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 2024

Prepared in accordance with Section 4.6 of the NYSDOH

Revised 2017 Filtration Avoidance Determination

NYC Environmental Protection

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List of Acronyms

ACM	Active channel margin
AEP	Annual exceedance probability
AL	Alluvium
ANCOVA	Analysis of covariance
ANOVA	Analysis of variance
AWSMP	Ashokan Watershed Stream Management Program
BEMS	Bank erosion monitoring study
CL	Colluvium
DEM	Digital Elevation Model
DEP	New York City Department of Environmental Protection
DLM	Dynamic linear modeling
EI	Erosional index
FAD	Filtration Avoidance Determination
FFA	Flood frequency analysis
FNU	Formazin nephelometric units
GLS	Glacial legacy sediment
GT	Glacial till
LS	Lacustrine sediment; glacial lacustrine sediment
LiDAR	Light detection and ranging
MAR	Mean annual runoff
MBS	Mean basin slope
PQR	Peak streamflow runoff
Q	Streamflow
REM	River erosion model
RI	Recurrence interval
SCI	Sediment connectivity index
SFI	Stream feature inventory
SfM	Structure-from-motion

SS	Suspended sediment
SSC	Suspended sediment concentration
SSL	Suspended sediment load
SSY	Suspended sediment yield
STRP	Stream turbidity reduction project
SWCD	Soil and Water Conservation District
Tn	Turbidity
UAS	Uncrewed aerial system (AKA drone)
UEC	Upper Esopus Creek
USGS	United States Geological Survey

1. Introduction

1.1 Background

The New York City Department of Environmental Protection (DEP) and the U.S. Geological Survey (USGS) initiated a 10-year study in October 2016 to characterize stream turbidity source conditions in the Esopus Creek watershed upstream of the Ashokan Reservoir and to evaluate the turbidity reduction efficacy of stream turbidity reduction projects (STRP) in the Stony Clove sub-basin. The study and STRPs are mandated by the 2017 Filtration Avoidance Determination (FAD). Several previously submitted FAD reports document the initial study design and preliminary study status on a recurring biennial basis (DEP, 2017; DEP, 2019a; DEP, 2021). The November 2022 mid-term study FAD report presented the preliminary findings of the first five years of the study (DEP, 2022). This March 2024 FAD report serves to provide the latest update on study results advanced since the mid-term study report. It also provides an update on additional ongoing and planned research activity that will inform the final study FAD report due November 2027.

In Catskill streams, turbidity (Tn) is generally a function of the suspended sediment (SS) concentration (SSC) in streamflow (Q) – as SSC increases, so does Tn (Siemion et al., 2021). upper Esopus Creek (UEC) serves as a representative eastern Catskill fluvial system to investigate turbidity and SS production and source dynamics at the basin to sub-basin scale (Figure 1.1). It has a documented history of chronic and acute elevated turbidity levels during and following large floods (Effler et al., 1998; Mukundan et al., 2013; McHale and Siemion, 2014). Stony Clove Creek is the largest tributary to UEC and serves in this research as an experimental sub-basin fluvial system for enhanced turbidity source and production investigation as well as evaluating STRP turbidity reduction efficacy from the reach to sub-basin and reservoir basin scales. The study began in water year 2017 (October 1, 2016) and data acquisition will continue through water year 2026 (September 30, 2026). Per the FAD, DEP will submit a final study report in November 2027.

The study is a collaborative effort led by USGS and DEP with support from the Ashokan Watershed Stream Management Program (AWSMP). USGS is responsible for: (1) monitoring and analyzing Q, Tn, SSC, SS load (SSL) and SS yield (SSY); (2) evaluating STRP impacts on monitored Tn and SS metrics; (3) using SS fingerprinting as a source sediment characterization technique in the study area; and (4) publishing peer-reviewed scientific literature documenting research findings. Starting in 2024, USGS will add additional geologic and geomorphologic study components to their part of the study. DEP is responsible for: (1) research project funding, coordination, and FAD reporting; (2) developing an interpretive conceptual model of turbidity production and reduction to guide the study; (3) geologic and geomorphologic investigations; and (4) 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). Ongoing grants fund additional USGS monitoring Q, SSC and Tn in Woodland Valley.

A quantitative understanding of turbidity or SS production is necessary for achieving some measure of success in turbidity reduction management practices. Research by Mukundan et al. (2013) demonstrated that Tn and SSC scale with increasing streamflow in the study area and that big floods account for most of the load of turbid streamflow to the Ashokan Reservoir. For an 8-year monitoring period, 80% of the estimated SS load delivered to Ashokan Reservoir by Esopus Creek occurred during large runoff events that represented less than 4% of the monitored streamflow over the same period. They found the spatial and temporal variability in turbidity and SSC can be largely explained by watershed runoff variability, antecedent hydrologic conditions, and seasonal conditions. Hydraulic conditions such as stream power and geologic sources were assumed to be other important controlling factors but were not directly examined.

This study is intended to further investigate the driving conditions and other factors that generate turbid streamflow in the UEC watershed through a more expansive stream monitoring network operating over a longer period and coupling the stream monitoring with SS source investigations. An assumption in the past and current studies is that turbidity production is controlled not only by streamflow sediment transport capacity but also by sediment supply. This study aims to collect the data needed to evaluate that assumption. The watershed management objective of this study is to evaluate whether stream management practices (STRPs in this case) can measurably reduce stream turbidity delivered to the Ashokan Reservoir through reducing sediment entrainment at the reach scale and to identify the limits of measurable reduction.

1.2 Report Purpose

This biennial status report uses the same content structure as the mid-term report, and provides updates to previously reported content and results, as available. If there are no updates, for example data analysis is still ongoing or further data has not been collected, this is identified in the report and the previously reported results are not repeated. The stream monitoring data analyzed is from the first seven water years (October 2016 to September 2023) unless otherwise specified. Streamflow and turbidity data are still in provisional status for some portion of the latter months of water year 2023 for all the USGS monitoring stations, as of the time of report preparation.

Section 1 provides the basic information to set the context for the research results and discussion. **Section 2** presents the current conceptual framework for investigating the study area turbidity and SS production conditions and the approach to turbidity reduction through source treatment; this section has been reduced and simplified for the purposes of this report. **Section 3** describes the methods used in the research and details revisions to the methods made through the course of the study; this section also includes a presentation of the study limitations and assumptions that define the study conceptual boundaries with implications for management. Updates to this section are primarily associated with monitoring instrumentation changes and the expanded USGS scope of work. **Section 4** presents the streamflow, turbidity and suspended sediment monitoring, turbidity source investigation, and STRP turbidity reduction monitoring results. The data and results are updated to include (1) water years 2022 and 2023 data, (2) a summary of the reach-scale channel erosion monitoring project, (3) summary of turbidity source sediment sampling analysis, and (4) an update to the STRP evaluation. Sediment load and yield measurements and estimates are not updated since they are dependent upon ongoing revisions to the Tn-SSC regression relationships. **Section 5** presents a brief interpretive account of study findings covering applicability and limitations of the research presented in the mid-term study report. **Section 6** presents an updated summary of the key points made throughout the report. **Section 7** lists the cited research resources informing the study mid-term report.

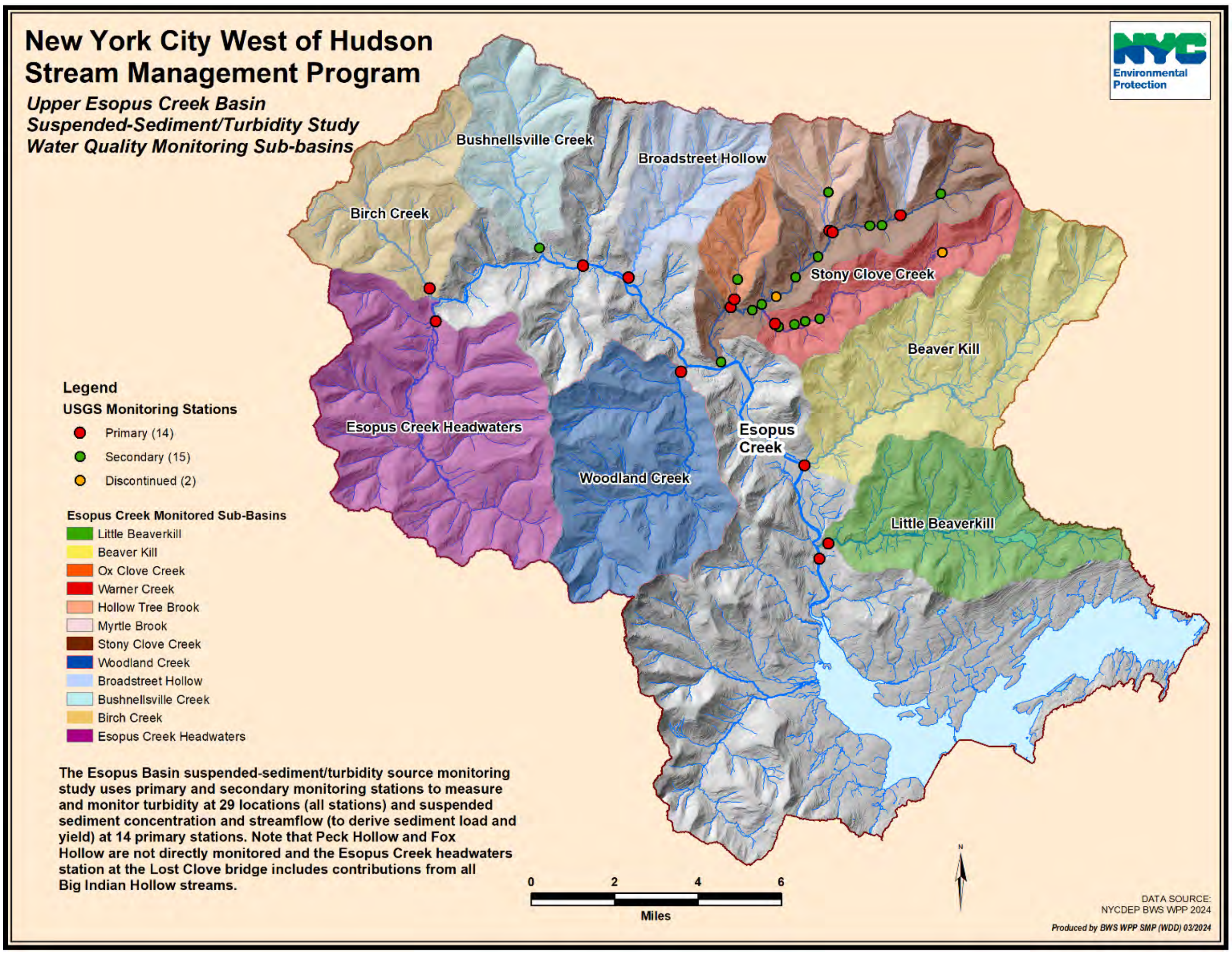

Figure 1.1 UEC watershed study area with USGS water quality monitoring stations.

1.3 Study Goals and Objectives

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 study addresses three research goals that will inform DEP's efforts to protect and improve source water quality through stream turbidity reduction. The study goals and objectives have been streamlined for this report to focus the results presentation on ranking sub-basin Tn and SS production, source conditions, and evaluating STRP efficacy. This report provides an update to the provisional results for the objectives posed for each study goal.

A. UEC watershed investigation: Characterize how turbidity and SS production dynamics vary among the monitored UEC sub-basins and identify their relative ranking.

   1. Quantitatively rank UEC sub-basin turbidity production and SS load and yield in streamflow to the Ashokan Reservoir for the first seven years.
   2. Document how these rankings change over the course of the study period.
   3. Identify driving conditions and source factors that influence measured differences in turbidity and SS in the monitored UEC sub-basins through the course of the study period.
   4. Characterize how the study results through water year 2023 can inform stream management turbidity reduction strategies within the UEC watershed.

B. Stony Clove sub-basin investigation: Using the Stony Clove as a model sub-basin, characterize how different stream segments (turbidity monitoring reaches) and tributary sub-basins vary in terms of turbidity and SS condition metrics within the same sub-basin.

   1. Quantitatively rank Stony Clove Creek and tributary sub-basin turbidity production and SS load and yield for the first seven years.
   2. Using the data from the 20 turbidity monitoring stations in the Stony Clove sub-basin identify the highest turbidity production reaches for each monitored stream.
   3. Identify driving conditions and source factors that influence observed spatial and temporal variability in turbidity and SS production within the Stony Clove sub-basin.

C. STRP evaluation: Using the Stony Clove Creek sub-basin and Esopus Creek basin Q, SS, and turbidity monitoring data, evaluate the effectiveness of existing and future STRPs on reducing turbidity and SS for the monitoring reach scale, the sub-basin scale and the reservoir basin scale across a range of flows.

1. Using monitored turbidity and SSC quantify impacts of extant STRPs across a range of spatial, temporal, and hydrologic scales at measurably reducing turbidity and SS.
2. Identify any observed limits of STRP efficacy or limits on detecting efficacy.
3. Characterize how the study results can inform future STRP siting and design.

1.4 Study Area

The UEC watershed drains 192 square miles of mostly forested mountainous terrain, ranging in elevation from 585 feet at the Ashokan Reservoir to 4,180 feet at Slide Mountain with 21 peaks exceeding 3,000 feet, creating a high topographic relief catchment basin (Figures 1.1 and 1.2). The National Hydrography Dataset available for the study area includes more than 330 miles of streams draining the UEC watershed. The high gradient fluvial system is a heterogeneous network of alluvial channels, bedrock channels, and non-alluvial channels incised into glacial and colluvial deposits.

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

The stream network includes 10 primary tributaries that contribute to UEC (Table 1.1; Figure 1.1). The USGS monitors eight UEC tributaries and three locations along Esopus Creek for Q, SSC and/or Tn. Additional enhanced sub-basin and reach scale monitoring occurs in the Stony Clove Creek sub-basin. USGS monitoring stations are described in Section 3.

Large floods are the primary disturbance events producing turbidity in UEC watershed streams (Mukundan et al., 2013; McHale and Siemion, 2014; Wang et al., 2021). 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 study area in the southeastern Catskills due to orographic effects and the track of many high precipitation storms. The mountainous terrain can magnify flooding from heavy precipitation events, maximizing runoff volume and potential stream power forcing stream channel geomorphic adjustment (Davis et al., 2009; Matonse and Frei, 2013; Siemion et al., 2023). Rainfall intensity, duration and sequencing has a strong seasonal influence on streamflow with many high magnitude precipitation events associated with late summer/early fall tropical storms (Frei and Kelly-Voicu, 2017). Historically, however, the high magnitude tropical storm events don't necessarily yield the highest runoff events. On a seasonal basis, runoff events between December and April have produced nearly 60% of the annual peak streamflow events and most of the biggest floods in the 92 years of monitored streamflow at the Esopus Creek monitoring station upstream of Ashokan Reservoir (Figure 1.3).

Table 1.1 UEC 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 include streams ranging in drainage area from <2 mi^2 to 5 mi^2.

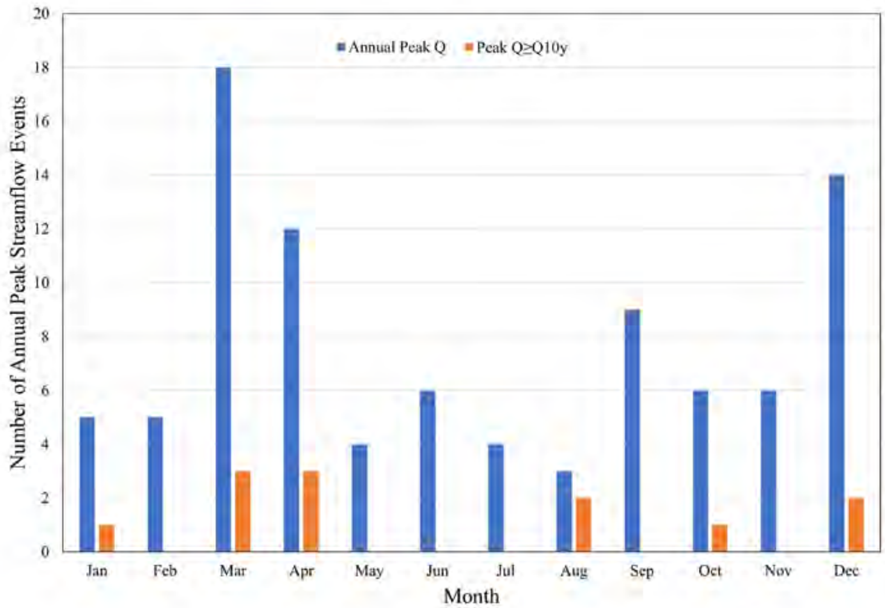

Figure 1.3 Esopus Creek at Coldbrook, NY USGS monitoring station 01362500 histogram chart of annual peak streamflow occurrence by month for 92 years and the 12 highest magnitude events with a recurrence interval ≥10-years.

Catskill Mountain geology influences valley and channel geometry, substrate erosional resistance, spatial heterogeneity in fluvial sediment sources, and composition of bedload and suspended sediment. Bedrock consists of repeating sequences of Devonian fluvial sandstones, mudstones, and conglomerates (Ver Straeten, 2013). The fluvial drainage network is strongly influenced by the bedrock layering and fracture orientations, lithologic variations, and lack of structural deformation (Haskins et al., 2010). Surficial geology is primarily a complex distribution of Pleistocene continental glacial and proglacial deposits variably covered or replaced in stream valleys by Holocene alluvium and colluvium (Rich, 1935; Cadwell, 1986; Davis et al., 2009; Rayburn et al., 2015). Glacial legacy sediment (GLS) is enriched in fine sediment (silt and clay) and channel erosion into these deposits can account for acute and chronic sources of turbidity. Past research in the Esopus Creek watershed found that silica and clay minerals accounted for greater than 87% of suspended sediment composition (Effler et al., 1998).

Valley bottom margins are a complex configuration of mountain slopes, glacially constructed features, pro-glacial lake deltas and glaciofluvial terraces at higher elevations and Holocene fluvial terraces at lower valley elevations. Stream planform geometry is variably confined to unconfined based on proximity to these valley bottom features and anthropogenic confining boundaries (roads and revetment).

Most of the human population in the UEC watershed resides in the valley bottoms and lower slopes of the mountains. This centuries-long co-existence between streams and people (and associated infrastructure) in the limited area of the valley bottoms imposes limitations on the streams' ability to adjust in response to high runoff events. Most streams in the UEC watershed 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. Many valley bottoms hosted sawmill dams and modified channels in the 19th century. Extensive deforestation in the 18th and 19th centuries very likely impacted sediment delivery to streams and floodplains. These human legacy impacts on the streams in the study area are not included in the scope of this study. The AWSMP has produced several stream management plans for UEC watershed 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).

2. Study Conceptual Model

DEP and USGS use a geomorphic connectivity framework to inform a conceptual model of turbidity production dynamics in the study area and to examine the individual and cumulative turbidity reduction efficacy of STRPs across a range of spatial, temporal, and hydrologic scales (Fryirs and Brierley, 2013; Wohl et al., 2019; Heckmann et al., 2018; DEP, 2022). Table 2.1 presents a description of the conceptual model components, the methods to measure component parameters and potential study result metrics associated with each component. There have been no substantive changes to the conceptual model guiding the research since it was described in DEP's mid-term study report.

Turbidity production is defined in this report as the generation of turbid streamflow caused by suspended sediment concentration entrained through hydraulic energy applied in the landscape, and the delivery of that turbid streamflow to any reference point (e.g., monitoring station, catchment outlet, or a reservoir). Since turbidity is not a mass-based property, standard quantification terms such as load (mass transported by a stream) or yield (mass transported from a source area over time) are not normally applied to turbidity, though there is precedent for using turbidity load as a metric (Effler et al. 1998). Production in this usage is a descriptive term that can be more appropriately quantified using SS data and metrics such as SSC, SSL and SSY. Since this study is largely designed to answer questions about turbidity reduction efficacy through stream management projects, the term production is useful for discussion.

The Ashokan Reservoir can fill with turbid streamflow during and following very large floods capable of entraining and transferring fine sediment throughout the UEC stream network. The process is largely driven by precipitation and resulting runoff hydrology and hydraulics influenced by the intrinsic terrain properties of channel slope, confinement, and roughness. Past research finds that seasonal and antecedent hydrologic conditions influence the hydrological role in turbidity production and SS flux (Mukundan et al., 2013). The stream monitoring network in this study is designed to help quantify hydrology, turbidity, and SS flux through the stream fluvial system from stream reach to reservoir basin scale. The multi-scalar approach is necessary to answer most of the posed research questions on spatial and temporal variability and trends in turbidity production and measured turbidity reduction response to STRPs.

The current study results continue to support the hypothesis that the climate-driven hydrologic forces acting in the landscape can exceed geomorphic resistance or stability thresholds that increase access to fine sediment sources. The scaling of this relationship is not linear. There are hydrologic thresholds that once exceeded result in breeching intrinsic geomorphic stability thresholds. Localized reach scale geomorphic adjustment (erosion, sediment transfer and deposition) can occur in sensitive reaches at lower hydrologic forcing thresholds, such as the bankfull streamflow, often associated with the 1.5 to 2-year recurrence interval flow. Basin-wide reach scale geomorphic adjustment can occur at higher hydrologic forcing thresholds (e.g. the 10-year recurrence interval flow) capable of forcing more adjustment throughout the fluvial system, resulting in acute and chronic elevated turbidity production. The basin-wide geomorphic adjustment can consequently lower the hydrologic forcing threshold for elevated turbidity production if the adjustment significantly increases erosional connectivity with turbidity source sediment.

Table 2.1 Study turbidity production/reduction conceptual model components, study methods and metrics.

Model Component	Description	Study Method	Metrics
Turbidity or suspended sediment production	Generation of turbid streamflow or SSL from a geomorphic response to a disturbance process (e.g. bank erosion or bed mobilization forced by flooding), controlled by erosional resistance and supplied by geologic composition. The UEC watershed is sensitive to elevated turbidity production from fluvial erosion and mass wasting of glacial legacy fine sediment.	Mapping erosional contacts; Morphologic monitoring of Tn hot spots; source sediment sampling for grain size analysis and SS fingerprinting; sediment budget and connectivity modeling; USGS stream monitoring and analysis	Erosional contact indices; geologic source attribution probabilities; Reach-scale Tn or SSL
Turbidity or suspended sediment reduction	Natural and managed turbidity reduction through post-disturbance geomorphic recovery reducing sediment connectivity, and stream management projects at production hot spots to enhance sediment dysconnectivity by removing erosional contact with fine sediment sources and increasing erosional resistance.	STRP implementation; mapping erosional contacts; USGS stream monitoring and data analysis	Changes in turbidity or SSL and SSY quantified through upstream/downstream, before/after, and paired watershed comparisons of monitored Tn and SSL associated with single or multiple STRP
Turbidity or suspended sediment transfer	Transfer of turbid streamflow or suspended sediment transport through the fluvial system. Some fine sediment is periodically stored and resuspended in the mobile bedload.	USGS stream monitoring and data analysis; streambed sediment samples	Tn-Q or SSC-Q regression parameters; Tn, SSC and Q exceedance percentiles; SSL; percent fine sediment in streambed AL
Turbidity or Yield	Cumulative transfer of turbid streamflow or SS load integrated over time ranging from event to multiple years and over space ranging from reach to sub-basin to reservoir basin scales.	USGS stream monitoring and data analysis; sediment budget	SS yield

The conceptual model assumes that turbidity inducing sediment input (new production) predominantly originates at discrete erosional connections between the stream and sediment sources (e.g., eroding banks, beds and adjacent hillslopes). Other inputs include road and roadside ditch runoff, construction sites with exposed soils, and upland erosion not directly or typically hydrologically linked to the stream. The study currently does not include measuring these inputs, other than through sediment fingerprinting of forest soils as discussed in Section 3.2. Stream turbidity is also systemically supplied during streamflow capable of mobilizing stored channel alluvium and re-suspending stored fine sediment.

The geologic composition of the landscape is a primary control on turbidity production. The study area has a complex Pleistocene glacial history that has resulted in a heterogeneous distribution of GLS that influences the total (fine and coarse fraction) sediment supply. Table 2.2 describes the four assumed principal SS source geologic categories currently used in this study: alluvium (AL), glacial lacustrine sediment (LS), glacial till (GT), and colluvium (CL). DEP's previous FAD study reports describe these geologic or sedimentologic units in detail (DEP, 2019a; DEP, 2021; DEP, 2022). Preliminary sediment fingerprinting investigations by USGS tested for and found sufficiently different geochemical signatures for AL, LS and GT to support this categorization (Staub et al., 2022). CL is mapped but is not currently tracked as a distinct source since the fine sediment composition varies considerably as a function of the original geologic source material.

