2	62.5	0	37.5
SC1-GT1	GT	22	14.2	26	37.8	36.2
SC1-LS2	LS	50.9	49	0	0	99.9
WC1-AL1	AL	0	0	17	83	0
WC1-LS1	LS	51.7	15.3	33	0	67
WC1-LS2	LS	53.6	16.4	30	0	70
WC2-LS1	LS	53	22	24.8	0.2	75
WC2-AL1	AL	0	0	6	94	0
WC2-AL2	AL	0	0	8	92	0
WC3-LS1	LS	53.2	20.8	25.9	0.1	74
WC3-LS2	LS	56.4	18.6	25	0	75
WC3-LS3	LS	53	22	23	2	75
OC1-CO1	GT	23.8	4.8	28.8	42.6	28.6
OC1-CO1	CO	9.6	3.8	37.5	49.1	13.4
OC1-CO2	CO	14.7	3.7	16.4	65.2	18.4
OC2-AL1	AL	1.8	6.2	16.9	75.1	8
OC2-LS1	LS	55.6	43.8	0.6	0	99.4
OC2-LS2	LS	54.9	44.8	0.3	0	99.7

[1] Sediment Unit key: LS = lacustrine sediment; GT = glacial till; AL = alluvium; CO = colluvium

4.6 Stream Morphodynamic Modeling

Between 2019-2020, DEP collaborated with Cornell University on testing the use of a spatially distributed mechanistic model to simulate stream power as a driver of stream channel erosion and SS load and yield. With input from DEP, Cornell researchers constructed and calibrated a stream network scale model of the Stony Clove sub-basin using the River Erosion Model (REM) developed by Colorado State University (Lammers and Bledsoe, 2018). The REM model comprises a set of linked stream reaches representing a stream network. The model developed for the Stony Clove sub-basin includes all monitored streams. A stream power-based sediment transport equation and a geotechnical failure algorithm are used to simulate streambed and bank erosion. The Stony Clove sub-basin model was developed using the 2009 1-meter DEM to obtain stream slope and stream channel geometry, and was further parameterized by using estimates and assumed bank and bed material properties, partially informed by the SFI and BEMS data. Continuous daily streamflow from the Stony Clove Creek primary monitoring station #01362370 was used to estimate a streamflow time series for every modeled reach.

This modeling work is part of an ongoing doctoral research project that uses mechanistic and probabilistic modeling to evaluate impacts of changes in hydrology and changes in basin and stream reach conditions on SS dynamics. Using the modeling methods, Cornell researchers evaluated the impact of the Stony Clove sub-basin STRPs and the period of low magnitude flood hydrology on observed SS dynamics. There was sufficient agreement between model predictions and measured spatial variation in erosion and entrainment of SS source material to evaluate the relative roles of STRPs versus decadal-scale variation in higher magnitude flows on sub-basin scale SS dynamics. The 2020 REM modeling results were presented at the annual American Geophysical Union conference in December 2020 (Wang, et al. 2020) and a peer-reviewed journal manuscript is planned for submission in early 2021.

5. Sediment and Turbidity Reduction Projects

One of the primary goals of the Study is to evaluate the efficacy of STRPs in the Stony Clove sub-basin on measurably reducing turbidity and SSC at a range of spatial, temporal and hydrologic scales. It is still too early in the scope of the current Study to present any conclusive findings on this goal. DEP anticipates a first thorough presentation of the preliminary findings in its five-year summary report due November 2022. In addition to that FAD report, DEP is collaborating with USGS and Cornell University researchers on two peer-reviewed journal articles that will present different approaches to evaluating STRP turbidity reduction efficacy.

For purposes of this report, USGS provided updated SSC-Q relations in the Warner Creek and Stony Clove Creek sub-basins. This report will also summarize the recent modeling work by Cornell University researchers on evaluating STRP efficacy. Information and photos of all STRPs can be accessed via the interactive Catskill Streams website: https://catskillstreams.org/stream-management-program/project-maps/.