There are other factors that influence turbidity production. Biogeomorphic interactions based on riparian vegetation composition, integrity, and in-stream large wood influence stream channel stability thresholds. Past and ongoing stream management and land use practices can attenuate or exacerbate channel erosion. The current study scope includes acquiring data for some of these factors (e.g., riparian buffer width and adjacent land use, in-stream large wood features, and stream bank revetment are recorded during stream channel mapping); however, these data are not currently factored into development of explanatory metrics presented in this report. Some of the assumptions in this conceptual model about turbidity production source conditions may be modified as data are obtained and analyzed, and/or as other researchers use the available data to pursue other lines of investigation.

The discrete stream bank and hillslope erosion and bed incision connections with the GLS are reach-scale sources that can be considered as "point" sources or turbidity production "hot spots". Resuspended fine sediment in streambed AL is considered a "non-point" or systemic areal source in this conceptual model. The experimental objective of the STRPs implemented in this study is to reduce turbidity production. This is pursued through the design objective of disconnecting the stream channel from reach scale hot spot turbidity sources to measurably reduce fine sediment input. This is referred to as STRP enhanced sediment dysconnectivity in the modeling framework. The areal "conveyor belt" of AL-sourced resuspended fine sediment in the stream network is not the direct target for STRP treatment, although reach scale STRPs at disproportionately large GLS sources may, over time, reduce the amount of fine sediment stored downstream of these projects in the stream network available for resuspension.

Table 2.1 Primary geologic sources of turbidity in the upper Esopus Creek watershed.

Geologic Source	Description	Example
Alluvium (AL)	Mixed grain size deposits of streams that predominantly are composed of sand up to boulder-sized sediment, yet also have some small percentage of finer sediment in the mix. AL can be stored in stream banks, Holocene terraces and streambeds. Fine sediment content is generally well below 5%.	
Glacial lacustrine sediment (LS)	A predominantly silt/clay cohesive and layered sediment deposited in pro-glacial Pleistocene lakes that inundated much of the UEC terrain as glacial ice meltwater drained into the blocked valleys. Fine sediment content is generally > 90%.	
Glacial till (GT)	An abundant consolidated and unsorted glacial deposit composed of the mixed grain size deposits from the base and margins of glacial ice. Sampled fine sediment content varies between 30 – 51% depending on mode of glacial transport, deposition and source terrain.	
Colluvium (CL)	An unconsolidated to semi-consolidated mixed grain size deposit from mass-wasting in stream banks and connected hillslopes. Fine sediment content in CL is a function of the mass-wasted source sediment and is assumed to range from the low of AL to the high of LS.	

3. Study Methods, Assumptions and Limitations

The study has progressed since fall 2016 using a range of empirical, analytical, geospatial and computer modeling methods. DEP's initial FAD study design report presented the overall research goals, specific objectives, and the planned methods to achieve study objectives (DEP, 2017). Several assumptions informing the study have been made based on past and ongoing research, assessment, and monitoring efforts in the study area. Similarly, there are several limitations to the study that constrain the result interpretations. The assumptions and limitations are detailed in this section.

The methods have not remained static as researchers learn more about what is important and what is not so important to help answer the primary questions regarding UEC watershed turbidity production and reduction potential through stream management. The overall approach of spatially distributed, high frequency stream monitoring of Q, SSC and Tn for a minimum 10-year period coupled with turbidity source characterization through geomorphic investigations remains essentially the same. Through the course of the study, some methods have changed, some have been dropped, and others have been added to this adaptive research project. In some cases, monitoring or survey equipment changes were made to improve the data quality. In other cases, data collection efforts expanded and/or protocols were revised for data quality improvement. In 2023, DEP and USGS developed a new scope of work to enhance the geologic and geomorphic investigations that will utilize expertise within USGS. The following sub-sections describe the methods used and highlight key changes since DEP submitted the initial 2017 FAD study design report.

When the study was initially designed, it was clear that a successful research project needed to capture temporal variability in hydrology and turbidity conditions in the study area. A ten-year period was established as the minimum needed to provide enough data for robust statistical analysis. Further, the initial design assumed that monitoring stations and source investigations needed to be broadly distributed (UEC watershed) yet also intensively focused in a sample area (Stony Clove sub-basin) to help understand how stream reach to segment scale source conditions and dynamics can influence reservoir watershed scale conditions and dynamics. This "telescopic" focus has so far proven to be well-suited to the need for investigating complex conditions, while maintaining a practical feasibility for implementation.

3.1 Streamflow and Water Quality Monitoring Stations

USGS uses a network of 29 stream monitoring stations distributed across the UEC watershed to measure and monitor Q, SSC and Tn to support the statistical analyses detailed in the study design report. Additional short-term stations have been added using funding from the AWSMP. Primary monitoring stations are those where Q and Tn are continuously monitored in 15-minute increments and SSC is measured across most of the range of observable Q conditions. SSC-Tn regression relationships are developed for each primary station to estimate continuous SSC and SSL. Secondary stations are those where only Tn is measured and monitored every 15-minutes. 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. Additional Tn and

SSC monitoring stations funded by the AWSMP are also listed in Table 3.1. Changes in monitoring locations within the Stony Clove sub-basin are listed in Table 3.2. The most notable change in stream monitoring since the mid-term study report is that the Broadstreet Hollow Tn secondary monitoring station (01362232) was converted to a primary monitoring station to include Q and SSC monitoring in August 2022. Results from the seven water years (2017-2023) suggest the monitoring design has been mostly successful in measuring SSC and turbidity for the flows observed during that period, except for some stations impacted by a high magnitude flood in December 2020 and some limits on turbidity probe detection range (DEP, 2022). Details on the equipment and methods used at the monitoring sites are available in Siemion and others (2021).

The 20 Stony Clove sub-basin monitoring stations include six primary stations measuring Q, Tn and SSC for four tributary sub-basins and two locations on Stony Clove Creek, and 14 secondary stations to delineate water quality monitoring sections across the five streams: Stony Clove Creek, Ox Clove Creek, Warner Creek, Hollow Tree Brook, and Myrtle Brook (Figure 1.1). The primary and secondary monitoring stations segment the monitored streams into discrete SS loading and turbidity production sections. Two of the secondary monitoring stations were discontinued, and two new locations were activated based on discussions between DEP and USGS. Warner Creek headwater monitoring station 01362354 was discontinued because the stream reach went dry for long periods and Stony Clove Creek station 01362350 was discontinued because of poor mixing of suspended sediment from an upstream hillslope source into the streamflow. Monitoring station 0136235585 was established at a location between two nearly adjacent STRPs in Warner Creek, and station 01362352 was established in a well-mixed stream reach of Stony Clove Creek downstream of the discontinued station 01362350.

Since the inception of the study, USGS has monitored turbidity using DTS-12 probes, which were the stand-alone turbidity probe supported by the USGS Hydrologic Instrumentation Facility. However, the DTS-12 had a limited range of 1,600 FNU which was exceeded during the December 2020 flood at some locations. In 2020, USGS recommended switching the turbidity monitoring probes from DTS-12 probes to Analite NEP-5000 probes for the remainder of the study period because the Analite NEP-5000 probes measure a greater range of values and can be calibrated on site. The Analite NEP-5000 are the stand-alone turbidity probe currently supported by the USGS Hydrologic Instrumentation Facility. The output from the two turbidity probes are not equivalent, and so new turbidity-SSC regression equations will need to be developed as well as a relation between the DTS-12 and Analite NEP-500 probes. SSC will continue to be comparable for long-term monitoring. Turbidity probes at three monitoring stations were upgraded from DTS-12 probes to Analite NEP-5000 probes when the DTS-12 were damaged. The probes were changed at Myrtle Brook (01362322) on January 10, 2020, Hollow Tree Brook (01362345) on January 31, 2020, and Birch Creek (013621955) on February 3, 2021. Analite NEP-5000 probes were added to the other primary monitoring sites in summer 2022. Concerns over long-term turbidity data comparability resulted in DTS-12 probes being re-installed at all primary monitoring sites during the summer of 2023. The two turbidity probes will be run side-by-side for at least one year to collect data for a comparability study (Messner et al., 2023).

USGS anticipates publishing the results in 2025 when new turbidity-SSC regression equations are developed for the primary monitoring sites.

Table 3.1 UEC watershed USGS monitoring stations listed from upstream to downstream. Source: USGS.

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, Tn
Birch Cr @ Big Indian[1]	013621955	12.5	Primary	Q, SSC, Tn
Bushnellsville Creek @ Shandaken	0136219702	11.1	Secondary	Est. Q, Tn
Esopus Cr @ Allaben[1]	01362200	63.7	Primary	Q, SSC, Tn
Broadstreet Hollow Brook at Allaben[3]	01362232	9.2	Primary	Q, SSC, Tn
Woodland Cr at Wilmot Way nr Woodland[2]	01362286	5.2	Secondary	Est. Q, SSC, Tn
Panther Kill at Panther Kill Rd nr Phonecia[2]	01362295	3.0	Secondary	Est. Q, SSC, Tn
Panther Kill at Woodland Valley Rd nr Phonecia[2]	01362297	3.5	Primary	Q, SSC, Tn
Woodland Cr abv mouth @ Phonecia[1]	0136230002	20.6	Primary	Q, SSC, Tn
Stony Clove Cr blw Ox Clove @ Chichester[1]	01362370	30.9	Primary	Q, SSC, Tn
Beaver Kill @ Mt Tremper	01362487	25.0	Primary	Q, SSC, Tn
Little Beaver Kill at Beechford nr Mt Tremper[1]	01362497	16.5	Primary	Q, SSC, Tn
Esopus Cr at Coldbrook[1]	01362500	192	Primary	Q, SSC, Tn

[1]Existing monitoring station funded through a separate DEP-USGS agreement. Note that Stony Clove Creek blw Ox Clove @ Chichester (01362370) is included in both the UEC watershed monitoring count and the Stony Clove sub-basin monitoring count.
[2]Short-term site funded by the AWSMP.
[3]Broadstreet Hollow Brook station converted from Secondary to Primary station in August 2022.

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

Station Name	USGS Station ID	Drainage Area (mi^2)	Station Type	Measurements
Stony Clove Cr @ Edgewood	01362312	2.3	Secondary	Est. Q, Tn
Myrtle Br @ SR 214 @ Edgewood	01362322	1.8	Primary	Q, SSC, Tn
Stony Clove Cr nr Lanesville	01362330	7.5	Secondary	Est. Q, Tn
Stony Clove Cr @ Wright Rd nr Lanesville	01362332	8.1	Secondary	Est. Q, Tn
Stony Clove Cr @ Jansen Rd @ Lanesville	01362336	9.3	Primary	Q, SSC, Tn
Hollow Tree Br @ SR 214 @ Lanesville	01362345	4.6	Primary	Est. Q, SSC, Tn
Hollow Tree Br @ Lanesville[1]	01362342	2.0	Secondary	Q, Tn
Stony Clove Cr @ Lanesville	01362347	15.4	Secondary	Est. Q, Tn
Stony Clove Cr abv Moggre Rd nr Chichester	01362349	16.4	Secondary	Est. Q, Tn
Stony Clove Cr @ Chichester[2]	*01362350*	*17.5*	*Secondary*	*Est. Q, Tn; Discontinued Mar 2021*
Stony Clove Cr abv Warner Cr at Chichester[3]	01362352	17.5	Secondary	Est. Q, Tn; Established Jul 2021
Warner Cr blw Silver Hollow Notch nr Edgewood[2]	*01362354*	*2.3*	*Secondary*	*Est. Q, Tn; Discontinued Nov 2018*
Warner Cr nr Carl Mountain nr Chichester	0136235575	7.1	Secondary	Est. Q, Tn
Warner Cr in Silver Hollow nr Chichester	0136235580	7.3	Secondary	Est. Q, Tn
Warner Cr in Silver Hollow nr Phoenicia[3]	0136235585	7.4	Secondary	Est. Q, Tn; Established Dec 2018
Warner Cr @ Silver Hollow Rd nr Chichester	01362356	8.6	Secondary	Est. Q, Tn
Warner Cr nr Chichester	01362357	8.9	Primary	Q, SSC, Tn
Stony Clove Cr @ Silver Hollow Rd, Chichester	01362359	26.6	Secondary	Est. Q, Tn
Ox Clove @ Chichester	01362365	3.1	Secondary	Est. Q, Tn
Ox Clove nr mouth @ Chichester	01362368	3.8	Primary	Q, SSC, Tn
Stony Clove Cr blw Ox Clove @ Chichester[1]	01362370	30.9	Primary	Q, SSC, Tn
Stony Clove Cr abv SR 214 @ Phoenicia	01362398	32.4	Secondary	Est. Q, Tn

[1]Existing monitoring station funded through a separate DEP-USGS agreement.
[2]Sites listed in italics have been discontinued.
[3]Site installed during 3rd or 4th year of study.

3.1.1 Streamflow Monitoring

Streamflow at primary monitoring stations is monitored through use of a stage-discharge rating curve that is developed and maintained, or revised as needed, through repeat measurements of stream stage and streamflow, as per standard USGS methods (Sauer and Turnipseed, 2010; Turnipseed and Sauer, 2010). USGS also measures streamflow at three of the secondary stations (01362312, 01362345, and 01362365) to calibrate estimates at these stations.

Streamflow was not measured at the Broadstreet Hollow Brook (01362232) and Bushnellsville Creek (0136219702) sub-basins through July 2022. Daily mean streamflow at these two stations was estimated based on daily mean streamflow from West Kill Creek (01349810) and methods used in Gazoorian (2015). The Broadstreet Hollow Brook station was converted to a primary station in August 2022. Accuracy of the estimation method will be assessed when sufficient measured data is available at Broadstreet Hollow Brook. Fifteen-minute streamflow was estimated for Hollow Tree Brook (01362345) based on 15-minute streamflow from station 01362342 approximately 0.9 miles upstream and equation #5 in Lumia and others (2006). The estimated streamflow data are available from Siemion (2022). Daily mean streamflow at secondary stations in the Stony Clove sub-basin was estimated by drainage area weighting daily mean streamflow from the nearest downstream primary station.

3.1.2 Turbidity Monitoring

Turbidity has been measured through use of Forest Technology Systems DTS-12 turbidity probes following standard methods (Wagner et al., 2006). Starting in 2020, USGS determined that observed limitations of the original DTS turbidity probes – long calibration times, measurement range limited to 0-1,600 FNU – merited replacement at all primary stations with Analyte probes that can be more efficiently calibrated and have a greater measurement range (0-4,000 FNU). One impact of the lower FNU limits of the DTS probes is that during some high streamflow magnitude-high turbidity events, turbidity exceeded the upper limit of the DTS, resulting in peak turbidity values not being measured for some runoff events. DEP and USGS recognize that the switch in turbidity measurement technology can impact continuity in data comparability if there are significant differences between the measurement results. To determine the differences in results, USGS will measure turbidity with side-by-side deployments of DTS and Analite probes at all primary monitoring sites for at least 1 year. New turbidity-SSC regression equations will be developed for all primary monitoring stations. The resulting SSC dataset will be compatible with the SSC derived from the DTS probe regression equations. USGS intends to develop a relation between the DTS-12 and Analite NEP-5000 turbidity probes and publish a comparable turbidity dataset in a future USGS data release.

3.1.3 Suspended Sediment Monitoring

Water samples are collected for analysis of SSC throughout the range in streamflow and turbidity following standard 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. Cross-section and point samples were analyzed for SSC at either the USGS Ohio Kentucky Indiana Water Science Center or the Cascade Volcano Observatory sediment laboratories using methods described in Guy (1969). The cross-section samples were used to calibrate and ensure the representativeness of the point samples. Periods of high streamflow and turbidity were targeted for more frequent sampling because this was when most suspended sediment was transported. More than 160-point samples and 14-20 cross section samples were collected at each primary station during the first seven years of the study. Six cross-section samples have been collected at

Broadstreet Hollow Brook since its conversion to a primary site. The SSC samples and continuous turbidity data were used to develop turbidity-SSC regression equations (Siemion et al., 2021). The equations were then used to estimate SSC at a 15-minute timestep. Particle size was measured on a subset of suspended sediment samples from each primary station, generally when turbidity exceeded 200 FNU and for every cross-section sample.

3.2 Suspended Sediment Source Characterization

The original study design relied on a combination of stream feature inventory mapping (SFI) methods for synoptic measurements of stream channel erosional sources of SS and topographic monitoring cross-sections at several potential high turbidity producing reaches to measure stream channel erosion. Additional potential methods described available remote-sensing data to obtain estimates of stream power and complete historic channel alignment delineations. The intent of these methods was to obtain data that could help explain the geomorphologic and geologic components that influence turbidity production in the study area. As with the Q, SSC and turbidity monitoring, the Stony Clove sub-basin was selected for most of the sediment source characterization.

DEP made several improvements to the proposed methods within the first year of the study as detailed in previous reports (DEP, 2021; DEP, 2022). Some of the proposed GIS-based methods were either modified, discontinued, or replaced as needed to improve the study quality and efficiency. DEP modified the SFI methods and the stream bank erosion monitoring survey methods described in the study design report. The primary change to the stream bank sediment characterization was to integrate this method into the bank erosion monitoring study (BEMS) component and to add streambed sediment sampling for grain size distribution analysis. The changes for each of these source characterization components are presented below.

3.2.1 GIS Analysis of Watershed and Stream Channel Characteristics

One objective in the original study design was to obtain watershed characteristics in monitored sub-basins and reaches utilizing remote-sensed data. Most methods were to be applied to the Stony Clove sub-basin only. Many of the original methods described in the study design were completed as part of past stream management planning (e.g., historic channel alignment analysis using digitized stream centerlines, computing drainage areas, delineating stream geomorphic management reaches).

In 2018, DEP added digitizing active channel margins (ACM) using available time series of orthophotography (principally 2009 and 2016) to increase the potential value of the historic channel alignment analysis. This was discussed in detail in DEP's 2021 biennial FAD status report (DEP, 2021). There have been no further advances in this geospatial data set development as of this report. DEP is still considering the value of further developing this method and exploring metric potential with USGS.

The proposed stream power assessment using digital elevation model (DEM) slopes and reference streamflow magnitudes has been deferred until an optimized stream power modeling method can be added. Stream power or specific stream power is a demonstrated driver forcing stream channel adjustment through erosion and deposition (Magilligan et al., 2015). A variation of the utility of stream power was explored with the use of the River Erosion Model (Lammers and Bledsoe 2018; Wang et al., 2021) to simulate stream channel adjustment based on specific stream power; however, this is a very labor-intensive method to apply across the UEC monitored sub-basins and is not advised for general application.

DEP investigated stream channel-hillslope connectivity through the application of techniques described in Fryirs et al. (2015). This method uses available DEM and orthophotography to delineate channel confinement margins (valley margins, valley bottom feature margins, anthropogenic margins) and measures the connection of the stream to these margins to produce spatial distribution of confined, partly confined, and unconfined stream reaches. The pilot application of this method in 2018 indicated that it was useful for detecting potential for channel-hillslope connectivity, yet field observations during SFI mapping found that the dated 1-meter DEM (2009) did not always represent the observed 2018 conditions. DEP will continue to explore this method with USGS in the latter phase of this study.

As reported in prior FAD reports, DEP has investigated GIS-based DEM differencing techniques to measure geomorphic changes in the stream channel corridor by using raster math to subtract the elevation values of one temporal DEM from another. The available DEM for the entire study area is a 2009 1-meter DEM based on April 2009 LiDAR-derived data (RACNE 2012). An additional 2014 1-meter DEM for the Ulster County portion of the study area (~75%) based on November 2013 to June 2014 LiDAR-derived data is available for computing changes between the two periods (Dewberry, 2015). DEP has learned there is a 2019 LiDAR dataset available for Greene County that can be evaluated and potentially used to extend the DEM differencing into all the UEC study area; however, there would be spatial limitations on comparison given the spatially segregated two different time periods (2009-2014; 2009-2019). This DEM differencing technique was successfully used in a study in the nearby Biscuit Brook drainage in the Neversink basin (Hinshaw et al., 2020). DEM differencing is used at the reach scale in the BEMS site investigations, as detailed below. DEP has since amended the scope of work and budget within its contractual agreement with USGS to enable USGS to advance the DEM development and differencing components of the study.

3.2.2 Stream Feature Inventory Mapping

Erosional contact with suspended sediment sources in the study area is largely measured and characterized using SFI methodology. SFIs in the monitored UEC sub-basins conducted by DEP and UCSWCD and Greene County SWCD between 2001 and 2023 are used to estimate the potential SS source conditions in those sub-basins. Suspended sediment source characterization investigations in the Stony Clove sub-basin use a modified SFI protocol to facilitate explaining variations in water quality monitoring reach and tributary sub-basin turbidity dynamics. DEP determined that the standard SFI features, attributes and protocol used for general stream management planning purposes identified in the original study design were insufficient for the more detailed suspended sediment source characterization investigations needed for the Stony Clove sub-basin. DEP created a new SFI protocol and data attribute dictionary specifically for the study prior to collection of any study SFI data. DEP revised the bank erosion feature to include more detailed information on stream confinement, erosional status, bank composition, SS production potential, and several diagnostic attributes. Since streambed erosion into GLS is also a primary turbidity input source, a bed erosion feature and a headcut feature were added.

The SFI methodology is used to map spatially variable erosional contact with suspended sediment sources at a given point in the timeline of the temporal variability in a stream's turbidity production potential. The SFI data represents a temporally constrained sampling of the erosional contact conditions that reflect antecedent hydrologic disruptions, post-flood management actions and/or geomorphic recovery periods. The SFI results can be used to compute erosional contact metrics that might influence turbidity production and to identify potential turbidity production hot spots. In the Stony Clove sub-basin, DEP used recurring SFI mapping to measure the geomorphic response to a large disturbance event (the December 2020 flood), demonstrating the utility of this approach to obtain stream network scale geomorphic measures influencing turbidity production and how those measures change in response to geomorphic process.

SFI features (e.g., bank erosion) are mapped using high resolution, hand-held GPS units (Trimble Geo-XH) that are H-Star enabled and claim mapping accuracy to well under 1 foot. In practice, mapping accuracy and precision varies from inches to many feet and is partially a function of satellite availability, terrain and vegetation obscuration, and antenna models. DEP constrains use of the SFI data for developing erosional contact or connectivity metrics based on a minimum 3-feet (~1-meter) scale of accuracy. This presumed level of accuracy is considered by DEP to be sufficient for computing a sub-basin scale erosion connectivity index – ratio of total mapped bank erosion length to total assessed channel length – since computed total bank erosion and assessed channel lengths are hundreds to thousands of feet.

User bias is an additional source of uncertainty in mapping erosional sediment connectivity and selecting feature attribute values. Determining whether a section of apparent eroding stream bank is active (i.e., sediment can be entrained during bankfull-scale flows), dormant or recovering requires experienced observation. Similarly, identifying the geologic composition of the eroding bank requires experienced familiarity with the fluvial and glacial legacy sediment in the study area. SFI mapping quality assurance and control measures used in this study included requiring that all data collection and processing is supervised by a regionally experienced fluvial geomorphologist leading a team trained in the research SFI protocol. This was achieved for the 2018-2023 data by having a DEP geomorphologist supervise all training and data collection. An exception is the 2023 Broadstreet Hollow SFI data collection that was supervised by a consulting stream scientist that participated in the 2018-2021 SFI investigations. In 2021, the SFI mapping teams included a DEP geomorphologist and other experienced field staff, college interns, and a consulting geologist. For 2018, 2019 and 2021 mapping, the SFI team included the same three SUNY Ulster Watershed Conservation Corp members in addition to the DEP science team. In 2020, all data was collected by DEP. SFI data collected in 2023 was also collected by the DEP geomorphologist and other trained and experienced field staff. User bias was limited by having a small set of the same trained and experienced individuals collect the data. DEP performed all post-processing of data.

3.2.3 Stream Channel Reach Monitoring

This section was formerly labeled Stream Bank Erosion Monitoring Surveys, based on the original study design. DEP has used the acronym BEMS for bank erosion monitoring study based on the original study design methods. Since the BEMS work includes morphometric monitoring of the entire channel reach and covers more than erosion monitoring, DEP has changed this section heading in this report to better reflect the data collected.

DEP contracted with Milone & MacBroom, Inc. (now SLR Consulting Ltd., referred to hereafter as SLR) to collect the data for the BEMS sites. The original intent of the BEMS analysis was to obtain recurring topographic surveys at monumented channel cross sections and along the channel longitudinal profile that can be used to determine time-averaged bank and bed erosion at up to 10 turbidity production hot spot sites that exhibited erosional connectivity with GLS. In the study design, the BEMS data was not intended to provide predictive metrics for turbidity production analysis. The primary utility of this study component is to help prioritize BEMS sites for possible STRP implementation and to monitor untreated sites for evolutionary trajectory. DEP initially proposed surveying previously established BEMS sites initiated in 2001, using laser level survey technology that provides data for two-dimensional topographic profiling and does not locate the survey in a geographic coordinate system. The original study design assumed recurring surveys every two years, with optional post-flood surveys. Many of the former monumented BEMS sites from the 2002-2003 Stony Clove stream management planning field phase were no longer monumented, replaced with STRPs, or had stabilized. DEP opted to select new sites based on SFIs completed between 2010 and 2015. These were supplemented by new hot spot turbidity production reaches following the 2018-2021 SFI mapping.

In 2017, DEP decided to increase the value of the topographic survey monitoring by having SLR perform reach scale three-dimensional topographic surveys using ground-based total station technology and uncrewed aerial system (UAS) technology. SLR uses the UAS to obtain high resolution orthophotography that can be converted to high resolution topography through Structure from Motion (SfM) techniques. This change in methods allows for the development of digital terrain or elevation models (DTM/DEM) that can be used for (1) measuring differences in reach scale channel morphology (erosion/deposition), (2) constructing hydraulic models to simulate varying hydrology and associated shear stress on channel boundaries, and (3) potentially computing sediment input/output budgets. The limitations of the UAS-based approach are that surveys must be performed during leaf-off and snow-free conditions, thus limiting the surveys to late fall/early winter and late winter/early spring. Also, not all sites are suitable for SfM topographic modeling due to obscuring presence of coniferous trees that mask the underlying terrain. DEP and SLR increased the frequency of surveys for active sites and/or sites selected for STRPs, while other sites that were either less active or more remote received surveys every 2-3 years.

In fall 2023, DEP and SLR made an additional change to the channel morphology monitoring surveys by testing use of LiDAR technology with a terrestrial scanner and UAS. The intention with this potential switch is to increase the topographic product resolution, improve “noise” reduction in the point cloud data and increase the seasonal period for data acquisition.

The results of the fall 2023 surveys are not available for this report, so it is premature to determine if this method will be the preferred method going forward.

In addition to increased topographic monitoring spatial and temporal resolution, DEP included funding for SLR to develop hydraulic models for monitored reaches and to integrate stream bank sediment sampling (a separate task in the original study design) into the BEMS scope of work. Streambed sediment sampling is also included through use of Modified Wolman Pebble Counts to obtain grain-size distribution data for the streambed surface susceptible to hydraulic shear stress. Bulk sediment sampling of streambed deposits to obtain estimates of fine sediment content was tested in 2021 and 2022 at two BEMS sites converted to STRPs. Track hoe excavators were available to collect very large sample sizes that were reduced to fill a 33-gallon container that was field screened to remove rocks greater than 63 mm (2.5 inches) and the rest was sent to a certified laboratory for further gradation analysis using sieves and hydrometers. DEP and SLR modified the methods for use without an excavator while still collecting a similar volume of alluvium and expanded the streambed sampling in 2023 throughout the Stony Clove sub-basin and at a couple of sites on Woodland Creek.

The BEMS component of the study concludes in spring 2024, having served the primary purpose of guiding STRP site selection for the study. Three STRPs have been constructed at BEMS sites and an additional one is planned for 2024 or 2025. DEP plans to continue monitoring a set of the BEMS and STRP sites beyond 2024 for purposes beyond the study.

3.2.4 Suspended Sediment Fingerprinting

Sediment fingerprinting is a technique that apportions the sources of fine-grained sediment in a watershed using diagnostic tracers or “fingerprints”. Sources are classed into geologic units where each unit because of its geologic history has a unique geochemical signature (Gellis and Walling, 2011). This technique was piloted in the Stony Clove and Woodland Creek watersheds from 2017 through 2020. The pilot study demonstrated the potential to develop a source sample library and use storm samples to identify the relative contributions of each source class as they vary through the storm hydrograph (Staub et al., 2022). Starting in 2023, sediment fingerprinting was expanded to the UEC basin and will continue through the duration of the study. Based on the pilot study, the sources of sediment have been identified as: (1) LS, (2) GT, (3) AL, and (4) forested upland soil. The source sample library will be expanded to include the Esopus Creek mainstem and the monitored tributaries. Storm samples for fingerprinting analysis will be collected at Stony Clove at Chichester (01362370), Woodland Creek at Phoenicia (0136230002), and Esopus Creek at Coldbrook (01362500). The storm samples will be used to identify the proportion of different geologic sources of suspended sediment at different points on the hydrograph.

3.2.5 USGS Expanded Geomorphology and Geology Investigations

The existing study methods will be augmented to include the following work performed by USGS between 2024 and 2027: (1) use a sediment budget framework to quantify sources, storage, and export of fine sediment from Stony Clove and Woodland Creeks, (2) evaluate how different management scenarios could affect sediment loading from Stony Clove and Woodland

Creeks, and (3) identify stream reaches with the potential for future contact with glacial legacy sediments in Stony Clove and Woodland Creeks using geophysical measurements to map subsurface fine-grained sediment The focus of this new work is on Stony Clove and Woodland Creeks because these sub-basins have historically been the greatest sources of turbidity to the upper Esopus Creek. Actual methodologies associated with the new scope of work will be documented in USGS data releases, a final USGS Scientific Investigation Report, and future peer-reviewed publications.

3.3 Study Assumptions

Based on past research, assessment and monitoring efforts, DEP has made some assumptions to inform methodology development and interpretation that are restated below. These are updated with each report, as needed.

- Turbidity production and related suspended sediment flux in the study area is primarily sourced in the channel network and connected hillslopes. The study acknowledges there are other sources but that these sources are sufficiently small contributions during runoff events that deliver turbid streamflow to the Ashokan Reservoir. The expanded scope of geomorphic investigations in 2024 through 2026 by USGS and DEP will examine the validity of this assumption.
- There are hydrologic thresholds that function as hydrogeomorphic thresholds that change the scale of geomorphic response contributing to sediment flux or turbidity production. This assumption is complicated by the condition that big floods frequently alter the erosion resistance threshold – variably, reach to reach – for subsequent lower magnitude flows for an extended period.
- There are two primary categories of suspended sediment generation evaluated in this study: (1) input of new sources through channel margin and connected hillslope erosion and sediment entrainment and (2) resuspension of stored fine sediment in mobilized streambed alluvium. Up to 2021, the study only directly accounted for the input of new sources through erosion. The 2021-2023 sampling efforts of stored fine sediment in channel AL and subsequent work by USGS may help extend the accounting to the resuspension source.
- Glacial legacy sediment stored in the watershed is the principal erosional source of suspended sediment and associated glacial lake sediment is the primary source for recruited input of suspended sediment in the fluvial system. Eroding stream channel boundaries composed only of AL contribute much less sediment per dimensional unit than those that include LS and/or GT, based on the fine sediment content.
- Turbidity production is heterogeneously distributed at the sub-basin to reach scale in the upper Esopus Creek basin and varies spatially and temporally as a direct function of hydrologic and hydraulic forcing and geomorphic connectivity with suspended sediment source geology. The study aims to quantify that distribution to the extent feasible.

- A small fraction of a stream channel length can account for significant turbidity/SS production (i.e. the turbidity hot spot concept), therefore strategic treatment placement can yield a significant reduction in turbidity/SS. STRPs that disrupt reach-scale stream channel fine sediment source connectivity can produce a measurable reduction in SSC and turbidity at the sub-basin scale, and multiple STRPs in a sub-basin can potentially reduce turbidity and SSC at the reservoir basin scale.

3.4 Study Limitations

There are several limitations to the study scope, methods and ultimately the findings. This section briefly describes each critical limitation that should be factored into evaluating the study findings to date.

1. The study currently does not investigate the following factors that influence turbidity in the UEC watershed:

   - The Schoharie Diversion is a measurable source of turbidity and SS to Esopus Creek and the Ashokan Reservoir. However, it is outside the original scope of this study, which is investigating the UEC contributions to identify which sub-basins may disproportionately yield turbid streamflow and would be targeted for STRP implementation. The measured turbidity and SSC at the Esopus Creek at Coldbrook station includes potential contributions from the Schoharie Diversion during non-flood flows. The Schoharie Diversion is typically shutdown during flood flows. Since October 1, 2022, USGS has received continuous turbidity monitoring data for the Schoharie Diversion from DEP. USGS has also started to include SSC sampling of the Schoharie Diversion discharge to develop Tn-SSC relations. USGS will begin to account for this contribution in future analyses.

   - The SFI sediment source investigations mapped static erosional connectivity conditions observed during a field season and primarily focused on fluvial erosion and adjacent geotechnical erosion. Seasonal and episodic erosional events not directly linked to streamflow (e.g., freeze-thaw processes and other mass-wasting processes not evident during field inspection such as saturated debris flow) are noted but not currently explicitly addressed in metric development.

   - Historic and recent human modifications to the landscape and stream corridor influence streamflow runoff, hydraulics, geomorphic process response, and sediment connectivity. The current study does not investigate the role of these human legacy effects, as distinct from non-anthropogenic influences on streamflow runoff, hydraulics, geomorphic response, and sediment connectivity. This is a potentially significant limitation that should be evaluated in subsequent investigations.

   - The role of riparian vegetation condition influencing channel stability thresholds and turbidity production is recognized but not investigated in the current study scope. Data is collected during SFI mapping that can be available for other studies to investigate this potential important explanatory variable.

2. There are some limitations to the methods and measuring equipment used in the study:

- Section 3.1.2 describes the upper limits of turbidity measurements in the Forest Technology System DTS probes as 1,600 FNU. This limit was met/exceeded during the December 2020 flood, thus limiting the quantification of the turbidity for portions of the event (and potentially other events). This is being addressed through targeted probe replacement with Analite models that reportedly have an upper limit of 4,000 FNU.
- Big floods damage monitoring equipment, especially in the smaller high-energy, high-sediment load streams. USGS optimizes sampling/monitoring locations to sample well-mixed streamflow, with infrastructure attached to stable natural features (large streamside boulders) or constructed features (bridge abutments). Site access and health and safety standards also influence monitoring station placement. It is understood that floods capable of generating sub-basin to basin scale turbidity production have the capacity to damage equipment.
- Field investigations of turbidity source conditions did not cover the entire stream network in a monitored sub-basin. The SFI mapping in Stony Clove sub-basin could not investigate every unit of channel length, in part due to a lack of landowner permission. Most headwater reaches and lower order streams were not assessed. This means probable connections with turbidity sources were not accounted for in the study.
- SFI mapping has limited accuracy and precision. Inconsistency in GPS accuracy limits the ability to rely on mapped features for detailed position analysis (e.g., time series bank retreat). The accuracy may be sufficient to show >3-feet differences in feature position and dimension that can be compared across time and space. The study currently only uses the data to compute dimensionless erosional sediment connectivity indices as described in Section 3.2.2. Further investigation into data accuracy may extend further use of the data in subsequent studies by other researchers.
- Not all contributing areas and sub-basins to UEC are monitored. The current stream monitoring network upstream of the Esopus Creek at Coldbrook gage accounts for 82% of the contributing area.

4. Study Data and Results Through Water Year 2023

This section presents an update of the research results presented in the mid-term study report for streamflow, turbidity and SS monitoring, sediment source characterization, and STRP evaluation through water year 2023. Rather than presenting all the data collected thus far, this report presents the first seven years of findings that address the research goals and objectives. All streamflow, turbidity and SSC data collected through the monitoring period are available through the USGS National Water Information System. The final geomorphic investigation data will be available for distribution upon completion of the final study FAD report in November 2027 and through DEP and USGS data releases.

Section 4.1 describes the metrics developed thus far based on the monitoring and source characterization data. Section 4.2 updates streamflow monitoring results for the reporting period. Sections 4.3 and 4.4 update turbidity and SS monitoring results, respectively, for the reporting period. Section 4.5 updates the turbidity and SS source investigations at the UEC watershed scale and the deeper dive into source characterization for Stony Clove sub-basin. Section 4.6 provides an updated provisional evaluation of STRP efficacy.

4.1 Metric Development

Streamflow metrics that help explain observed turbidity and SS production include mean annual streamflow (MAQ) and mean annual runoff (MAR), peak streamflow runoff (PQR), occurrence and magnitude of runoff events exceeding hypothetical hydrogeomorphic thresholds. Additionally, daily mean streamflow is used as an explanatory variable in measured daily mean turbidity and estimated daily mean SSC, and as a component variable in calculation of SS loads and yields. DEP and USGS will continue to investigate other potential turbidity production explanatory hydrology metrics.

Turbidity metrics used in this report to help identify a sub-basin's relative role in Ashokan Reservoir turbidity levels include statistical metrics of turbidity values derived by USGS: the relation of daily mean streamflow-daily mean turbidity for different hydrogeomorphic conditions and comparisons of turbidity at different streamflow exceedances.

Suspended sediment metrics examined in this research include SSC-Q, SSL (SSC*Q) and SSY (SSC*Q/DA). Continuous estimates of SSC and SSL are derived from Tn-SSC regression relationships developed by USGS using the first three years of SSC point and cross-section sampling and continuous turbidity measurements (Siemion et al., 2021). The regression equations are developed for each monitored sub-basin representing the unique relationships between the SS sources and concentrations and turbidity. Updated continuous SSC, loads, and yields are not presented in this report because the previous Tn-SSC regression equations need to be updated. The regression analysis will be completed in 2025 and the results will be reported in the November 2027 final study FAD report.

Suspended sediment and turbidity source geomorphic metrics are derived from the available SFI data through 2023. For the UEC sub-basin analysis, the pre-study and more recent SFI data is used to compute basic erosional and sediment connectivity indices. The stream bank erosion index (EI_{Bnk}) introduced in DEP's mid-term study report is a measure of the mapped bank erosion length divided by the total length of assessed stream channel. This index was presented as percent bank erosion in Table 4.1 in the 2021 biennial status report (DEP, 2021) and was computed as mapped bank erosion length divided by twice the length of assessed channel, to account for both banks. The change made for the mid-term report and this report is to improve consistency with recent scientific literature investigating bank erosion connectivity (Cienciala et al., 2020). Bank erosion is further categorized into two sediment connectivity indices (SCI) to represent whether the mapped bank erosion includes connectivity with GLS (SCI_{GLS}) or only AL (SCI_{AL}). These two indices are lengths normalized by the total length of mapped bank erosion used to compute EI_{Bnk}. The dominant source of GLS (LS or GT) in a mapped stream is also identified based on review of the SFI data. It is important to re-emphasize that this UEC watershed data spans 20 years, had multiple different observers, and used three different SFI data schema. Given that significant quality control limitation, these data are used to represent potential for connectivity conditions during the study period, not actual contemporaneous connectivity. Stony Clove index values presented at the UEC scale are for the pre-study 2013 data (DEP, 2022). The results used to compute study metrics for Stony Clove, reported separately, are based on different SFI methods and represent data coincident with the reporting period.

Erosional and sediment connectivity metrics for Stony Clove sub-basin can be more numerous and refined owing to the additional detail in the SFI data dictionary used for that component of the study. As a result, erosional sediment connectivity can include bed erosion and both bank and bed erosional connectivity can be further explored through more specific geologic composition and inclusion of confinement conditions. In the mid-term report, bank and bed erosional connectivity indices (EI_{Bnk}, EI_{Bed}) were investigated and sediment connectivity indices included the previous SCI_{GLS} and SCI_{AL}, along with SCI_{LS} and SCI_{GT} to quantify the relative proportions of the respective GLS component of connectivity. There are no updates to the Stony Clove SFI data analysis presented in this report.

4.2 Streamflow Monitoring

The USGS streamflow monitoring network successfully monitored continuous streamflow at 15-minute intervals for all UEC sub-basins and the two mainstem EC monitoring stations through the duration of the reporting period. Streamflow data (continuous, daily and annual means, annual peak) for the reporting period are available from the USGS National Water Information System.

Streamflow represents energy applied to the landscape that powers fluvial processes (Castro and Thorne, 2019). 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. Figures 4.1 and 4.2 show the continuous streamflow hydrographs for Esopus Creek at Coldbrook station (01362500) and Stony Clove Creek at Chichester station (01362370), covering a 24-year period from water year 2000 through water year 2023. The study monitoring period is marked on the hydrographs. The depicted 24-year record places the monitoring period in a temporal and hydrologic context.

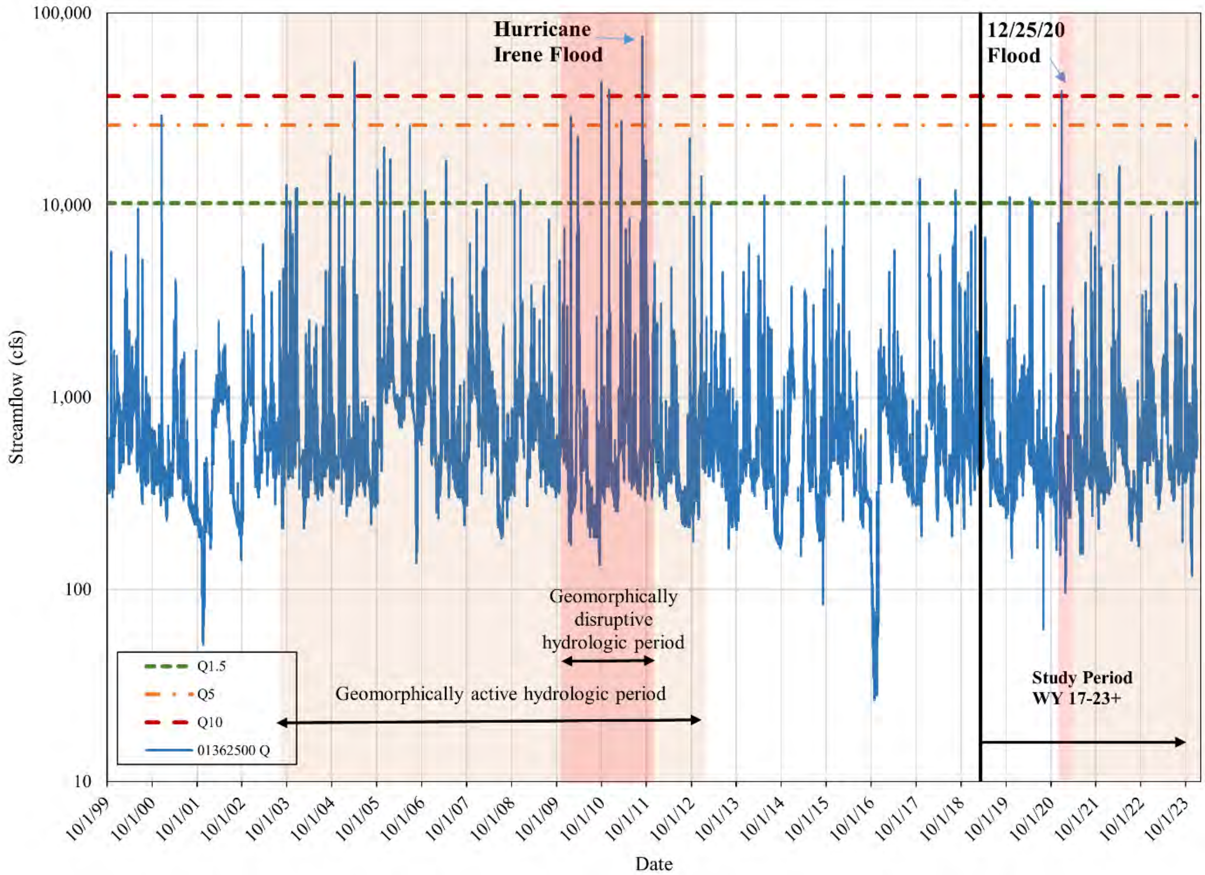

Figure 4.1 Continuous streamflow hydrograph for Esopus Creek monitoring station 01362500 with reference recurrence interval streamflows using the full period of record for FFA. Water year 2023 and 2024 data are provisional and subject to change.

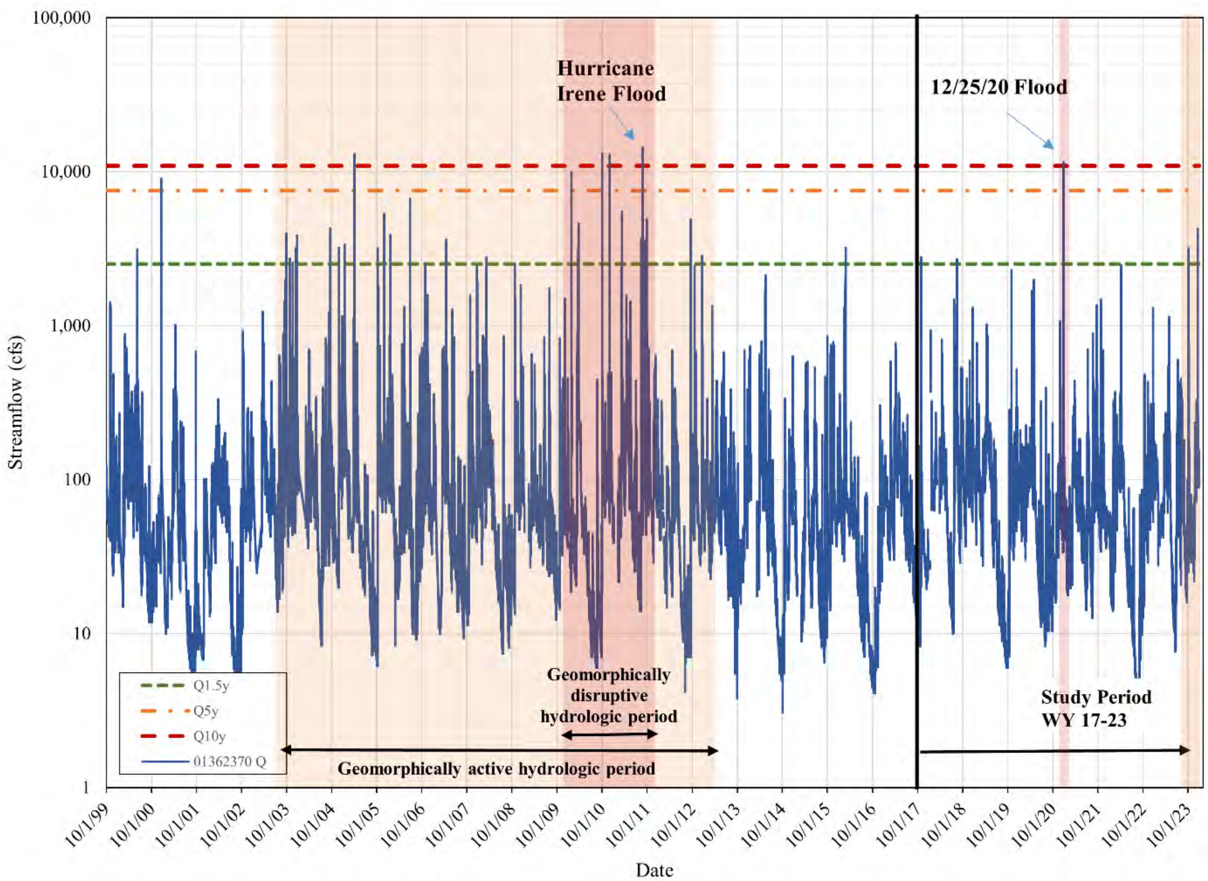

Figure 4.2 Continuous streamflow hydrograph for Stony Clove Creek monitoring station 01362370 with reference recurrence interval streamflow using the full period of record for FFA. Water year 2023 and 2024 data are provisional and subject to change.

4.2.1 Annual Streamflow and Runoff Results

The daily mean streamflow reported by USGS for each primary monitoring station is used in this study to compute some basic streamflow metrics that can be used to consider the relative contributing streamflow volume from each monitored sub-basin to the total flow measured at the Esopus Creek at Coldbrook station just upstream of the Ashokan Reservoir.