5.1 Existing STRPs

Esopus Creek Basin STRPs

Though STRPs constructed outside the Stony Clove sub-basin are not explicitly part of the Study, DEP and USGS track when and where they are constructed. If observed measurable reductions in turbidity and SSC at the sub-basin scale coincide with STRP implementation and project monitoring surveys performed by UCSWCD determine sustained geomorphic stability and removal of erosional contact with SS sources, then DEP can investigate the available data to assess if turbidity reductions are associated with STRPs. There were no STRPs constructed in the UEC basin during 2019 to 2020. The AWSMP funded upstream and downstream turbidity monitoring by USGS for the 2018 Woodland Creek STRP as a separate evaluation effort. USGS completed monitoring at that location in 2020. Regression of before and after STRP construction monitored turbidity shows that the STRP was effective at measurably reducing turbidity for the brief monitoring period.

Stony Clove Sub-basin STRPs

DEP funded the design, construction and morphometric monitoring of eight STRPs in the Stony Clove sub-basin from 2012 to 2016 (Figure 5.1). UCSWCD managed all STRP work with the exception of the Stony Clove Creek at Lanesville STRP, originally completed as a stream restoration demonstration project in 2006 by Greene County SWCD. Post-Irene flood damage in 2011 to this project required revised engineering design and implementation completed in 2015; this project was subsequently incorporated into the set of Stony Clove STRPs.

The Study design includes “bracketing” most existing STRPs with upstream and downstream monitoring stations in an attempt to detect differences in turbidity above and below monitoring reaches that have STRPs. The timing of the Study started after the construction of the existing STRPs preventing before/after analysis for all but one STRP. The set of STRPs will be evaluated for the cumulative sub-basin scale effect as detected at the long-term Stony Clove Creek monitoring station 01362370 and the Warner Creek monitoring station 01362357.

UCSWCD conducts recurrent post-construction morphometric monitoring for all STRPs as part of the stream disturbance permit requirements for each project. Note that the description for the physical condition of the STRPs excludes impacts from the December 25, 2020 flood, which DEP will discuss in its five-year summary report. Monitoring includes photos, longitudinal profile surveys, cross-sectional surveys and pebble counts. Through water year 2020, DEP did not observe any resumed stream channel erosional contacts with non-alluvial SS source sediment at any of the eight STRPs. There were observed channel adjustments from in-stream deposition and minor erosion at several sites, and some minor ongoing mass wasting on stabilized hillslopes. The Stony Clove Creek at Stony Clove Lane project reach includes an adjacent mass wasting hillslope composed of glacial till and lacustrine sediment. The ongoing mass wasting in the hillslope is related to upland drainage, freeze-thaw process and direct precipitation runoff. The toe of the slope is protected by a two-tiered rock wall to prevent stream erosion from triggering mass wasting. This site is known to contribute measurable turbidity following rain events and freeze-thaw conditions recorded at station #01362350 which is located at the downstream end of the project (Figure 3.7).

Past research by USGS and DEP concluded that cumulative STRPs in the Stony Clove sub-basin appear to reduce turbidity and SS flux and yield for a limited range of streamflow for a short monitoring period following implementation (Siemion, et al. 2016). Status of ongoing sub-basin scale monitored SS flux is presented in this report for Warner Creek and Stony Clove Creek.

USGS station #01362357 on Warner Creek monitors the sub-basin scale SS flux and turbidity response to hydrologic conditions and STRPs. The Warner Creek "Site 5" STRP constructed in 2013 is the only STRP in the sub-basin. The pre-treatment site condition was a chronic source of turbidity from a channel-hillslope coupled mass failure in lacustrine sediment that contributed SS in non-flood conditions. The initial analysis (upper panel in Figure 5.2) showed an immediate post-project reduction in the SSC-Q relationship. The SSC-Q relationship during the first three years of the Study period (2017-2019) is trending back toward pre-construction conditions for the observed range in streamflow for that time, though there is still a clear reduction (lower panel in Figure 5.2). The 2020 water year data is still under USGS review.