The study assumes most turbidity production takes place during big floods capable of forcing a lot of geomorphic work and sediment transport through the fluvial system; however, an examination of the mean streamflow runoff conditions through the course of the study can provide some insight into each sub-basin's role in supplying water at the reservoir basin scale and help quantify the interannual variability. Mean annual streamflow is obtained by dividing the sum of all the individual daily flows by the number of daily flows recorded for a year. The study period mean annual streamflow for each water year and all primary stations in the UEC are presented in Table 4.1 and the mean annual streamflow data for the Stony Clove sub-basin primary stations are presented in Table 4.2. The values in the table are color-coded to show the range from lowest to highest value across the seven years for each streamflow monitoring station. Water years 2018 and 2019 had the highest monitored streamflow for all UEC sub-basins, except for Little Beaver Kill (2023 and 2019) and Esopus Creek at Coldbrook (2018 and 2023). The spatial and temporal variability in streamflow over the course of the study so far supports the study design requiring a minimum of ten contiguous years of monitoring to help ensure there is a sufficient range of observed conditions.

Table 4.1 Mean annual streamflow (MAQ) reported in cfs for each UEC streamflow monitoring station for water years 2017-2023, excluding the Stony Clove sub-basin stations. Values for UEC sub-basins are color-coded to represent relative ranking, with green to red scaling depicting the range from lowest to highest values for each station. The MAQ for the total seven years is presented without color-coding.

Stream (USGS Station ID)	2017	2018	2019	2020	2021	2022	2023	Mean MAQ
Esopus Creek (0136219503)[1]	69.0	80.8	82.0	75.1	76.8	68.1	75.7	75.4
Birch Creek (013621955)	29.0	38.1	35.0	29.0	28.4	30.9	26.9	31.0
Esopus Creek (01362200)	140.5	204.8	204.0	159.0	167.1	182.2	173.3	175.8
Woodland Creek (0136230002)	53.6	75.1	74.3	60.5	65.4	58.5	71.1	65.5
Stony Clove Creek (01362370)	73.4	99.0	101.6	78.4	94.5	67.5	92.1	86.6
Beaver Kill (01362487)	38.8	74.7	79.5	57.7	61.1	44.9	51.5	58.3
Little Beaver Kill (01362497)	29.6	40.7	44.0	35.0	37.4	34.0	51.7	38.9
Esopus Creek (01362500)	638.1	751.7	680.8	587.1	650.8	613.1	734.8	665.2

[1]Station 0136219503 is missing the first 11 days of October 2016.

Table 4.2. Mean annual streamflow (MAQ) reported in cfs for each Stony Clove sub-basin streamflow monitoring station for water years 2017-2023. Values are color-coded to represent relative ranking, with green to red scaling depicting the range from lowest to highest values for each station. The MAQ for the total seven years is presented without color-coding. NA is entered if the water year is incomplete.

Stream (USGS Station ID)	Drainage Area	2017	2018	2019	2020	2021	2022	2023	Mean MAQ
Stony Clove Creek (01362370)	30.9	73.0	99.0	102.0	79.0	95.0	67.5	92.1	86.8
Myrtle Brook (01362322)	1.8	NA	6.0	5.3	4.7	5.8	3.9	4.9	5.1
Stony Clove Creek (01362336)	9.3	NA	32.8	27.7	23.6	30.5	20.4	29.6	27.4
Hollow Tree Brook (01362342)	2.0	4.5	6.8	6.4	5.6	5.9	4.8	5.4	5.6
Warner Creek (01362357)	8.7	17.5	26.9	24.9	22.0	26.2	18.0	27.5	23.3
Ox Clove Creek (01362368)	3.8	NA	9.1	9.8	8.3	9.5	7.5	10.2	9.1

Annual runoff is a measure of the streamflow normalized by the contributing drainage area. It can be considered a streamflow yield and serves to rank which sub-basins produce the most streamflow per unit area. Annual runoff magnitude is known to influence channel dimensions in the study area (Miller and Davis, 2003). Mean annual runoff (MAR) is computed by normalizing the annual sum of daily mean streamflow (Q) by the monitored drainage area (DA). MAR supports comparison of streamflow availability among the monitored sub-basins. MAR values are presented for each study period water year through 2023 in flow per drainage area units (cfs/mi^2) in Table 4.3. It is clear in Table 4.3 that some sub-basins have a higher flow yield than other sub-basins. The highest MAR sub-basins are Woodland Creek and Stony Clove Creek, respectively, while Little Beaver Kill has the lowest MAR. Factors that are known to influence MAR variability include, precipitation, basin slope, landcover, geology, and storage.

Table 4.3 Mean annual runoff (MAR) reported in cfs/mi^2 for each UEC streamflow monitoring station for water years 2017-2023. Values for UEC sub-basins excluding 01362500 are color-coded to represent relative ranking, with green to red scaling depicting lowest to highest values for each year. Note MAR for 01362500 is influenced by contributions from the Schoharie Diversion.

Stream (USGS Station ID)	2017	2018	2019	2020	2021	2022	2023	Mean MAR
Esopus Creek (0136219503)[1]	2.3	2.7	2.8	2.5	2.6	2.3	2.6	2.5
Birch Creek (013621955)	2.3	3.1	2.8	2.3	2.3	2.5	2.2	2.5
Esopus Creek (01362200)	2.2	3.2	3.2	2.6	2.6	2.9	2.7	2.8
Woodland Creek (0136230002)	2.6	3.6	3.6	2.9	3.2	2.8	3.6	3.2
Stony Clove Creek (01362370)	2.4	3.2	3.3	2.5	3.1	2.2	3.0	2.8
Beaver Kill (01362487)	1.6	3.0	3.2	2.3	2.5	1.8	2.1	2.3
Little Beaver Kill (01362497)	1.8	2.5	2.7	2.1	2.2	2.1	3.1	2.4
Esopus Creek (01362500)	3.3	3.9	3.6	3.1	3.4	3.2	3.8	3.5

[1]Station 0136219503 is missing the first 11 days of October 2016.

Table 4.4 Mean annual runoff (MAR) reported in cfs/mi^2 for each Stony Clove sub-basin streamflow monitoring station for water years 2017-2023. Values are color-coded to represent relative ranking, with green to red scaling depicting lowest to highest values. Note MAR for 01362500 is influenced by contributions from the Schoharie Diversion.

Stream (USGS Station ID)	2017	2018	2019	2020	2021	2022	2023	Mean MAR
Stony Clove Creek (01362370)	2.4	3.2	3.3	2.5	3.1	2.2	3.0	2.8
Myrtle Brook (01362322)	NA	3.3	2.9	2.6	3.2	2.2	2.7	2.8
Stony Clove Creek (01362336)	NA	3.6	3.0	2.6	3.3	2.2	3.2	3.0
Hollow Tree Brook (01362342)	2.3	3.5	3.3	2.9	3.0	2.4	2.8	2.9
Warner Creek (01362357)	2.0	3.1	2.9	2.5	3.0	2.1	3.2	2.7
Ox Clove Creek (01362368)	NA	2.4	2.6	2.2	2.5	2.0	2.7	2.4

4.2.2 Flood Hydrology

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 will require the full ten years of monitoring and geomorphic investigations to provide an empirically informed estimate. In the study conceptual model, there are streamflow event magnitudes or magnitude ranges that can breach a range of geomorphic stability thresholds that influence turbidity production. These are referred to as hydrogeomorphic thresholds in this study. The lower threshold range represents frequently recurring floods capable of geomorphic work and the upper range thresholds represent a less frequently recurring flood that is capable of "excess" geomorphic work resulting in a more widely distributed disturbance to reaches in 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 disturbed area. Geomorphic disturbances typically do not destabilize the entire stream network, but rather specific reaches, with specific geomorphic conditions, while other reaches, with different, more stable geomorphic conditions, may remain undisturbed. The destabilized reaches that have erosional contact with GLS can be turbidity production hot spots.

Three reference streamflow magnitudes are depicted in Figures 4.1 and 4.2. The streamflow values are flood frequency recurrence interval (RI) streamflows and were computed using the available period of record through water year 2022 for each station in a log-pearson Type III (LPT3) flood frequency distribution analysis. The 1.5-year RI streamflow ($Q_{1.5y}$) is a common surrogate for the bankfull flow, which over decadal time scales performs most of the fluvial geomorphic work in maintaining the stream channel and conveying sediment. This frequently recurring event is set as a value in the lower threshold range, as it is generally not associated with a stream network scale channel disturbance event but can perform geomorphic work. The 10-year RI streamflow (Q_{10y}) is an event capable of geomorphic work that has the potential to cause disruptive channel reach disturbance at the stream network scale and represents a value in the upper threshold range. Flood events at or exceeding this threshold may result in potential reach-level or 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_{10y} floods will have this effect in all reaches of a stream system, though observations of similar magnitude events in the study area demonstrate its potential for geomorphic response in several reaches. An intermediate 5-year RI streamflow (Q_{5y}) is also depicted.

Table 4.4 presents updated flood frequency flow values and corresponding runoff values (PQR) for the $Q_{1.5y}$ and Q_{10y} for those primary monitoring stations with a sufficient period of record (10 years) through water year 2023. Hollow Tree Brook (01362342) and Warner Creek (01362357) have been added to the table for this report. The flood frequency flows in Table 4.3

were computed using (1) the period of record through water year 2023 for each station, and (2) the LPT3 frequency distribution method and regionalized skew coefficients. Given the range in periods of record (12-92 years), the uncertainty for each probabilistic flow varies considerably. Table 4.5 presents alternate LPT3 flood frequency results for streams with a shared minimum 21-year record (2003-2023) to test for uncertainties associated with differing periods of record and potential non-stationarity in the long-term flow record. The Woodland Creek station period of record is 21 years so there is no difference between the tables.

As expected, there are differences between the full period of record and the shared 21-year period of record analyses for each gage and there are differences between the results reported in the mid-term report (DEP, 2022). This sensitivity in the results to the addition of two more years (2022 and 2023) for each station, highlights the "moving target" of this metric. The differences in the $Q_{1.5y}$ flow between the shared 21-year record and full period of record were generally small percentage increases ranging from 2% to 7% except for Hollow Tree Brook and Esopus Creek at Coldbrook with a 13% and 15% increase, respectively; and an 8% decrease for Stony Clove Creek. The biggest increase in the Q_{10y} is for Esopus Creek at Allaben (15%) and the biggest decrease is for Stony Clove Creek (-10%). The percent difference for the other gages ranged from -4% to 3%. This analysis was conducted by DEP and did not use the regional regression weighting method that USGS uses, so the results would also differ based on computational methods.

While there are differences in results depending on flood frequency distribution methods and different periods of record, the values in Tables 4.4 and 4.5 do provide a reasonable range estimate of what scale of runoff event may influence turbidity production in these streams. The highest PQR values for these reference flows are in Stony Clove Creek, Warner Creek, Woodland Creek and Beaver Kill; the lowest by a significant amount is in Birch Creek. Birch Creek is on the western margin of the UEC and is partially influenced by lower precipitation amounts (Miller and Davis, 2003). Birch Creek can be a high turbidity producer (Section 4.3) so using PQR as an indicator of potential turbidity production without considering the relative magnitude of PQR compared to a sub-basin specific reference flow and the geology and geomorphology of the sub-basin is inadequate. Ongoing work by researchers at the University of Vermont on developing turbidity forecast models for Esopus Creek at Coldbrook station is exploring several other potential hydrology metrics that can improve the utility of monitored hydrology to predict turbidity.

Table 4.4 Hydrogeomorphic streamflow and PQR (Q/DA) metrics ($Q_{1.5y}$, Q_{10y}) for each streamflow monitoring station with records ≥10 years. Period of record is through water year 2023. Flood frequency flows are computed by DEP using log-Pearson Type III methods without regional regression weighting and may differ from other methods.

Stream (USGS Station ID)	Period of Record (yrs)	$Q_{1.5y}$ (cfs)	$PQR_{1.5y}$ (cfs/mi^2)	Q_{10y} (cfs)	PQR_{10y} (cfs/mi^2)
Birch Creek (013621955)	24	342	27.4	1,014	81.1
Esopus Creek (01362200)	61	2,490	39.1	10,850	170.3
Woodland Creek (0136230002)	21	1,539	74.7	5,137	249.4
Hollow Tree Brook (01362342)	26	91	45.5	360	180.0
Warner Creek (01362357)	12	644	74.0	1764	202.8
Stony Clove Creek (01362370)	30	2,481	80.3	10,922	353.5
Beaver Kill (01362487)	13	1,516	60.6	5,231	209.2
Little Beaver Kill (01362497)	26	927	56.2	2,197	133.2
Esopus Creek (01362500)	92	10,300	53.6	37,133	193.4

Table 4.5 Hydrogeomorphic threshold streamflow and PQR (Q/DA) metrics ($Q_{1.5y}$, Q_{10y}) for streamflow monitoring stations with a coincident 21-year period of record (2003–2023). Flood frequency flows are computed by DEP using log-Pearson Type III methods without regional regression weighting and may differ from USGS computed values.

Stream (USGS Station ID)	Period of Record (yrs)	$Q_{1.5y}$ (cfs)	$PQR_{1.5y}$ (cfs/mi^2)	Q_{10y} (cfs)	PQR_{10y} (cfs/mi^2)
Birch Creek (013621955)	21	365	29.2	1,008	80.6
Esopus Creek (01362200)	21	2,538	39.8	12,514	196.5
Woodland Creek (0136230002)	21	1,539	74.7	5,137	249.4
Hollow Tree Brook (01362342)	21	103	51.5	369	184.5
Stony Clove Creek (01362370)	21	2,276	73.7	9,871	319.4
Little Beaver Kill (01362497)	21	996	60.4	2,112	128.0
Esopus Creek (01362500)	21	11,800	61.5	38,299	199.5

The largest runoff event and most geomorphically impactful event since the study started continues to be the December 25, 2020 flood. The mid-term study report included a detailed accounting of the event hydrology and is not repeated in this report. There have been three events recorded at the Esopus Creek (01362500) and Stony Clove Creek (01362370) gages since the December 25, 2020 flood that were proximal to, or greater than, a $Q_{1.5y}$ event but less than a Q_{5y} event (Figures 4.2 and 4.3). USGS will continue to monitor hydrology through water year 2026. DEP will provide an updated analysis in the November 2027 final study FAD report.

4.3 Turbidity Monitoring

4.3.1 UEC Results

Comparison of SSC or turbidity between monitoring stations may be complicated by differences in monitoring periods between stations, missing data at some stations, and differences in the magnitude of storms across the Esopus Creek watershed. Use of the daily mean streamflow-daily mean SSC and daily mean streamflow-daily mean turbidity relations for comparisons between stations can minimize these concerns. The daily mean streamflow-daily mean turbidity relations for the sub-basin stations in previous reports were shown on a single figure displaying regression lines for the study period. A drawback of this was that periods of different geomorphic and sediment transport conditions were combined in one figure, and showing only the regression line for each site did not display the variability in the data. For this report the streamflow-turbidity relations for each site are subset into similar hydrogeomorphic conditions/time periods and into four streamflow exceedance classes.

Daily mean turbidity as a function of daily mean streamflow for each Esopus sub-basin site was subset into 5 distinct time periods with similar hydrogeomorphic conditions:

(1) an initial period of relatively stable conditions (October 1, 2016 to October 28, 2017; Figure 4.3),

(2) a period of sustained high turbidity after a storm with peak streamflows approximating $Q_{1.5y}$ (October 29, 2017 to February 28, 2018; Figure 4.4),

(3) a period of relatively stable conditions between geomorphically significant streamflows (March 1, 2018 to December 23, 2020; Figure 4.5),

(4) a period of sustained high turbidity after a storm with peak streamflows approximating Q_{5y} to Q_{20y} (December 24, 2020 to September 30, 2021; Figure 4.6), and

(5) a final period of relatively stable conditions (October 1, 2021 to September 30, 2023; Figure 4.7).

In general, turbidity at each sub-basin site was lower for a given streamflow during the relatively stable time periods and greater after the two storms. Birch Creek (013621955), Broadstreet Hollow Brook (01362232) and Woodland Creek (0136230002) tended to have the greatest base line turbidity at low streamflows, suggesting contact with chronic sources of fine sediment. Beaver Kill (01362487), Stony Clove Creek (01362370), and Woodland Creek (0136230002) all had a combination of high streamflow and high turbidity (suggesting high sediment load) relative to the other sub-basin sites during all time periods. Esopus Creek above Lost Clove (0136219503) also had relatively high streamflow and turbidity after the large storms.

The relative importance of each sub-basin in contributing sediment and turbidity to the upper Esopus Creek appears to shift through time as the sub-basins are affected differently by different storms. For example, the two large storms resulted in greater increases in turbidity per unit streamflow in Woodland Creek than in Stony Clove Creek. These results differ from earlier monitoring and research conducted by the AWSMP, DEP, and USGS between 2009-2014 (McHale & Siemion, 2014; Siemion et al., 2016). Previously, Stony Clove Creek had, by far, the highest turbidity-streamflow relationship in the UEC watershed followed by Woodland Creek. Published (Wang et al., 2021; Siemion et al., 2023) research by Cornell University, DEP, and USGS has demonstrated that much of the reduction in sediment transport and turbidity is due to successful application of STRPs that strategically disconnect the stream channel from erosional contact with glacial legacy sediment.

Streamflow and turbidity exceedance percentage is the percent of time a specific streamflow or turbidity is equaled or exceeded. For example, Q_1 is the streamflow that is equaled or exceeded 1 percent of the time. Q_1 would generally be associated with high streamflows and Q_{50} with moderate to low streamflows. Turbidity associated with streamflows $>Q_1$, Q_{10}, Q_{25}, and Q_{50} for the Esopus sub-basin sites is shown in Figure 4.8. Turbidity was generally high across the Esopus sub-basins and mainstem sites during streamflows $>Q_1$ with the exception of Little Beaver Kill which had much lower turbidity. These results suggest that sediment is being mobilized from all tributary watersheds during the highest streamflows. However, the magnitude of the contributions from sub-basins with larger drainage areas, and thus greater streamflows, such as Beaver Kill (01362487), Stony Clove Creek (01362370), Esopus Creek above Lost Clove (0136219503) and Woodland Creek (0136230002) are greater than a smaller sub-basin with equally high turbidity such as Birch Creek (0136321955). A similar pattern is observed at Q_{10}, though the Esopus Creek above Lost Clove (0136219503) has much lower turbidity at Q_{10}. Birch Creek (013621955) and Woodland Creek (0136230002) had the highest turbidity at Q_{25} and Q_{50}, suggesting these sub-basins have a greater contact with chronic sediment sources.

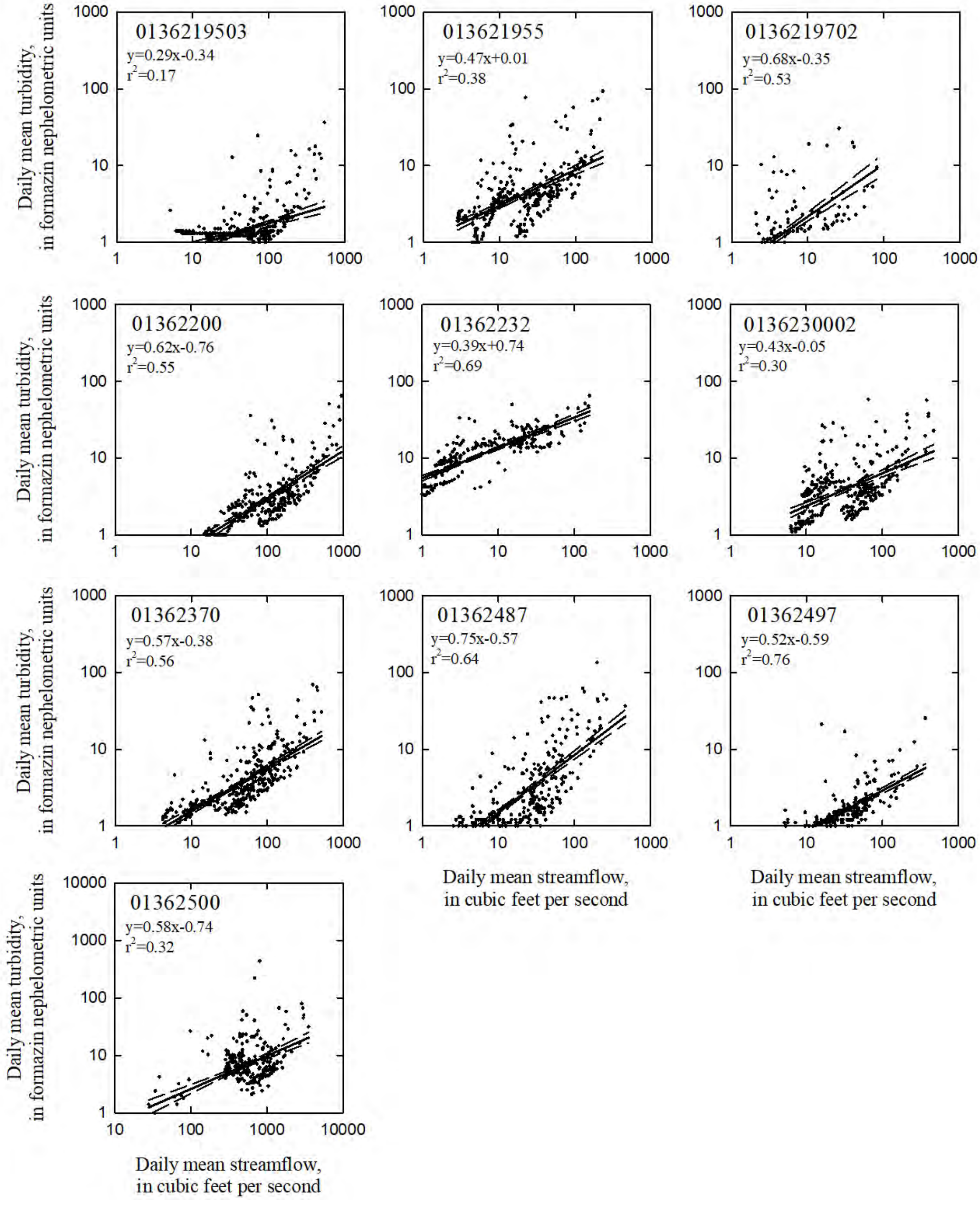

Figure 4.3 Daily mean turbidity as a function of streamflow for Esopus sub-basin sites for the period 10/1/2016 to 10/28/2017, a relatively stable geomorphic period. See Table 3.1 for streams represented by USGS stream station number. Source: USGS

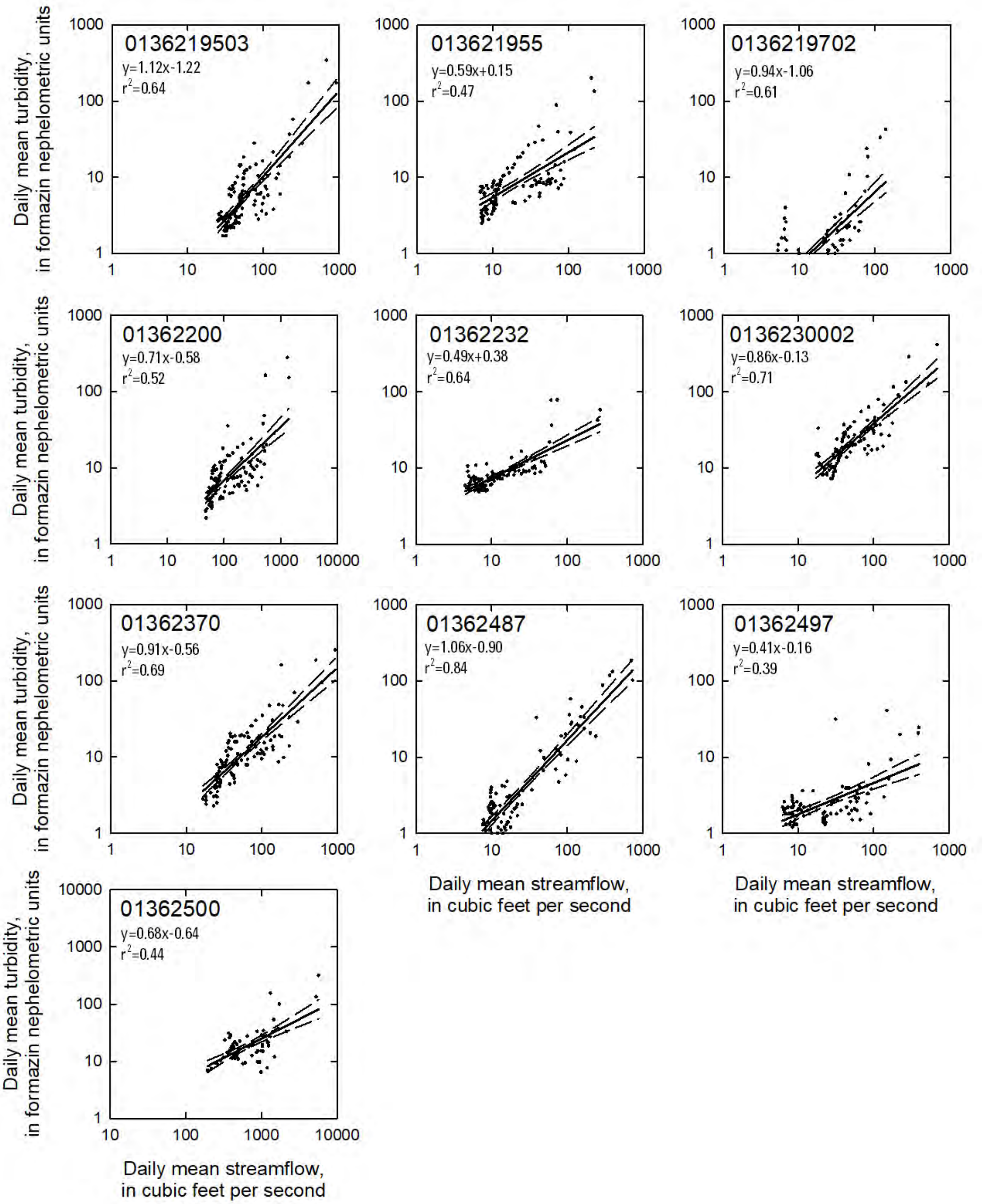

Figure 4.4 Daily mean turbidity as a function of streamflow for Esopus sub-basin sites for the period 10/29/2017 to 2/28/2018, a relatively active geomorphic period after a 1.5-year RI storm. See Table 3.1 for streams represented by USGS stream station number. Source: USGS

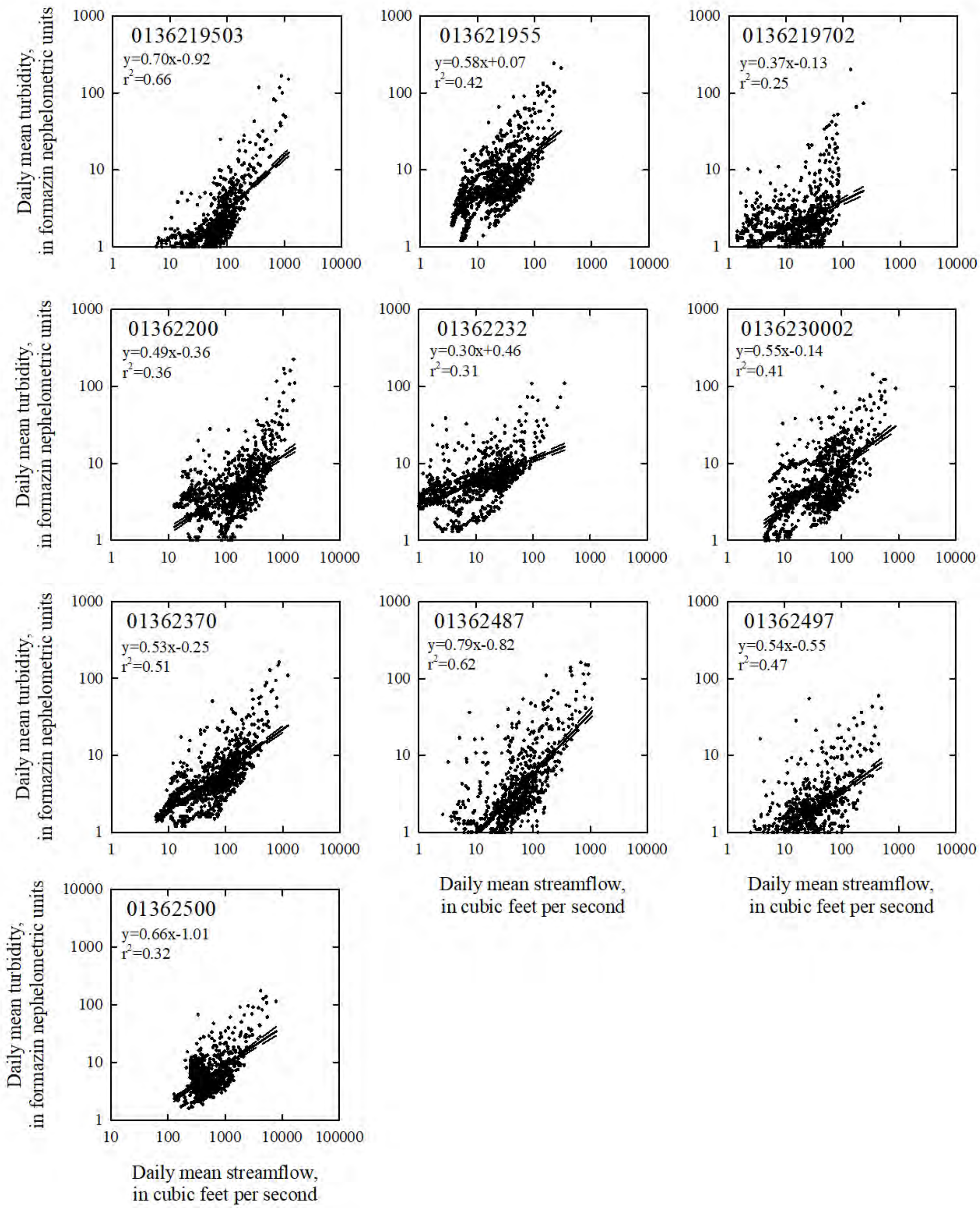

Figure 4.5 Daily mean turbidity as a function of streamflow for Esopus sub-basin sites for the period 3/1/2018 to 12/23/2020, a relatively stable geomorphic period. See Table 3.1 for streams represented by USGS stream station number. Source: USGS

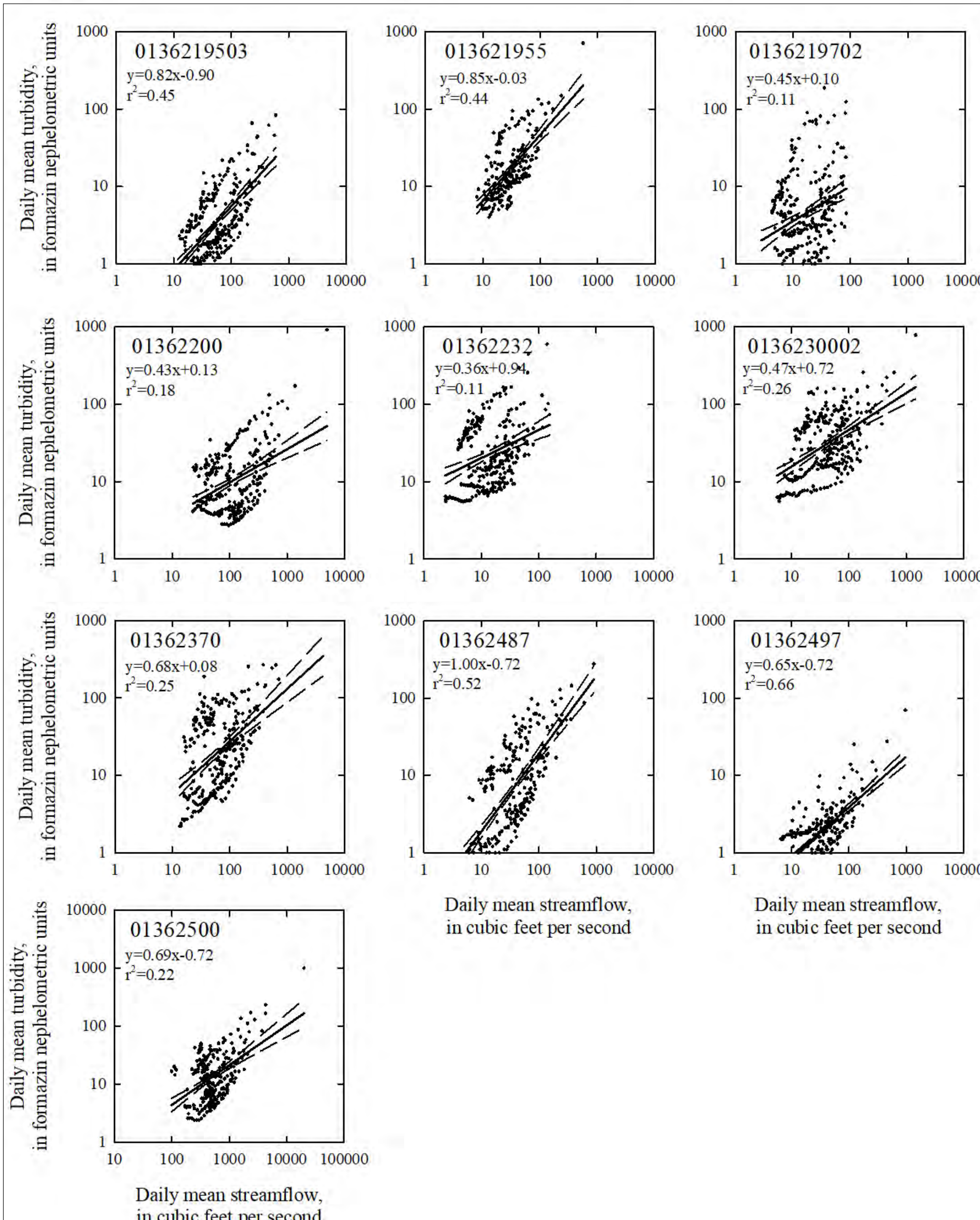

Figure 4.6 Daily mean turbidity as a function of streamflow for Esopus sub-basin sites for the period 12/24/2020 to 9/30/2021, a relatively active geomorphic period after a 5-year to 20-year RI storm. See Table 3.1 for streams represented by USGS stream number. Source: USGS

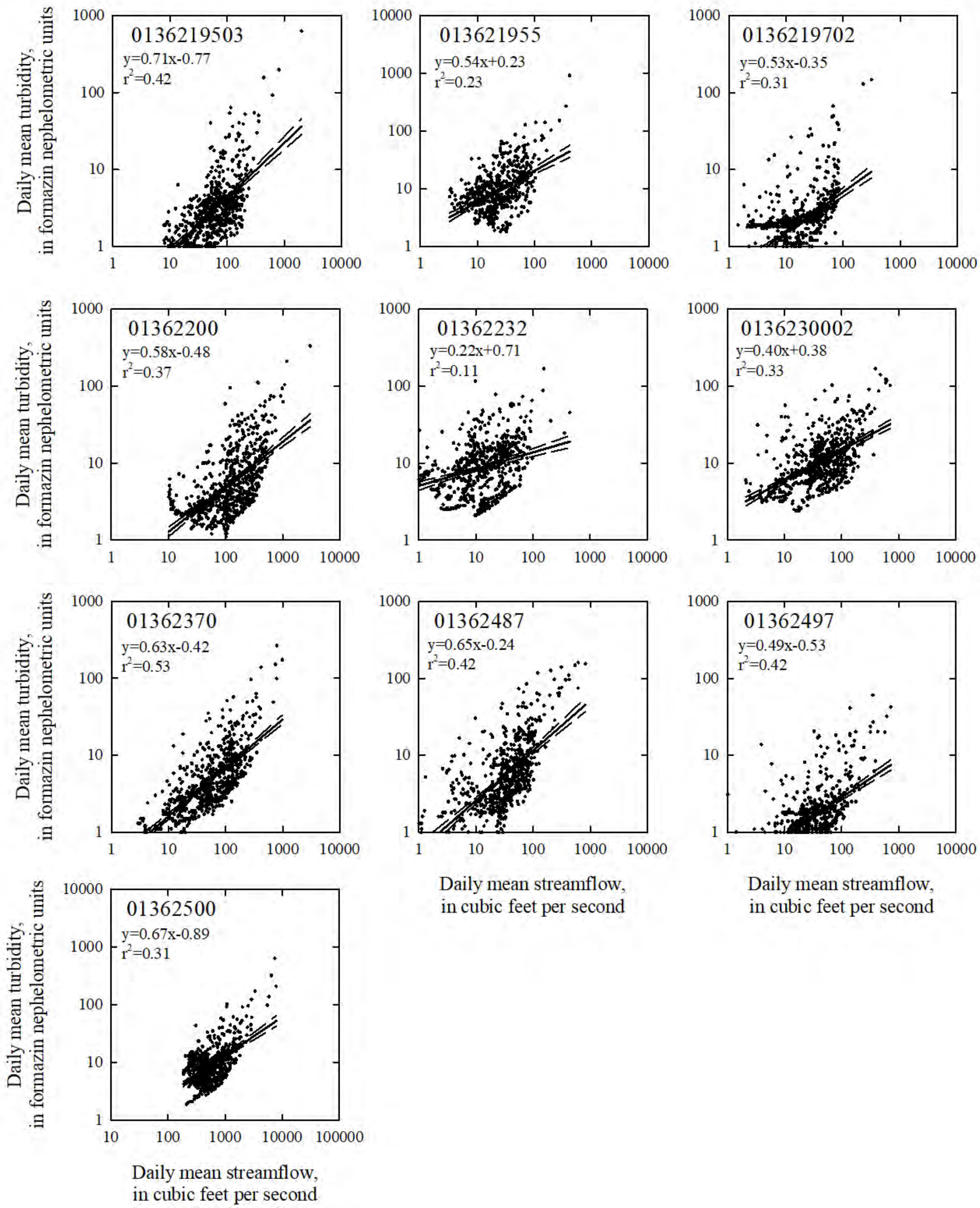

Figure 4.7 Daily mean turbidity as a function of streamflow for Esopus sub-basin sites for the period 10/1/2021 to 9/30/2023, a relatively stable geomorphic period. See Table 3.1 for streams represented by USGS stream station number. Source: USGS

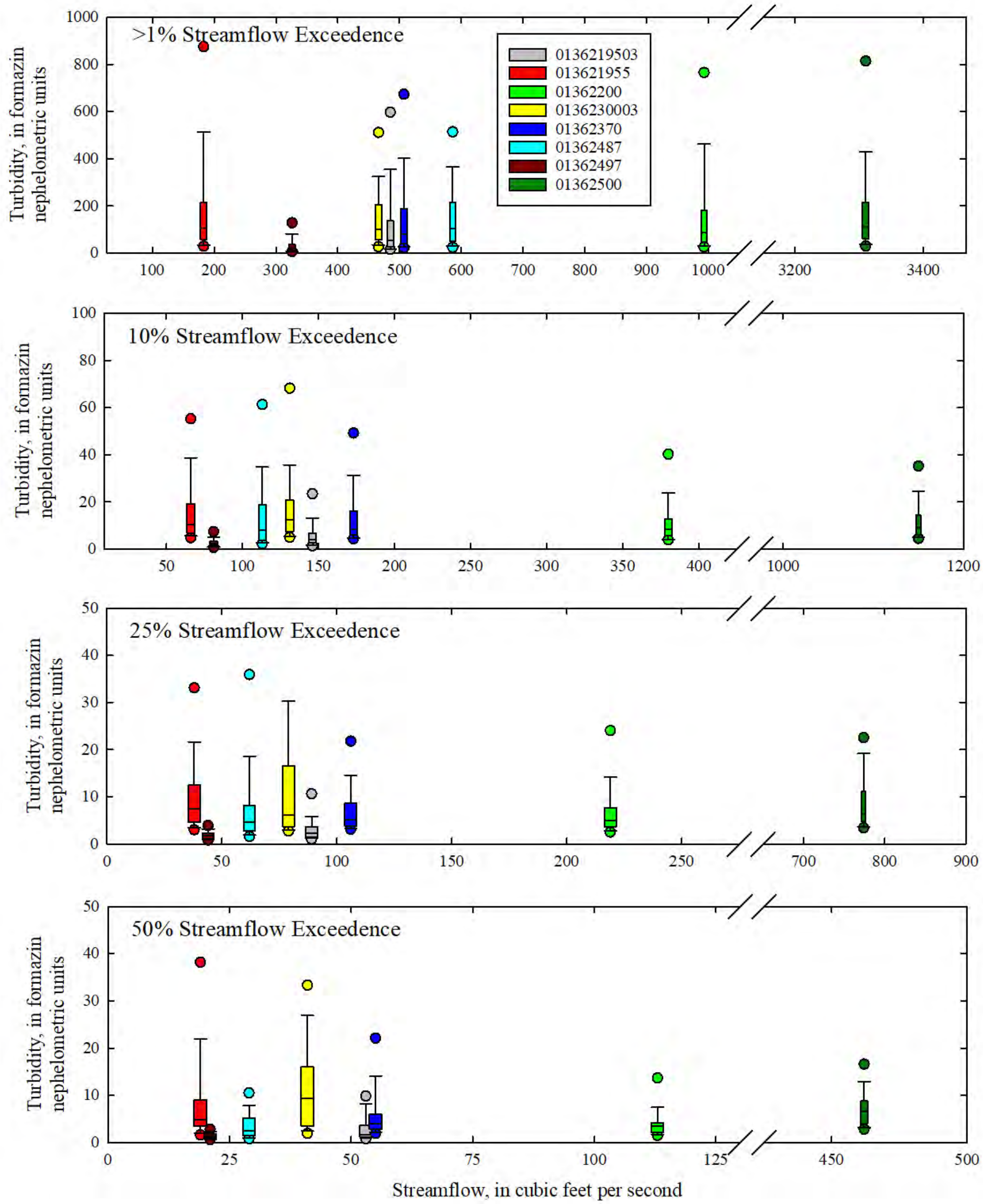

Figure 4.8 Turbidity associated with streamflows >Q1, Q10, Q25, and Q50 for the Esopus sub-basin sites water years 2017 through 2023. See Table 3.1 for streams represented by USGS stream station number. Source: USGS

4.3.2 Stony Clove Sub-basin Results

The daily mean streamflow-daily mean turbidity relations for the Stony Clove sub-basin sites were subset into the same five periods as the Esopus sub-basin sites and are shown in Figures 4.9 to 4.13. It should be noted that some of the relations during specific time periods had a very low coefficient of determination and should be interpreted with caution. Similar to the UEC sub-basins, turbidity at each Stony Clove sub-basin site was lower for a given streamflow during the relatively stable time periods and greater after the two storms. Ox Clove (01362368) had the highest turbidity during lower streamflows prior to the December 25, 2020 flood after which both Ox Clove (01362368) and Hollow Tree Brook (01362345) both had high turbidity at lower streamflows. Warner Creek (01362357) generally had the greatest increase in turbidity per unit streamflow of any of the Stony Clove sub-basins. Warner Creek (01362357) and Stony Clove at Jansen Rd (01362336) had a combination of high streamflow and high turbidity (suggesting high sediment load) relative to the other sub-basin sites during all time periods. Myrtle Brook (01362322) had a combination of low streamflows and low turbidity relative to the other Stony Clove sub-basins indicating it is not a large contributor of suspended sediment to the system.

Turbidity associated with streamflows $>Q_1$, Q_{10}, Q_{25}, and Q_{50} for the Stony Clove sub-basin sites is shown in Figure 4.14. Myrtle Brook (01362322) had the lowest turbidity through the four streamflow exceedances. Stony Clove at Jansen Rd (01362336) had similarly high turbidity to the other sub-basins at streamflows $>Q_1$ but was much lower at Q_{10}, Q_{25}, and Q_{50}. Ox Clove(01362368) and Warner Creek (01362357) had similar turbidity at $>Q_1$, Q_{10}, Q_{25}, but Warner Creek had lower turbidity at Q_{50}. The lower turbidity in Stony Clove and Warner Creeks measured at Q_{50} relative to Ox Clove and Hollow Tree Brook may be related to the multiple STRP constructed in the basins reducing contact with fine sediment sources at lower streamflows. Hollow Tree Brook had the highest turbidity at streamflows greater than Q_1. This was likely a result of the December 25, 2020 flood, which caused substantial geomorphic adjustment in the sub-basin, including increased contact with fine sediment sources (Siemion et al., 2023). The relatively low turbidity for Hollow Tree Brook at the 10% exceedance is unlikely to truly represent the levels in the system at those streamflows. The monitoring site was severely damaged during the December 25, 2020 flood.

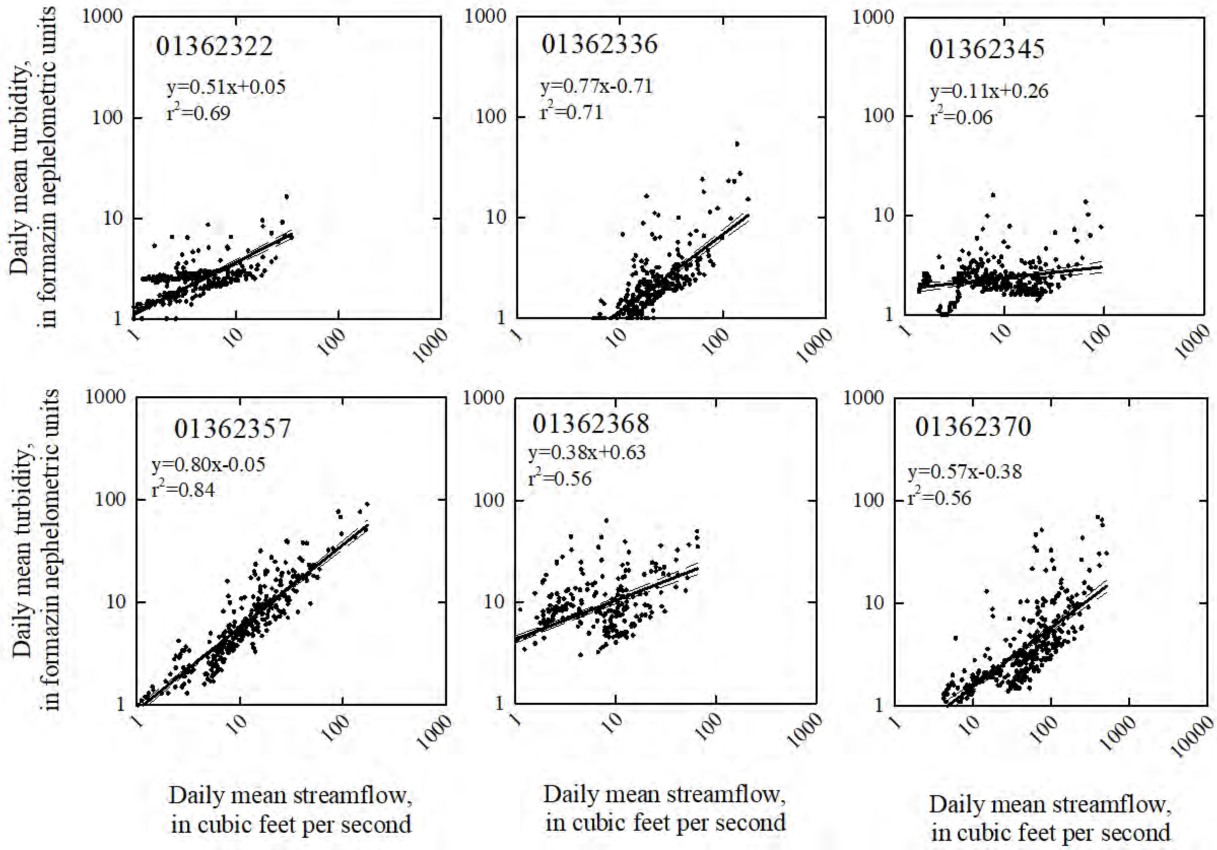

Figure 4.9 Daily mean turbidity as a function of streamflow for Stony Clove sub-basin sites for the period 10/1/2016 to 10/28/2017, a relatively stable geomorphic period. See Table 3.2 for streams represented by USGS stream station number. Source: USGS