Monitoring above/below the Warner Creek STRP for the current Study period shows an increase in turbidity through the monitored reach (Stations #01362356 and #01362357 in Figure 3.8). Since construction, the STRP has adjusted in response to storm hydrology, yet there are no observable erosional exposures of lacustrine sediment for the reporting period. One possible explanation is that there may be groundwater discharge-driven turbidity generated through this reach associated with the hydraulic head of a large impoundment on the terrace above the former mass wasting hillslope. The STRP included sub-surface drainage at the top and bottom of the regraded slope, which may be losing efficacy over time.

Figure 3.8 shows that there are significant turbidity sources upstream of the STRP reach that are actively contributing to the SSC-Q observed in the lower panel of Figure 5.2. The three BEMS sites in Warner Creek monitor chronic erosional contacts with lacustrine sediment and are separated by the turbidity monitoring network. Two of the BEMS sites are scheduled for STRP construction in 2021.

USGS monitoring station #01362370 on Stony Clove Creek is used to monitor the sub-basin scale SS flux and turbidity response to hydrologic conditions and STRPs. Figure 5.3 presents the SSC-Q monitoring results for the period through water year 2019. Prior to the first STRP constructed in 2012, Stony Clove Creek turbidity, SS flux and yield was statistically significantly higher than any of the other UEC sub-basins (McHale and Siemion 2014; Siemion et al., 2016). Turbidity and SS flux was elevated during and following the extreme hydrologic conditions in 2010 through 2011 (Figure 3.4).

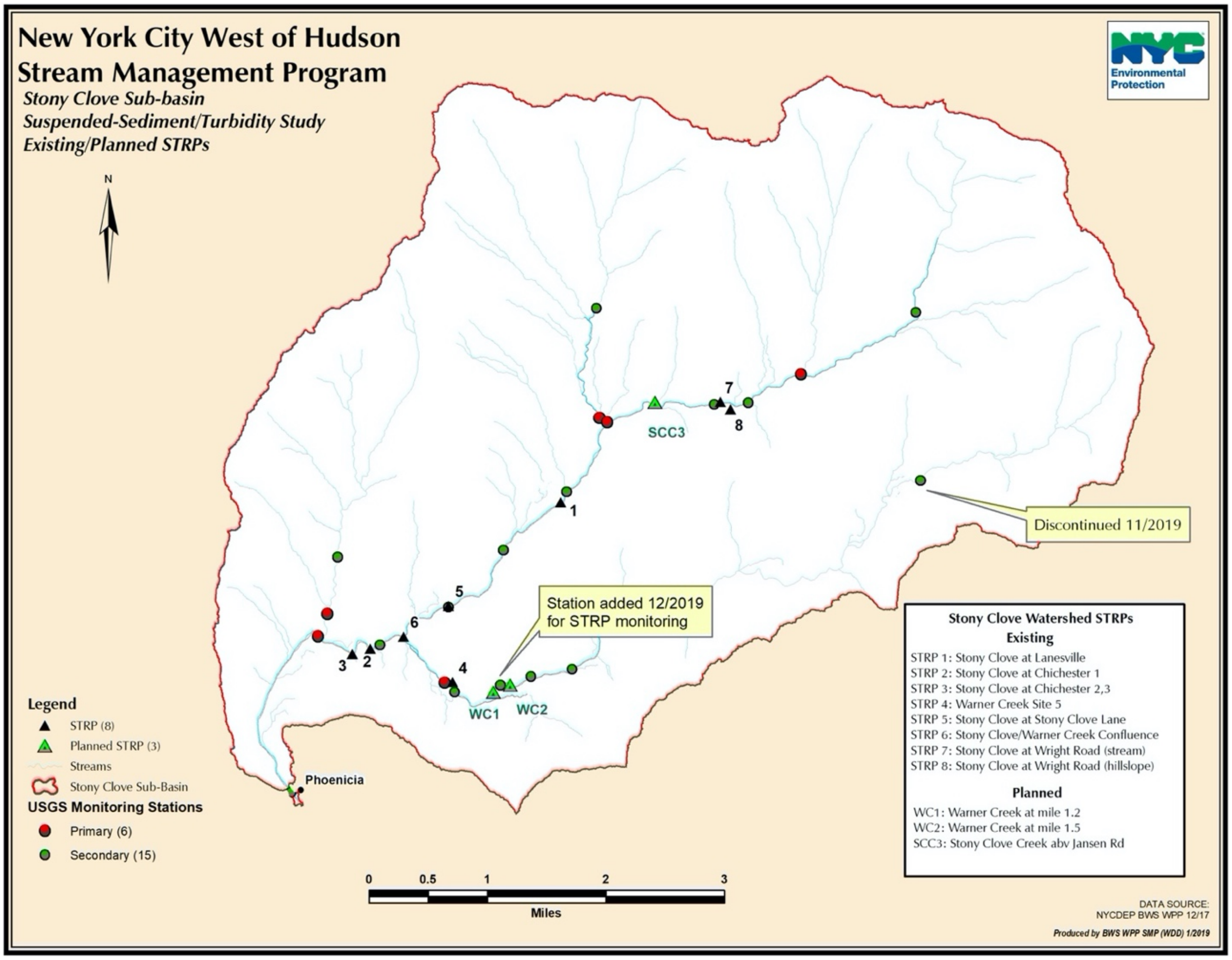
The elevated pre-construction SSC in Figure 5.2 represent a period of elevated turbidity and SS flux. All eight STRPs in the Stony Clove sub-basin were constructed during the five years following that active period. Between 2012 to 2013, three STRPs were constructed at sites previously identified as producing chronic turbidity in the sub-basin. The upper panel in Figure 5.3 shows that there was a substantial reduction in the SSC-Q relationship in the year following those initial STRPs. The reduction is more consistent for the lower Q conditions than the higher Q conditions. The SSC-Q relationship during the first 3 years of the Study period (lower panel of Figure 5.3) shows a sustained substantial reduction during the post-STRP implementation period. The Study data also extends the monitored Q into the lower range, showing consistently lower SSC-Q achieved through separating channels from hillslope sources. It is also clear in the Study data that as daily mean Q increases and approaches 1,000 cfs, the reduction in SSC-Q is less consistent. Further monitoring over the next few years may provide more data for assessing if there is an upper hydrologic limit to the efficacy of STRPs on influencing sub-basin scale turbidity and SS flux dynamics during a flood event when new SS sources can be activated. If the STRPs remain functional through a flood event, it is reasonable to assume that their efficacy would help reduce the SSC in the falling limb of the flood.