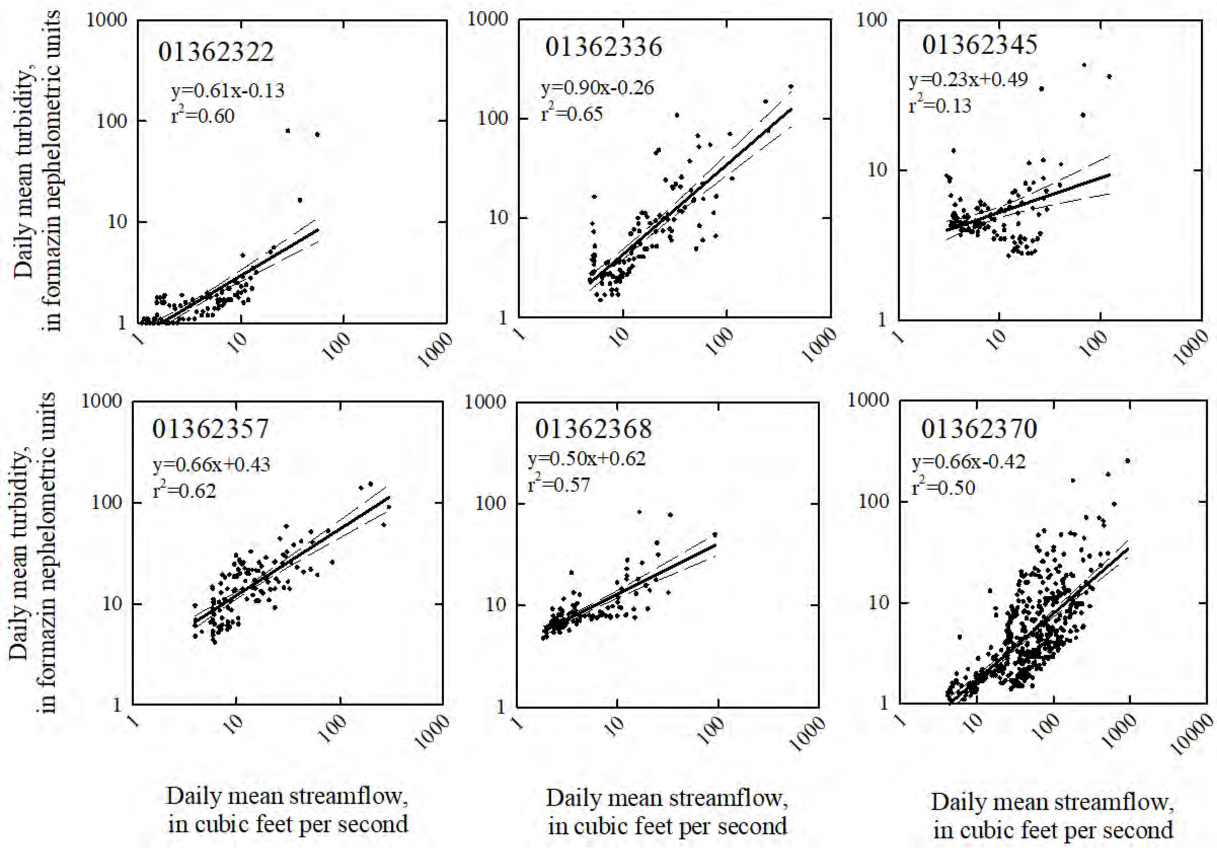

Figure 4.10 Daily mean turbidity as a function of streamflow for Stony Clove sub-basin sites for the period 10/29/2017 to 2/28/2018, a relatively active geomorphic period after a 1.5-year RI storm. See Table 3.2 for streams represented by USGS stream station number. Source: USGS

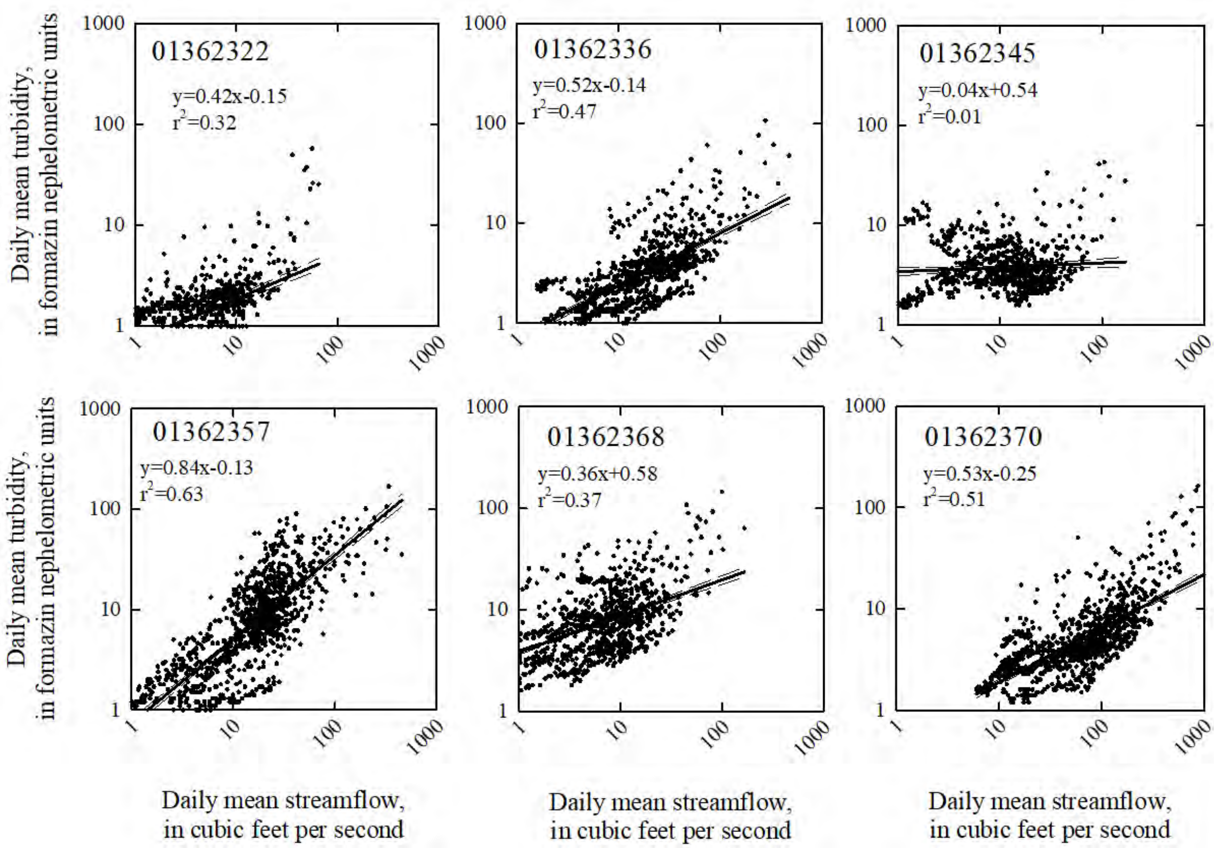

Figure 4.11 Daily mean turbidity as a function of streamflow for Stony Clove sub-basin sites for the period 3/1/2018 to 12/23/2020, a relatively stable geomorphic period. See Table 3.2 for streams represented by USGS stream station number. Source: USGS

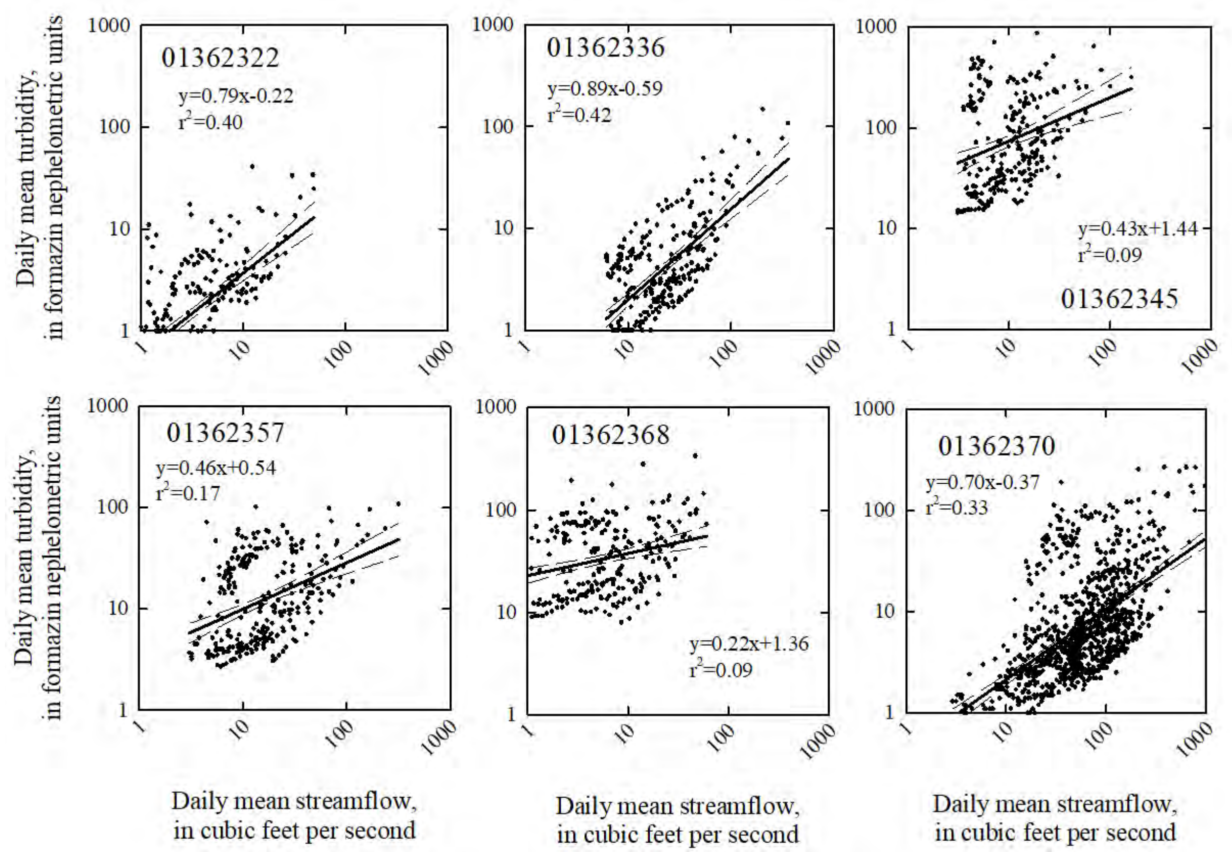

Figure 4.12 Daily mean turbidity as a function of streamflow for Stony Clove sub-basin sites for the period 12/24/2020 to 9/30/2021, a relatively active geomorphic period after a 5-year to 20-year RI storm. See Table 3.2 for streams represented by USGS stream station numbers. Source: USGS

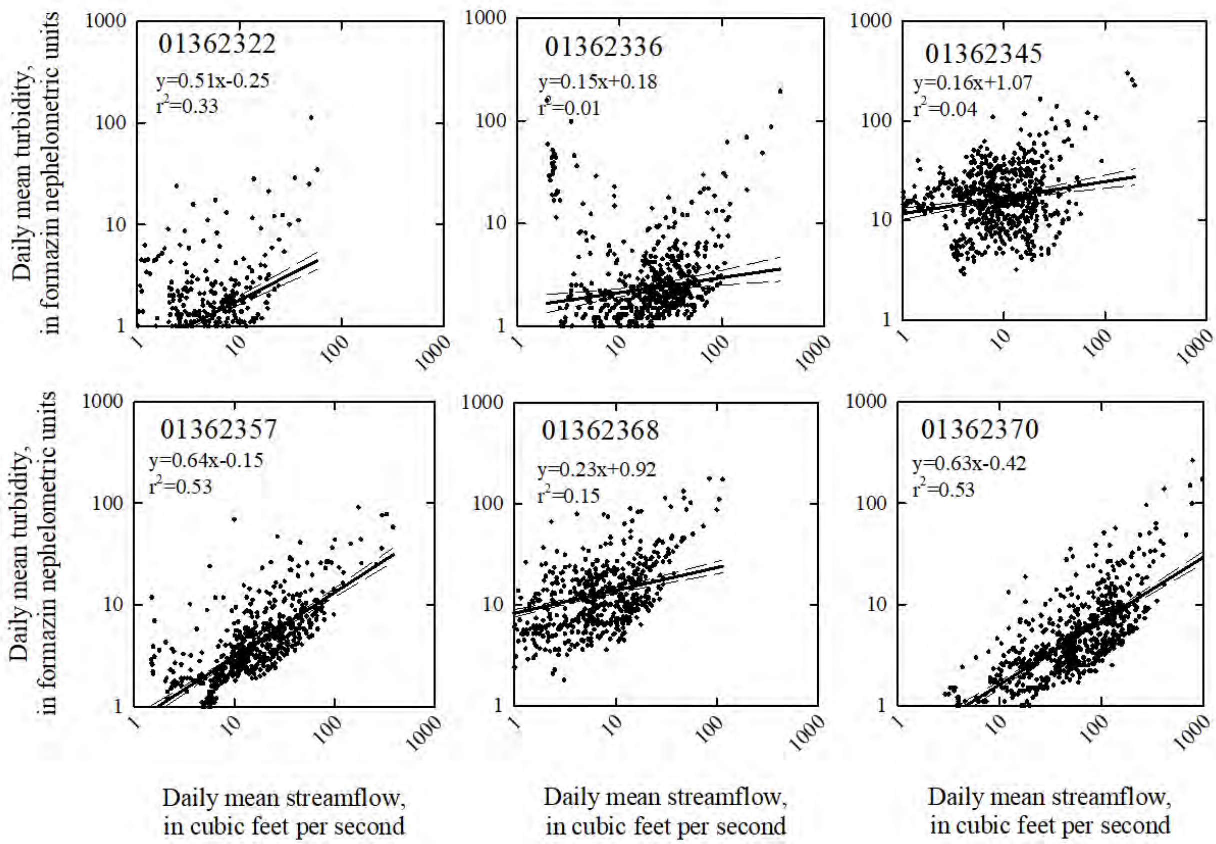

Figure 4.13 Daily mean turbidity as a function of streamflow for Stony Clove sub-basin sites for the period 10/1/2021 to 9/30/2023, a relatively stable geomorphic period. See Table 3.2 for streams represented by USGS stream station number. Source: USGS

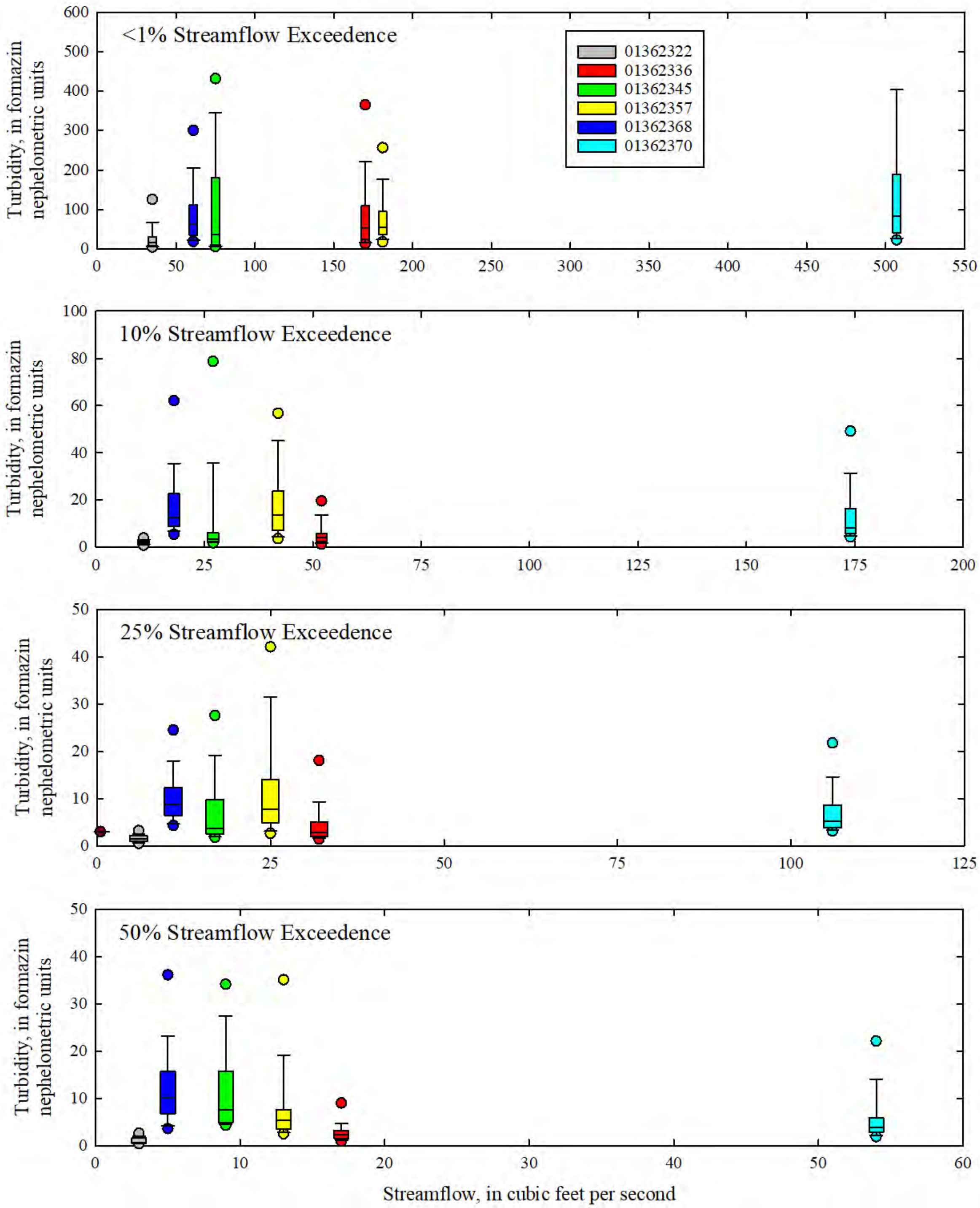

Figure 4.14 Turbidity associated with streamflows >Q1, Q10, Q25, and Q50 for the Stony Clove sub-basin sites water years 2017 through 2023. See Table 3.2 for streams represented by USGS stream station number. Source: USGS

Reach Monitoring Results

Turbidity associated with streamflows >Q_1, Q_{10}, Q_{25}, and Q_{50} for the Stony Clove Creek reach scale sites is shown in Figure 4.15, Warner Creek in Figure 4.16 as well as Ox Clove and Hollow Tree Brook in Figure 4.17. Streamflows for secondary sites are calculated using a simple drainage area weighting technique. Turbidity at the Stony Clove Creek reach scale sites generally increased in a downstream direction with notable increases at streamflows >Q_1 beginning downstream of the Stony Clove at Wright Rd site (01362332). Increases in turbidity were also notable at Q_{10}, Q_{25}, and Q_{50} between the Jansen Rd (01362336) and Lanesville (01362347) sites.

Turbidity generally increased in a downstream direction in Warner Creek at streamflow greater than 1% from the upstream site, 0136235575, to 01362356 and then held steady between 01362356 and the most downstream monitoring site, 01362357. The relative increases between reach scale monitoring sites varied at Q_{10}, Q_{25}, and Q_{50}. There was a notable increase in turbidity between 01362356 and 01362357 at Q_{10} and Q_{25}. There were small increases in turbidity through the reaches at Q_{50}.

Turbidity increased substantially from upstream to downstream for all streamflow exceedances in both Ox Clove and Hollow Tree Brook. The largest increase was at streamflows >1% exceedance in Hollow Tree Brook, likely as a result of the December 25, 2020 flood that caused substantial geomorphic adjustment to the Hollow Tree Brook stream channel with extensive increases in contact with fine sediment. The upstream Hollow Tree Brook reach scale monitoring site (01362342) had low turbidity at all streamflows while the upstream Ox Clove site (01362365) had relatively higher turbidity at >1% exceedance streamflows.

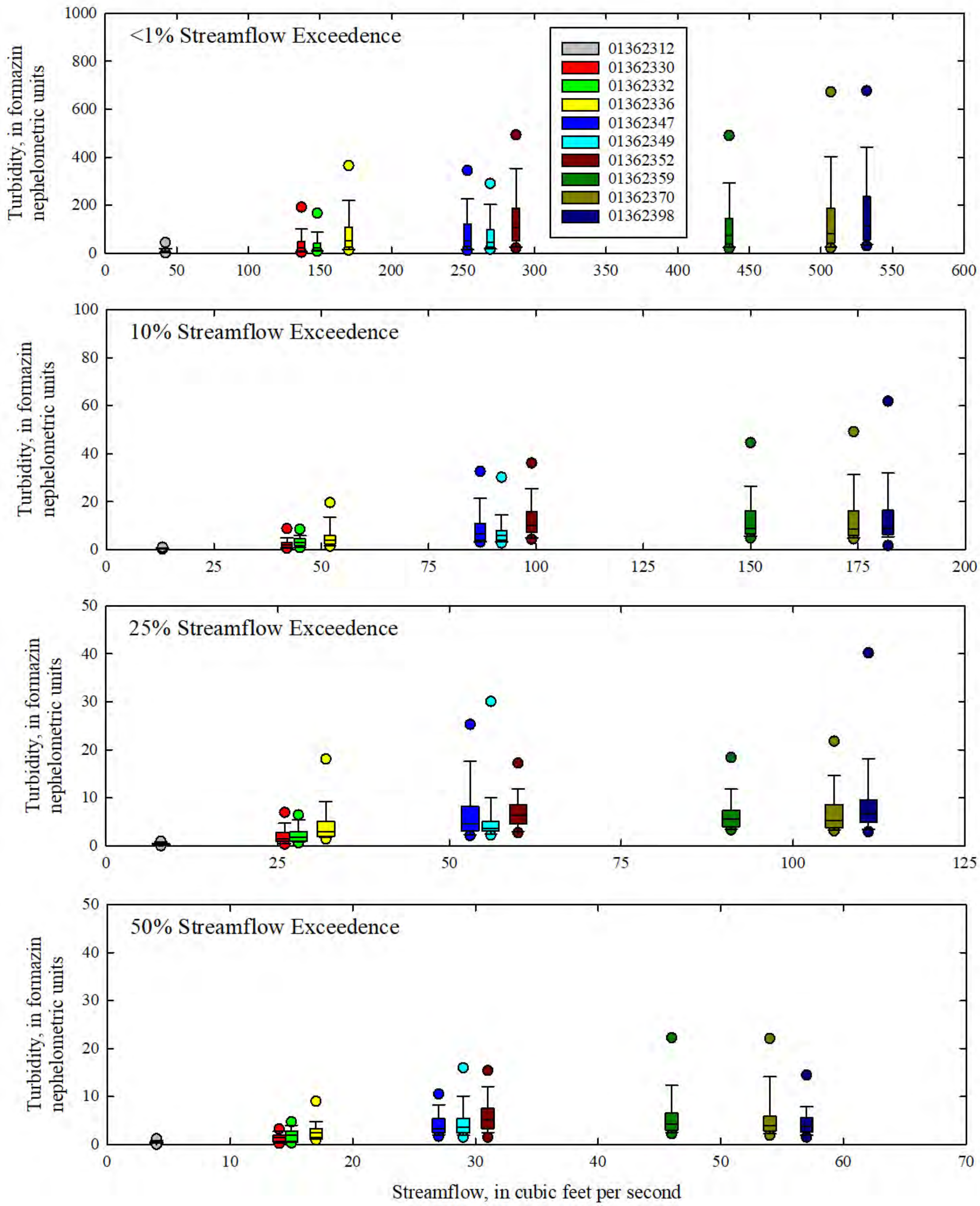

Figure 4.15 Turbidity associated with streamflows >Q1, Q10, Q25, and Q50 for the Stony Clove Creek reach scale sites water years 2017 through 2023. See Table 3.2 for streams represented by USGS stream station number. Source: USGS