As previously described, the period following 2012 up to the December 25, 2020 flood was a prolonged period of hydrologic conditions that allowed the UEC basin fluvial system to recover some geomorphic stability from the 2010-2011 hydrologic disturbance period. Recent research by Cornell University examines how much of the reduced SSC-Q relationship in the Stony Clove sub-basin observed during the Study period is attributable to natural geomorphic recovery leading to less sediment connectivity, and how much is attributable to the STRPs. Figure 5.3 demonstrates an immediate change in the SSC-Q relationship following the implementation of the STRPs in 2012 to 2013, even though this was not long after the disturbance period. This indicates STRP efficacy as a primary explanation for SSC-Q reduction for that time period. The modeling results support this finding and extend the STRP efficacy through the full monitoring period, though there is an apparent reduction also associated with the hydrology. Final results of this research will be included in DEP's five-year summary report.

5.2 Future Stony Clove STRPs

In January 2019, DEP proposed three priority STRPs in the Stony Clove sub-basin based on water quality monitoring data and the BEMS geomorphic assessment. The proposed STRPs include two reaches on Warner Creek (WC1 and WC2) and one reach on Stony Clove Creek (SCC3; note that SCC3 was referred to as SCC1 in the 2019 report and the number has been changed to be consistent with the BEMS site IDs) as depicted in Figure 5.1. Monitoring results presented in past Study reports (DEP 2019a; DEP 2019b) showed that Warner Creek was (and remains) the highest turbidity and SS yielding sub-basin source within the Stony Clove sub-basin. Using mean daily turbidity values for water years 2017-2018 and storm event turbidity values recorded at each monitoring station, USGS and DEP confirmed significant measurable increases in turbidity attributed to the proposed treatment locations. The two Warner Creek sites (WC1 and WC2) were located between two monitoring stations until November 2018, when USGS relocated the uppermost monitoring station (#01362354) from a problematic location to a location between WC1 and WC2 where the new station (#0136235585) will better serve to monitor the potential turbidity reduction effects associated with each project.

UCSWCD contracted with an engineering firm to design the three projects. The two Warner Creek projects were originally intended to be constructed in 2020, however delays associated with the design process and the COVID pandemic postponed planned construction until 2021. The designs are complete for both sites and UCSWCD is advancing the design for SCC3, also planned for construction in 2021. If all three STRPs are constructed in 2021, this will allow for five years of post-construction monitoring per the Study design.



New York City West of Hudson Stream Management Program
Stony Clove Sub-basin
Suspended-Sediment/Turbidity Study
Existing/Planned STRPs

Discontinued 11/2019

Station added 12/2019 for STRP monitoring

Stony Clove Watershed STRPs
Existing
STRP 1: Stony Clove at Lanesville
STRP 2: Stony Clove at Chichester 1
STRP 3: Stony Clove at Chichester 2,3
STRP 4: Warner Creek Site 5
STRP 5: Stony Clove at Stony Clove Lane
STRP 6: Stony Clove/Warner Creek Confluence
STRP 7: Stony Clove at Wright Road (stream)
STRP 8: Stony Clove at Wright Road (hillslope)

Planned
WC1: Warner Creek at mile 1.2
WC2: Warner Creek at mile 1.5
SCC3: Stony Clove Creek abv Jansen Rd

DATA SOURCE:
NYCDEP BWS WPP 12/17

Produced by BWS WPP SMP (WDD) 1/2019

Figure 5.1 Stony Clove sub-basin existing and nominated future STRPs.