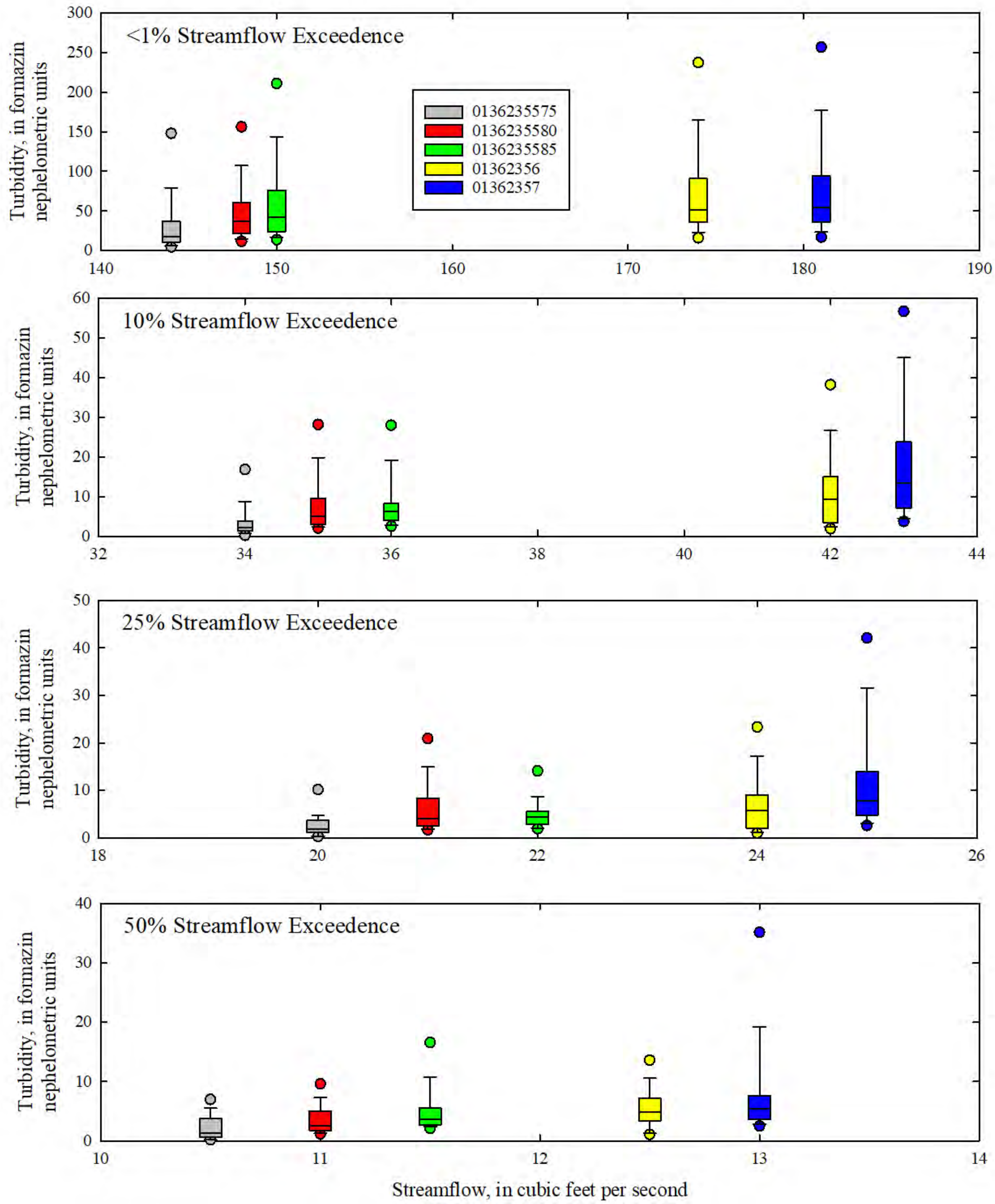

Figure 4.16 Turbidity associated with streamflows >Q1, Q10, Q25, and Q50 for the Warner Creek reach scale sites water years 2017 through 2023. See Table 3.2 for streams represented by USGS stream station number. Source: USGS

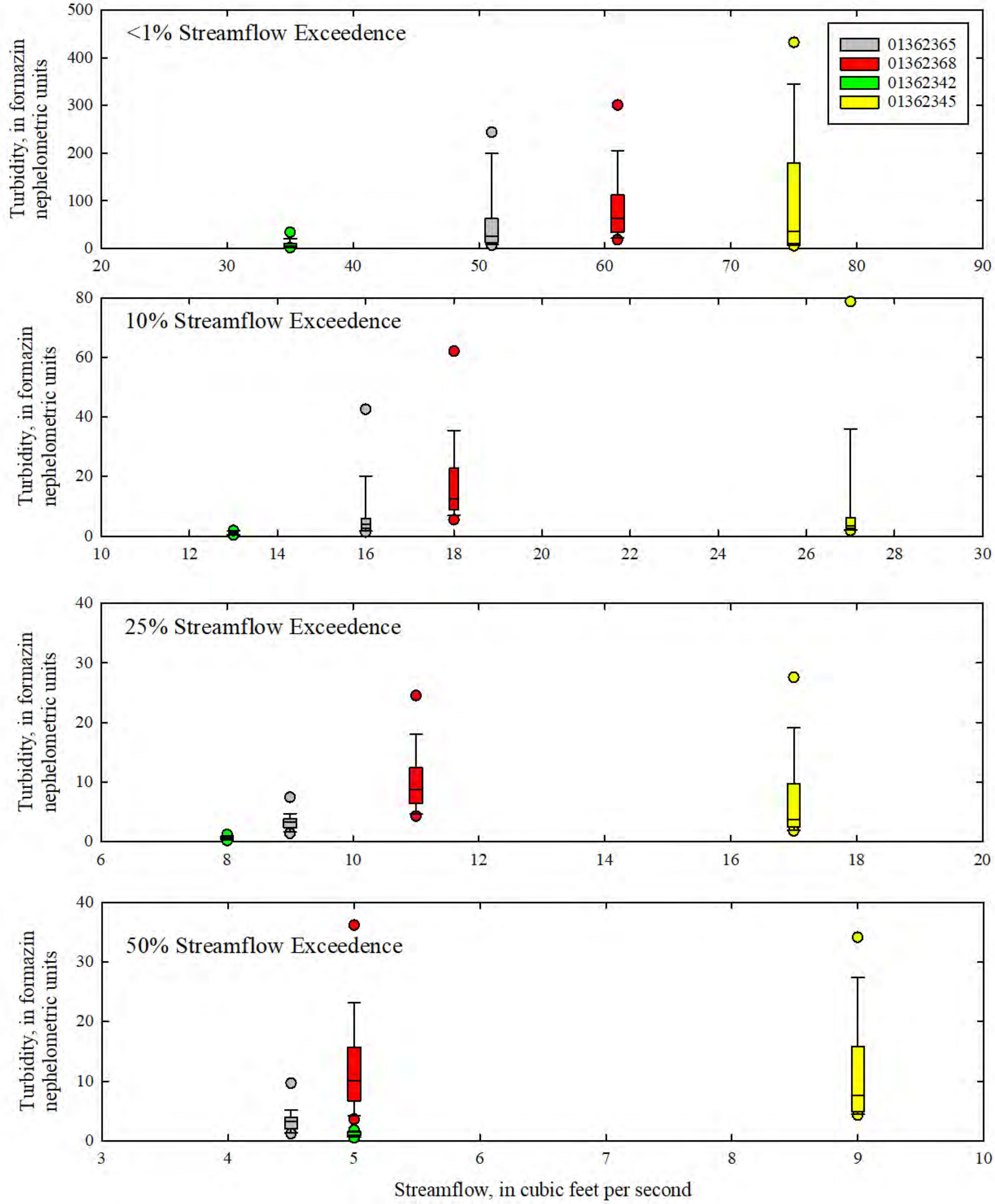

Figure 4.17 Turbidity associated with streamflows >Q1, Q10, Q25, and Q50 for the Ox Clove and Hollow Tree Brook reach scale sites water years 2017 through 2023. See Table 3.2 for streams represented by USGS stream station number. Source: USGS

4.4 Suspended Sediment Monitoring

4.4.1 UEC Results

Table 4.6 summarizes the point sample SSC for each sub-basin monitoring station for water years 2017 through 2022 and partial water year 2023 data. Minimum SSC measured in point samples ranged from below detection limits (<1) to 6 mg/L. Maximum SSC in point samples ranged from 603 to 9,570 mg/L and were measured during the December 25, 2020 flood event at all sites except Broadstreet Hollow Brook where SSC sampling did not begin until water year 2023. The highest median values were measured at Beaver Kill, Broadstreet Hollow Brook, Woodland Creek, and Birch Creek. It is important to note that the point samples may not be representative of the true cross-section concentrations. However, most point samples are collected during moderate to high streamflow conditions when the streams are considered to be well-mixed and cross-section adjustments to concentrations minimized.

Table 4.6 Summary of SSC in point samples for each sub-basin monitoring station for the period October 1, 2016 through September 30, 2023. Source: USGS.

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	184	<1	57	4,680
Birch Cr @ Big Indian	013621955	184	1	97	4,280
Esopus Cr @ Allaben	01362200	188	<1	66	9,570
Broadstreet Hollow Brook[1]	01362232	25	6	128	603
Woodland Cr abv mouth @ Phoenicia	0136230002	173	<1	119	7,340
Stony Clove Cr blw Ox Clove @ Chichester	01362370	176	2	70	6,990
Beaver Kill @ Mt Tremper	01362487	193	<1	147	5,290
Little Beaver Kill at Beechford nr Mt Tremper	01362497	178	1	73	5,320
Esopus Cr at Coldbrook	01362500	179	2	90	9,440

[1]SSC sampling initiated in water year 2022 at Broadstreet Hollow Brook.

Suspended sediment loads and yields are the product of SSC and streamflow at the monitoring stations. Periods of missing 15-minute SSC data are estimated using linear interpolation during periods of stable sediment transport conditions, using a streamflow-SSC relation during storms, and by linear interpolation between point sample SSC during the December 25, 2020 flood. The impacts on the streamflow-SSC and Tn-SSC relations of the December 2020 flood used to estimate continuous SSC forced USGS to develop new regression relationships. The suspended sediment loads and yields reported in the mid-term report cannot be updated until new regression equations can be developed and published, replacing the previous equations (Siemion, 2020).

The percent of suspended sediment less than 0.0625 mm (threshold between silt/clay and fine sand particle sizes) was measured for most cross-section samples and for storm samples collected by automated samplers when turbidity exceeded 200 FNU. The Esopus Creek at Allaben (01362200) and Esopus Creek at Coldbrook (01362500) had similar interquartile ranges and median particle size (Figure 4.18). Birch Creek (013621955), Broadstreet Hollow Brook (01362232), Woodland Creek (0136230002), and Little Beaver Kill (01362497) had similar interquartile ranges and median particle size. The interquartile ranges at these stations were smaller than at Esopus Creek at Allaben and Esopus Creek at Coldbrook. Esopus Creek below Lost Clove (0136219503) and Beaver Kill (01362487) had lower median values than the other sub-basins. Beaver Kill also had the largest interquartile range of all the sub-basins. Both streams had a higher percentage of suspended sediment greater than 0.0625 mm. The percentage of suspended sediment less than 0.0625 mm at Stony Clove Creek at Chichester (01362370) decreased from previous reports.

The relation of the percent of suspended sediment less than 0.0625 mm varied greatly across the Esopus Creek mainstem and sub-basin sites (Figure 4.19). The percent of suspended sediment less than 0.0625 mm ranged between <10% to 100%. The percent of suspended sediment less than 0.0625 mm at some monitoring sites decreased consistently with increasing streamflow up to a point at which the relation appeared to level off (Esopus Creek at Coldbrook for example). Other monitoring sites had a consistently declining relation, such as Woodland Creek (0136230002).

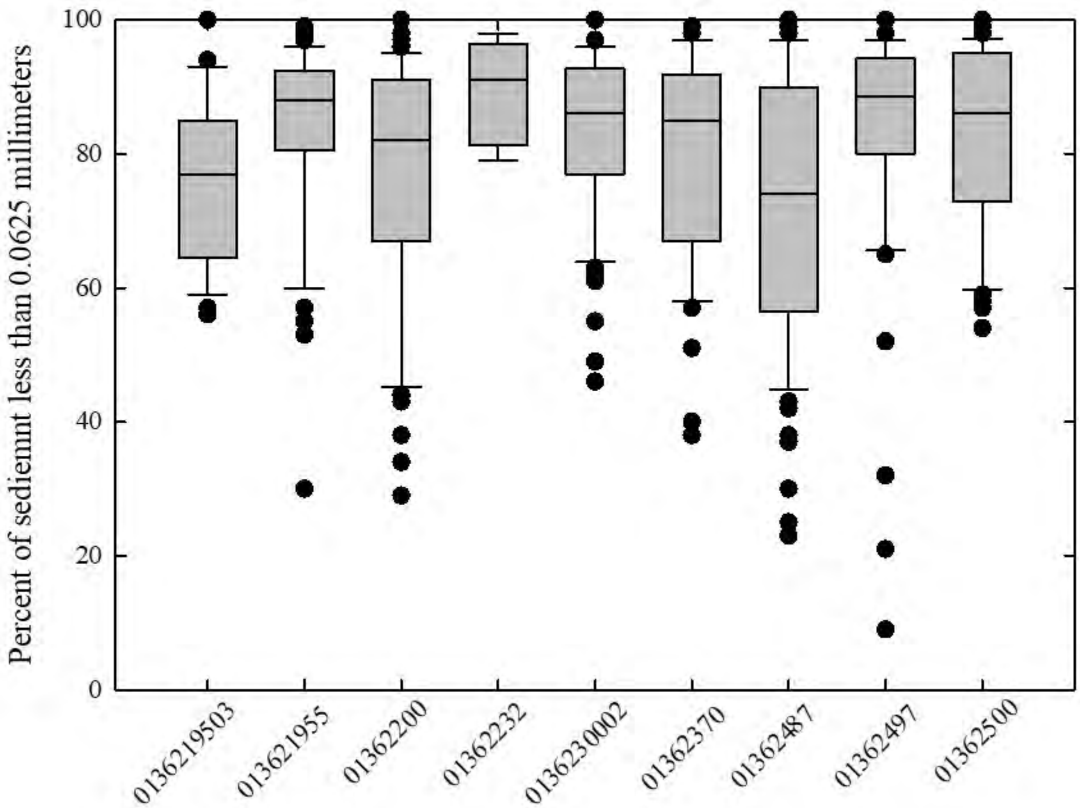

Figure 4.18 Box plots showing the interquartile range, median, and outliners of the percent of suspended sediment less than 0.0625 millimeters in samples collected at the Esopus sub-basin monitoring stations. See Table 3.1 for streams represented by USGS stream station number. Source: USGS

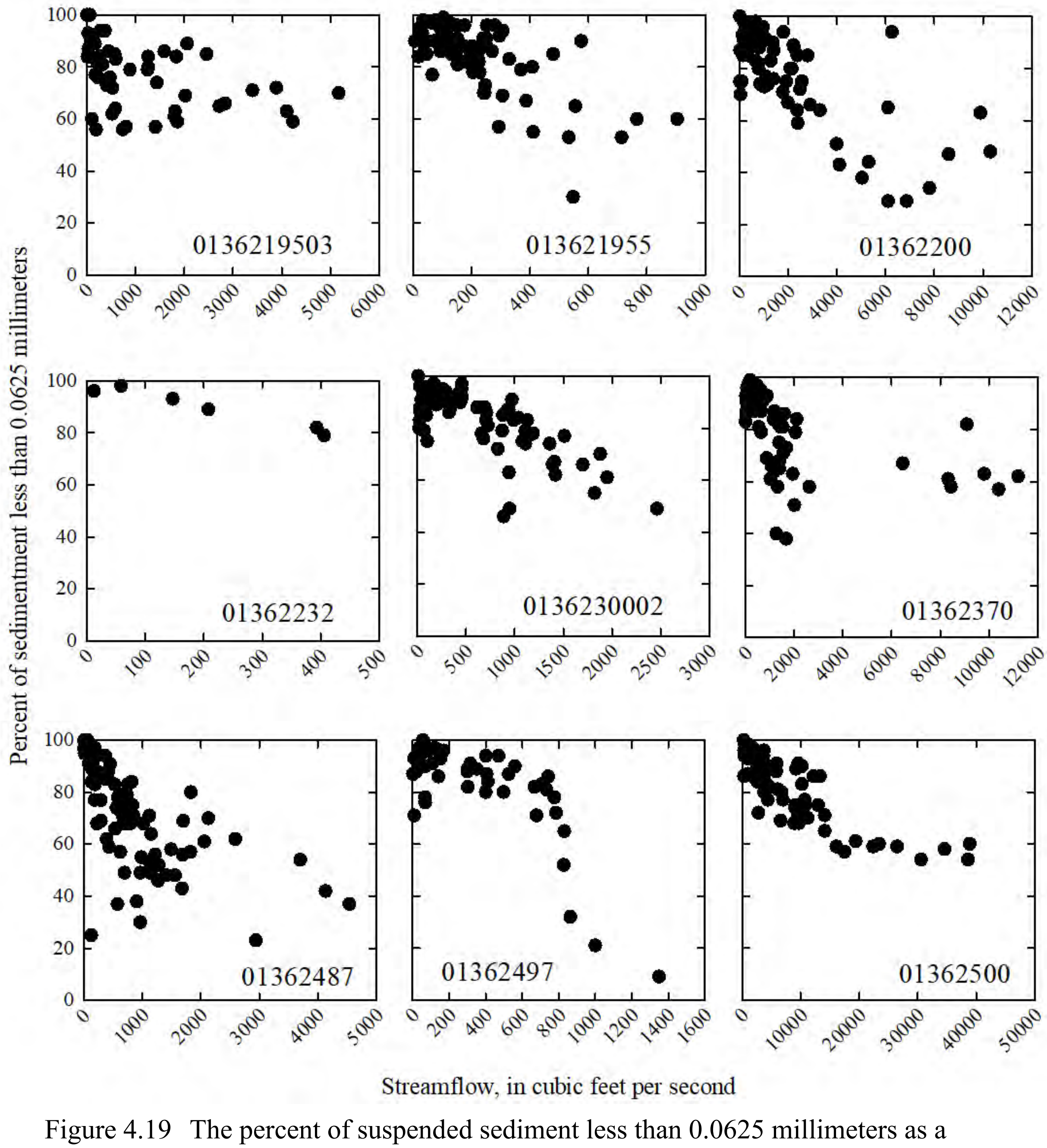

Figure 4.19 The percent of suspended sediment less than 0.0625 millimeters as a function of streamflow in samples collected at the Esopus sub-basin monitoring stations. See Table 3.1 for streams represented by USGS stream station number. Source: USGS

4.4.2 Stony Clove Sub-basin Results

Point sample SSC ranged between below detection limits to 2 mg/L at the Stony Clove Creek sub-basin monitoring stations (Table 4.7). Median SSC was greatest at Ox Clove and smallest at Myrtle Brook. The greatest maximum SSC was measured at Hollow Tree Brook while the smallest at Myrtle Brook. Maximum SSC in point samples was measured during the December 2020 flood at all monitoring stations in Stony Clove except for Myrtle Brook and Ox Clove, which were measured on October 29, 2017 and September 23, 2021, respectively. The Myrtle Brook monitoring station was severely damaged during the December 2020 flood and no point samples were collected during the storm as a result. The Ox Clove monitoring station was damaged near the peak of the December 2020 flood and so the maximum SSC may not have been sampled.

Table 4.7 Summary of SSC in point samples for each Stony Clove Creek sub-basin monitoring station. Source: USGS

Station Name	USGS Station ID	Number of Samples	Minimum (mg/L)	Median (mg/L)	Maximum (mg/L)
Myrtle Br @ SR 214 @ Edgewood	01362322	164	<1	14	920
Stony Clove Cr @ Jansen Rd @ Lanesville	01362336	193	<1	75	19,400
Hollow Tree Br @ SR 214 @ Lanesville	01362345	162	1	34	34,700
Warner Cr nr Chichester	01362357	180	<1	51	4,300
Ox Clove nr mouth @ Chichester	01362368	176	1	96	6,620
Stony Clove Cr blw Ox Clove @ Chichester	01362370	176	2	70	6,990

USGS cannot update the previously reported SSL and SSY results until new Tn-SSC regression relationships are developed and published.

The percent of suspended sediment less than 0.0625 mm in samples collected at the Ox Clove and Warner Creek had similar interquartile ranges and median values (Figure 4.20). Stony Clove Creek at Chichester and Hollow Tree Brook had slightly courser median values to Ox Clove and Warner Creek but had larger interquartile ranges. Myrtle had a median value that was outside the interquartile ranges of the other stations. There was a greater percentage of suspended sediment larger than 0.0625 mm at both Myrtle Brook (01362322) and Stony Clove Creek at Jansen Rd (01362336).

The relation of the percent of suspended sediment less than 0.0625 mm varied greatly across the Stony Clove Creek sub-basin sites, similarly to the Esopus Creek sub-basins (Figure 4.21). The percent of suspended sediment less than 0.0625 mm ranged between <20% and 100%. The percent of suspended sediment less than 0.0625 mm at most monitoring sites decreased consistently with increasing streamflow up to a point at which the relation appeared to level off, though some relations had much more variability than others.

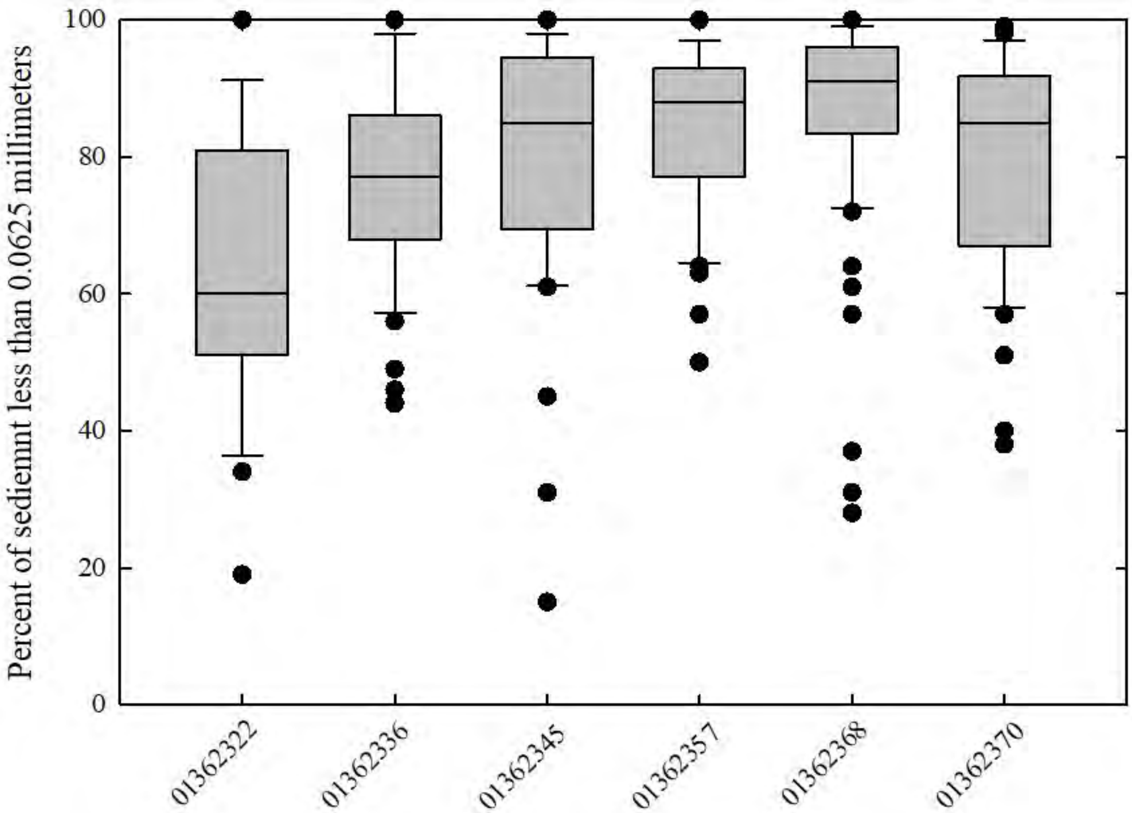

Figure 4.20 Box plots showing the interquartile range, median, and outliners of the percent of suspended sediment less than 0.0625 millimeters in samples collected at the Esopus sub-basin monitoring stations. See Table 3.2 for streams represented by USGS stream station number. Source: USGS

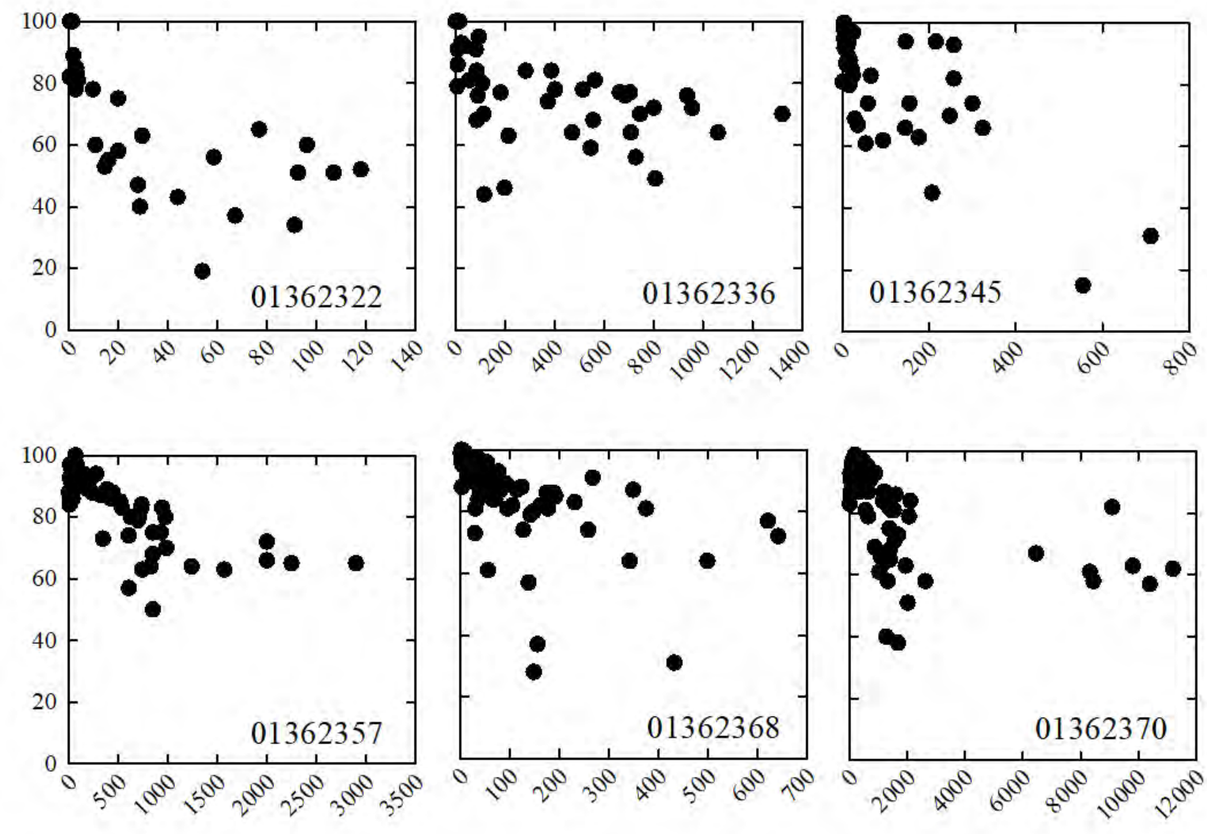

Figure 4.21 The percent of suspended sediment less than 0.0625 millimeters as a function of streamflow in samples collected at the Stony Clove Creek sub-basin monitoring stations. See Table 3.2 for streams represented by USGS stream station number. Source: USGS

4.5 Turbidity and Suspended Sediment Source Characterization

Sections 4.2 and 4.3 demonstrate the role of hydrology as a principal driver of Catskill stream turbidity production across spatial and temporal scales. The observed spatial and temporal variability in turbidity production measured by the USGS stream monitoring network is also supplied and controlled by the geology and geomorphology of the landscape. The heterogeneous geologic composition of the Catskill landscape supplies the fine sediment sources potentially accessible to streams. The Devonian fluvial sedimentary bedrock and the subsequent glacial and pro-glacial erosion, processing, and deposition of the source rock into glacial legacy sediment enriched in silt and clay creates a landscape capable of elevated turbidity production (Davis et al., 2009). The current landscape and fluvial geomorphology of the study area influences or controls the sensitivity of the landscape and "riverscape" to adjust, entrain and transfer the stocks of fine sediment into and through the fluvial system.