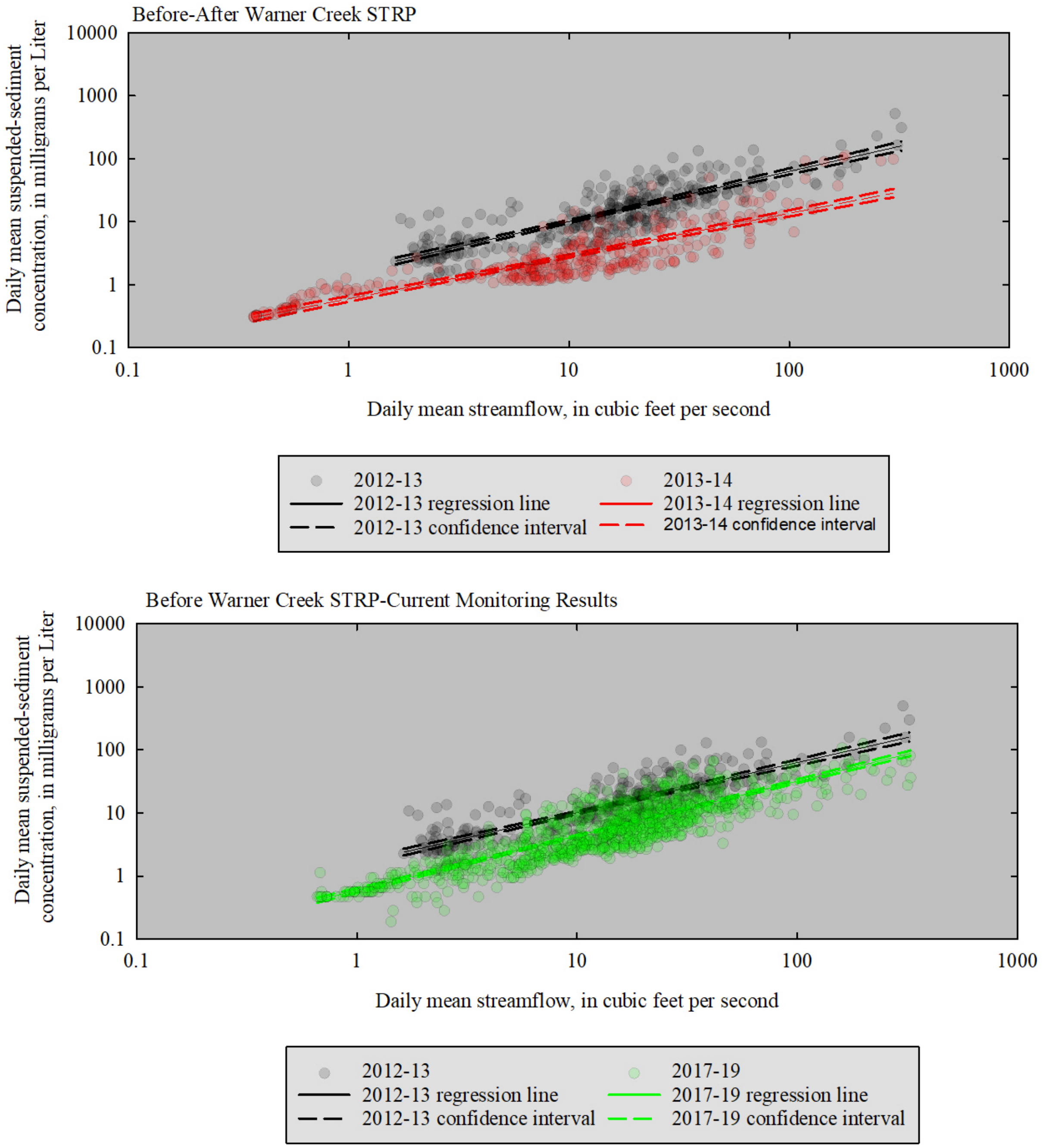


Figure 5.2 Plots provided by USGS. SSC-Q relations through time for Warner Creek primary station #01362357. The upper panel plots the pre-construction and first-year post-construction results showing a clear reduction in SSC for the monitored streamflow range. The lower panel plots SSC-Q for the pre-construction period and for Study period water years 2017-2019 showing a trend toward decreasing SS flux reduction for the monitored streamflow range.

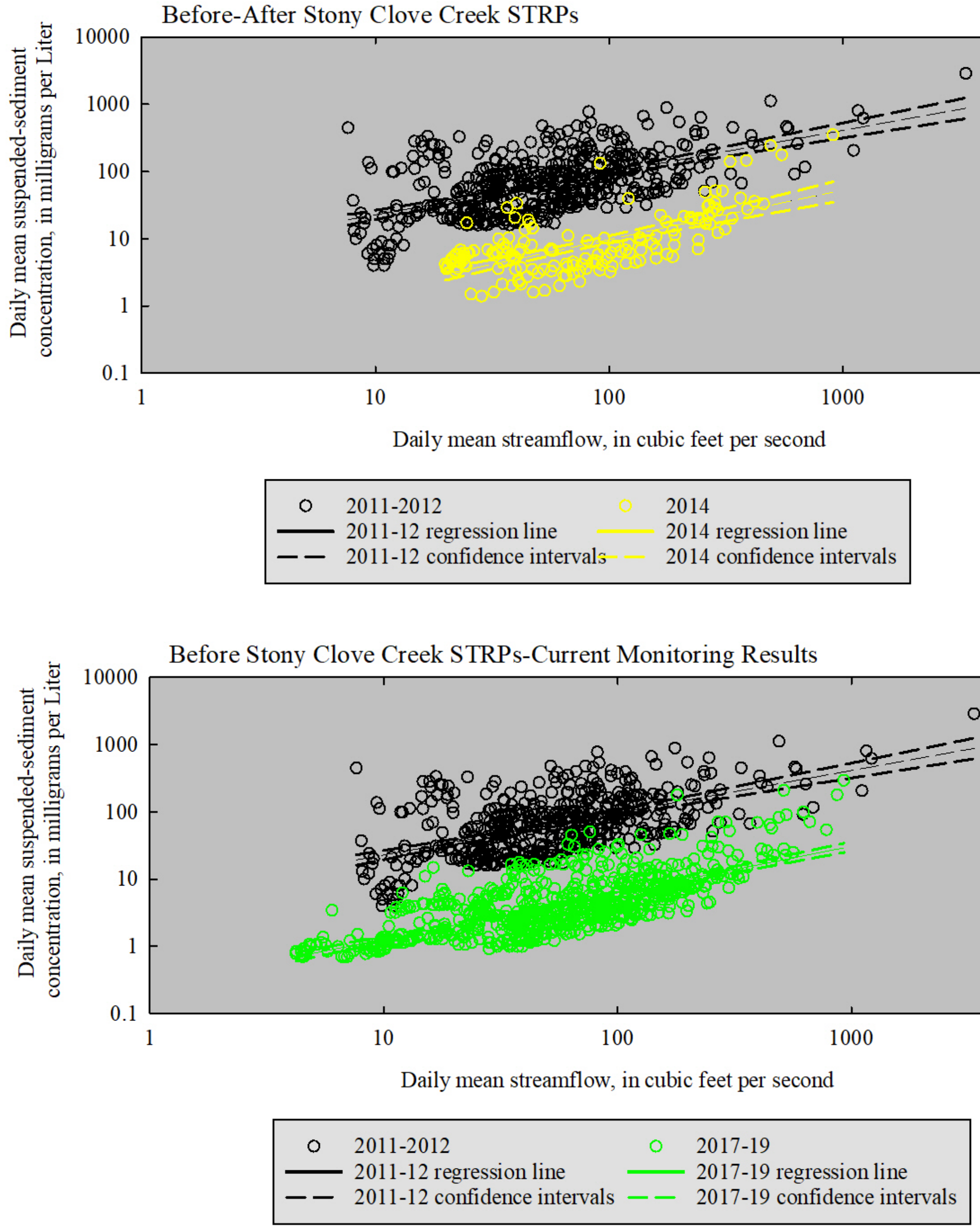


Figure 5.3 Plots provided by USGS. SSC-Q relations through time for Stony Clove Creek primary station #01362370. The upper panel plots the pre-construction period and post-construction results following STRP construction in 2012 and 2013 showing a clear reduction in SSC for the monitored streamflow range. The lower panel plots SSC-Q for the pre-construction period and for Study period water years 2017-2019 showing a sustained trend in SS flux reduction for the monitored streamflow range.

6. Conclusions

The USGS has successfully completed the first four water years of monitoring streamflow, turbidity and SS while DEP continues to quantitatively characterize geomorphic connectivity to turbidity/SS sources. DEP used water quality and geomorphic monitoring to select three new STRPs planned for 2021 construction and integrated into the Study. The data are already proving useful for stream management in the Ashokan Reservoir basin. In October 2020 DEP and USGS presented the preliminary findings of the monitoring data to the AWSMP to help inform future stream assessment and turbidity reduction management efforts. Woodland Creek, Birch Creek, Beaver Kill and Stony Clove Creek are highlighted as disproportionately higher contributors of turbidity in the basin.

Preliminary results of STRP monitoring indicate that for the observed range of streamflow conditions through water year 2020, the Stony Clove sub-basin STRPs are effective in reducing turbidity and SSC. The December 25, 2020 flood was a significant geomorphic disturbance in the Study area and will certainly impact turbidity and SS dynamics in water year 2021; however, the sustained high turbidity monitored in Stony Clove sub-basin following the flood was not evidently sourced by the STRP sites. New turbidity sources were exposed by the geomorphic response to the flood. The new sources will be mapped in 2021 and potentially significant chronic turbidity sources may be added to the BEMS network.

DEP plans to use peer-reviewed journal manuscripts under development and a pending USGS report on turbidity-Q, SSC-Q and SSC-turbidity rating curves to inform the November 2022 five-year summary report. That report will include an update on monitored data as well as present the preliminary findings of the first half of this 10-year research monitoring project.

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