The study continues to assume that turbidity and SS flux regime in the UEC watershed is primarily sourced by three primary types of fine sediment input: re-suspended fine sediment stored in streambed alluvium during bed mobilizing streamflow conditions, lateral erosion 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 4.22). The study assumes that an important part of the observed variability in turbidity and SS flux and yield in the UEC watershed is associated with spatially variable stream erosional contact with GLS enriched in fine sediment content, and the consequent development of turbidity production hot spots that can disproportionately influence turbidity at the sub-basin and reservoir basin scale. DEP currently uses two primary methods to map and monitor the geologic and geomorphologic conditions controlling turbidity production: SFI and BEMS investigations. This status report provides an update on advances in each of those investigations since DEP's 2022 mid-term study FAD report. DEP has put all remote-sensing and GIS-based investigations (aside from BEMS) on hold until DEP and USGS initiate the new scope of work discussed in Section 3.2. This section is organized to present the limited characterization work in the UEC sub-basins first (4.5.1) and the more extensive characterization in the Stony Clove sub-basin (4.5.2).

Figure 4.22 SS input conditions: (a) stored in streambed alluvium, (b) bank erosion, (c) mass wasting, (d) channel incision.

4.5.1 UEC Watershed Turbidity and SS Source Characterization

The study design does not include in-depth investigations into UEC watershed source conditions outside of the Stony Clove watershed. Source conditions are broadly characterized using previous and ongoing SFI mapping conducted by UCSWCD, Greene County SWCD and DEP from 2001-2021, along with some remote-sensed data GIS analysis.

Mapping Sediment Source Distribution

DEP used the SFI methodology to compute erosional sediment contact indices (referred to as "erosional sediment connectivity indices" in DEP's 2022 mid-term study report). Figure 4.23 depicts the extent of SFI data for the UEC watershed spanning over 20 years covering a period that includes three different data schema (pre-2008, 2008-2018, and 2019 to present), different SFI teams, different levels of QA/QC, and changes in GPS technology. An additional 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. Given these quality control issues, DEP uses the non-study SFI data to report a simple bank erosion contact index (EI_{Bnk}) and sediment contact indices (SCI) stratified by erosional contact with and without GLS (DEP, 2022). The indices are computed as follows:

Bank Length EI_{Bnk} = bank erosion length/SFI-assessed channel length

Bank Length SCI_{AL} = bank erosion length without GLS connectivity/bank erosion length

Bank Length SCI_{GLS} = bank erosion length with GLS connectivity/bank erosion length.

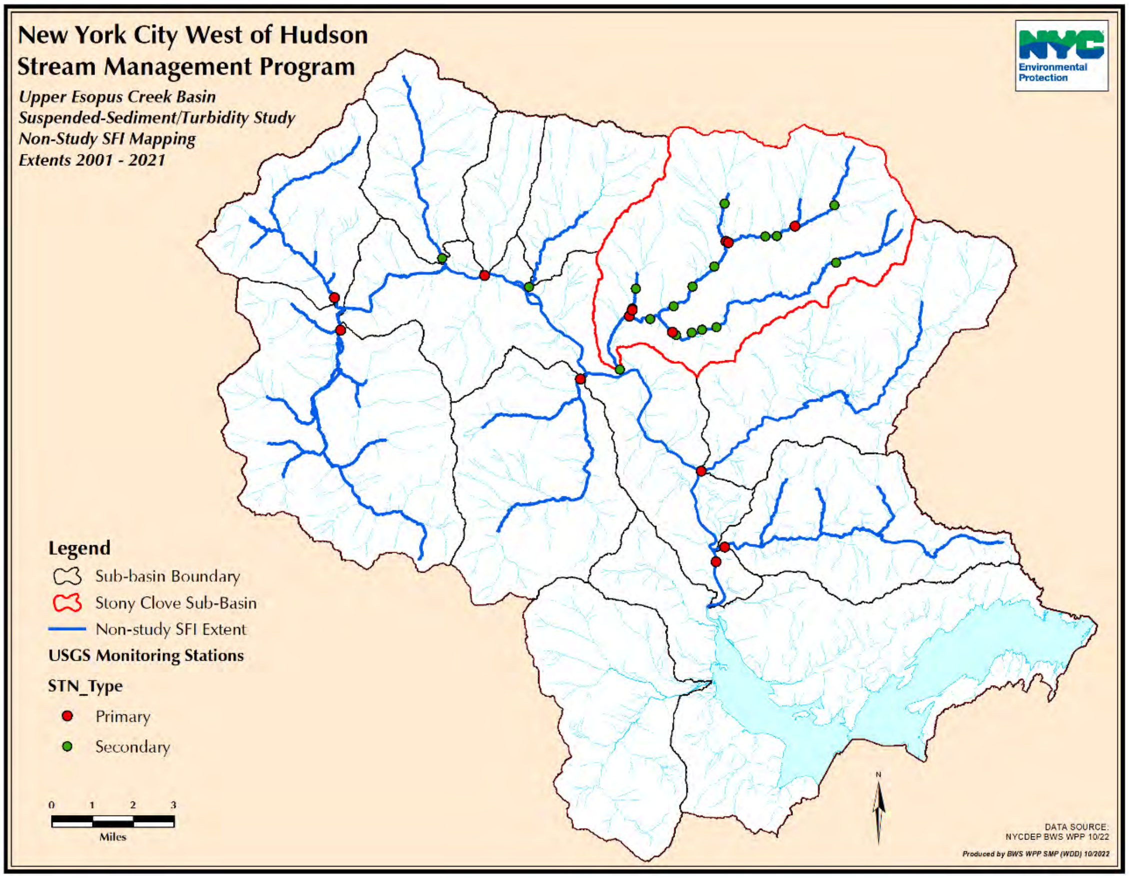

Figure 4.23 Extent of SFI mapping in the UEC watershed from 2001 to 2023, including the updated Broadstreet Hollow SFI.

DEP's mid-term study report included all SFI data for the UEC collected between 2001 and 2021. That table of UEC SFI results is not repeated in this report. The only update is for Broadstreet Hollow, which was first mapped in 2001 and re-mapped in 2023 using the study SFI data schema and protocol. Table 4. 8 shows the study-defined bank erosion and sediment connectivity indices for both years. Interestingly, the EI_{Bnk} for both years is quite similar, 0.26 for 2001 and 0.24 for 2023. The EI_{Bnk} value for the 2023 data includes bank erosion lengths mapped as active and dormant. The 2001 data did not have a similar attribute to identify if the erosion was active or dormant, so the inclusion of the dormant banks is considered a conservative potential overestimate. The notable difference between the years, and an important factor to consider when interpreting the increased turbidity detected by the Broadstreet Hollow monitoring station, is that the sediment contact indices are very different. The SCI_{GLS} for Broadstreet Hollow increased from 0.14 to 0.54, a marked increase in the potential for entrainment of fine sediment through bank erosion. The 2023 SFI mapping identified new turbidity production hot spots that will be considered for monitoring and potential STRP implementation.

Table 4.8 Update of Broadstreet Hollow Brook SFI data. The dominant GLS source is determined by reviewing the relative lengths of each recorded in the SFI data.

Stream Name	SFI Year	SFI Stream Length (ft)	Bank Erosion Length (ft)	Bank Length EI_{Bnk} (ft/ft)	Bank Length SCI_{AL} (ft/ft)	Bank Length SCI_{GLS} (ft/ft)	GLS Source ($1^{st}/2^{nd}$)
Broadstreet Hollow	2001	17,992	4,678	0.26	0.86	0.14	LS/GT
Broadstreet Hollow	2023	21,260	5,052	0.24	0.46	0.54	LS/GT

The monitored sub-basin streams can also be categorized by SCI *potential* for connectivity with GLS. Stony Clove and Woodland Valley streams tended to have the highest percentage of mapped erosional sediment connectivity with GLS, and Little Beaver Kill had the lowest percentage (DEP, 2022). Beaver Kill and Birch Creek had relatively low mapped erosional sediment connectivity with GLS yet can have high turbidity production during portions of the study period, indicating that turbidity production is not only influenced by magnitude of connectivity but also potentially by other factors such as distribution of occurrence (e.g., concentration near monitoring station), LS versus GT dominance, and modes of entrainment (bank failure, mass wasting, bed failure). This is generally consistent with the continued monitored turbidity conditions through 2023.

4.5.2 Stony Clove Sub-basin Turbidity and SS Source Characterization

The Stony Clove sub-basin serves as the experimental research area to investigate SS source conditions through intensive SFI mapping, reach-scale channel morphologic monitoring, sediment source sampling investigations, and remote-sensed data analysis. The primary focus in this section of the mid-term report was demonstrating the value of SFI mapping to help explain the measured turbidity and sediment flux (DEP, 2022). Thus far, this method has provided the most substantive contribution to help explain the source conditions influencing turbidity production in the Stony Clove sub-basin (Siemion et al., 2023). DEP will continue analyzing these results and other SFI-derived geomorphic metrics with USGS through 2026 as part of the new sediment budget and connectivity modeling study scope. The data exists for investigating several attributes as needed to meet the study objective. Consistent with recommendations of the 2020 National Academies of Sciences, Engineering and Medicine (NASEM) Expert Panel, DEP has made this data available to University of Vermont researchers for collaborative investigations into Esopus Creek watershed turbidity production.

The study also includes measuring and monitoring reach scale stream morphology at representative turbidity production hot spots – the BEMS sites. This work is performed under a DEP contract with SLR. The first six years of the BEMS project was documented in a report finalized in early 2023 (SLR Consulting, 2023). The report with appendices is 866 pages and is not included as an attachment to this report; a digital copy can be provided upon request. DEP's March 2024 biennial status report includes a brief descriptive summation of the BEMS work through water year 2023 and presents examples of some of the relevant topographic monitoring and sediment sampling results available in the BEMS report. DEP's final FAD study report in November 2027 will include a more comprehensive accounting of the BEMS findings.

Mapping Sediment Source Distribution

DEP's 2022 mid-term study report included a comprehensive accounting of the SFI mapping work performed to date in the Stony Clove watershed. The only notable change in the Stony Clove sub-basin SFI effort since the mid-term study report was the continuation of SFI mapping in 2023 of Hollow Tree Brook. The results are still undergoing quality control review and processing and are not presented herein. Given that there is no change in the SFI metrics for the Stony Clove watershed streams, the previously presented results are not repeated in this report.

Stream Channel Reach Monitoring

The BEMS component of the study includes morphologic monitoring of reach-scale channel adjustment, hydraulic modeling and sediment sample analysis at a set of sites in the Stony Clove sub-basin using a combination of topographic survey methods detailed in Section 3.2 (Figure 4.24 and Table 4.9). An additional BEMS site on Warner Creek (WC-04) was added since DEP's mid-term study report, bringing the total to 11 sites. Surveying, sediment sampling, and hydraulic modeling continued in 2023 at all sites. As planned, the BEMS study component concludes in spring 2024, with one additional round of measurements.

The BEMS sites continue to have four valuable roles in advancing this study thus far. The selected sites presented an opportunity to test methodology for optimizing topographic monitoring methods (as discussed in Section 3.2), sample and analyze stream bank and streambed sediment sources for fine sediment content, track several representative turbidity production hot spot reaches that could give quantitative insight into multi-year reach scale dynamics that influence sub-basin scale turbidity production, and serve as a pool of candidate STRP sites. The sediment sampling and STRP site selection have been the most useful results so far. DEP will consult with USGS on use of the BEMS data to support the planned sediment budget and connectivity modeling work that USGS will lead in 2024-2026.

The sediment sampling has helped to quantify the fine sediment content of the SS source sediment geology in stream banks categorized in this study. The BEMS monitoring has provided sufficient data for identifying priority hot spot production reaches to target for STRP implementation. To date, three of the BEMS sites became STRP sites: Warner Creek sites WC-1 and WC-02 in 2021 and Stony Clove Creek site SCC-03 in 2022. The Hollow Tree Brook site HTB-01 has been selected to be the next STRP constructed in the Stony Clove sub-basin. The advantage of BEMS to STRP conversion is having multiple years of pre-STRP morphologic monitoring for informing design and for comparison with post-STRP monitoring.

Topographic Monitoring

Table 4.9 presents the current status of BEMS site topographic monitoring through fall 2023. Several of the sites have received more surveys than others. The frequency of surveys is largely attributable to the observed sensitivity to adjustment at each site, accessibility, the potential STRP candidacy status, and post-STRP monitoring.

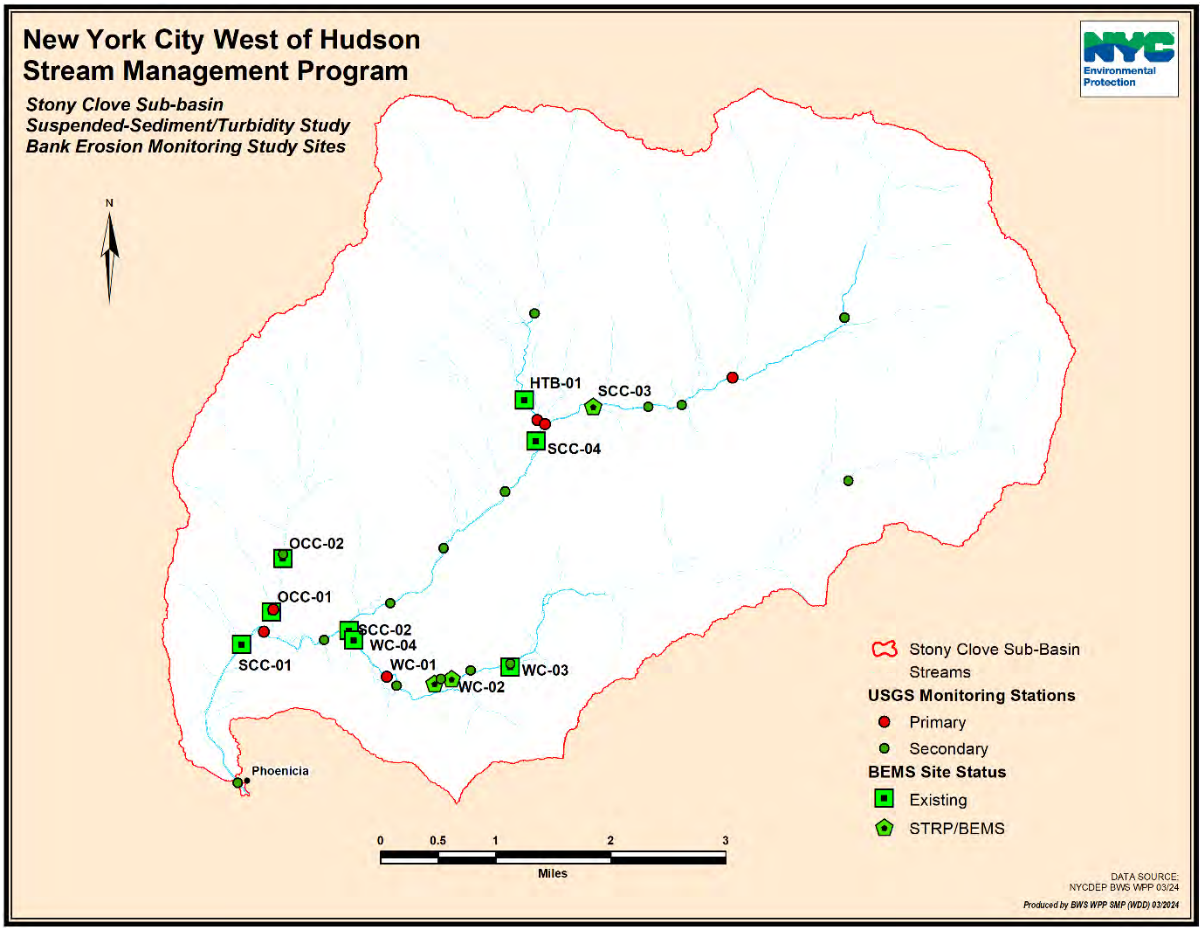

Figure 4.24 Stony Clove sub-basin BEMS locations and USGS monitoring stations.

Table 4.9 Stony Clove sub-basin BEMS status table.

Site	Length (ft)	Survey Dates	Survey Method[1]	Sediment Analysis[2]	Description[3]
SCC-01	700	12/05/2017 04/23/2021 03/18/2022 05/11/2023 11/01/2023	TS SfM SfM SfM LiDAR	Yes	Mass wasting of AL/GT in right VM; Bank erosion in LS and GT on left ACM.
SCC-02	750	12/05/2017 01/02/2021 12/07/2021 12/02/2022 10/25/2023	TS SfM SfM SfM LiDAR	Yes	Mass wasting of GT in left VBM (moraine); Channel incision in GT.
SCC-03	1,700	04/23/2018 01/15/2019 04/07/2020 11/20/2020 01/01/2021 12/22/2021 01/21/2023[4] 11/01/2023[4]	SfM SfM SfM SfM SfM SfM SfM LiDAR	Yes	Mass wasting of AL/LS in right VBM (delta terrace); Channel incision in LS. Bank erosion in AL/LS in left ACM. Converted to STRP site in summer-fall 2022.
SCC-04	1,800	04/23/2021 12/13/2021 04/27/2023 11/01/2023	SfM SfM SfM LiDAR	No	Aggrading and degrading reach with bank erosion into AL and history of incision into LS.
WC-01	500	06/23/2017 04/24/2018 12/28/2018 04/01/2020 11/19/2020 01/01/2021 11/11/2021[4] 05/03/2022[4] 04/11/2023[4] 11/02/2023[4]	TS SfM SfM SfM SfM SfM SfM SfM SfM LiDAR	Yes	Mass wasting of AL/LS in right VBM (terrace); Channel incision in LS. Converted to STRP site in summer-fall 2021.
WC-02	650	06/23/2017 11/15/2017 12/28/2018 04/01/2020 11/23/2020 01/02/2021 11/11/2021[4] 05/03/2022[4] 04/11/2023[4] 11/02/2023[4]	TS SfM SfM SfM SfM SfM SfM SfM SfM LiDAR	Yes	Mass wasting of AL/LS in left VBM (terraces); Channel incision in LS following channel avulsion. Converted to STRP site in summer-fall 2021.
WC-03	450	07/07/2017 05/14/2018 04/01/2020	TS SfM SfM	Yes	Mass wasting of AL/GT/LS in left VM; Channel incision in LS.

		11/20/2020 11/23/2021 02/22/2023 11/02/2023	SfM SfM SfM LiDAR		
WC-04	1,100	11/29/2022 10/25/2023	SfM LiDAR	Yes	Channel Incision and headcut migration in GT with upstream access to LS.
OCC-01	500	11/18/2016 11/15/2017 04/13/2021 12/07/2021 02/22/2023 11/02/2023	TS SfM SfM SfM SfM LiDAR	Yes	Mass wasting of GT in right VBM (moraine).
OCC-02	450	07/18/2017 04/13/2021 12/14/2021 12/05/2022 10/25/2023	TS SfM SfM SfM LiDAR	Yes	Mass wasting of AL/LS/GT in left VBM (glacial terrace); Channel incision in LS
HTB-01	2,300	04/14/2021 02/24/2022 12/02/2022 10/23/2023	SfM SfM SfM LiDAR	Yes	Mass wasting of AL/LS and extensive reach scale incision into LS with multiple headcuts

[1] Survey methods included traditional ground-based topographic surveys with total station (TS) and unmanned aerial system (UAS) technology for Structure from Motion (SfM) and LiDAR remote-sensed methods in combination with traditional ground survey.
[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.
[4] WC-01, WC-02 and SCC-03 continue to be surveyed following STRP construction.

Case Study: SCC-03

Because there are 11 BEMS sites and the results are so expansive, this report uses one site (SCC-03) to illustrate some of the results of the topographic monitoring presented in the BEMS report (SLR Consulting, 2023). All figures in this sub-section are taken directly from the BEMS report and therefore retain some information pertinent to the BEMS report and not this March 2024 FAD report. Site SCC-03 is in Lanesville 0.5 miles upstream of the Hollow Tree Brook confluence and six miles upstream of the confluence with Esopus Creek (Figure 4.24). The site was established as a BEMS site in April 2018 and the most recent monitoring took place in November 2023, for a total of eight topographic surveys spanning the 5.5 years (Table 4.9). Based on upstream and downstream water quality monitoring, SFI mapping and initial BEMS surveys, this site was nominated for STRP construction, which was completed in summer/fall 2022 (DEP, 2019b).

USGS maintains a primary monitoring station (01362336; Table 3.2) 0.4 miles downstream of the SCC-03 site. Figure 4.25 is a hydrograph for the station presented in the BEMS report. It includes the dates of SCC-03 surveys through 2021 to depict the hydrology between geomorphic measurements. Five discharge events met or exceeded the estimated bankfull threshold during the reported BEMS monitoring period, with three additional events nearly reaching this magnitude. Water year 2021 includes the December 25, 2020 flood, which crested at 1,700 cfs at the 01362336 monitoring station. This is less than the estimated Q_{5y} for station 01362336, and notably less than the estimated frequency-magnitude for the same event at the downstream portion of the Stony Clove sub-basin.

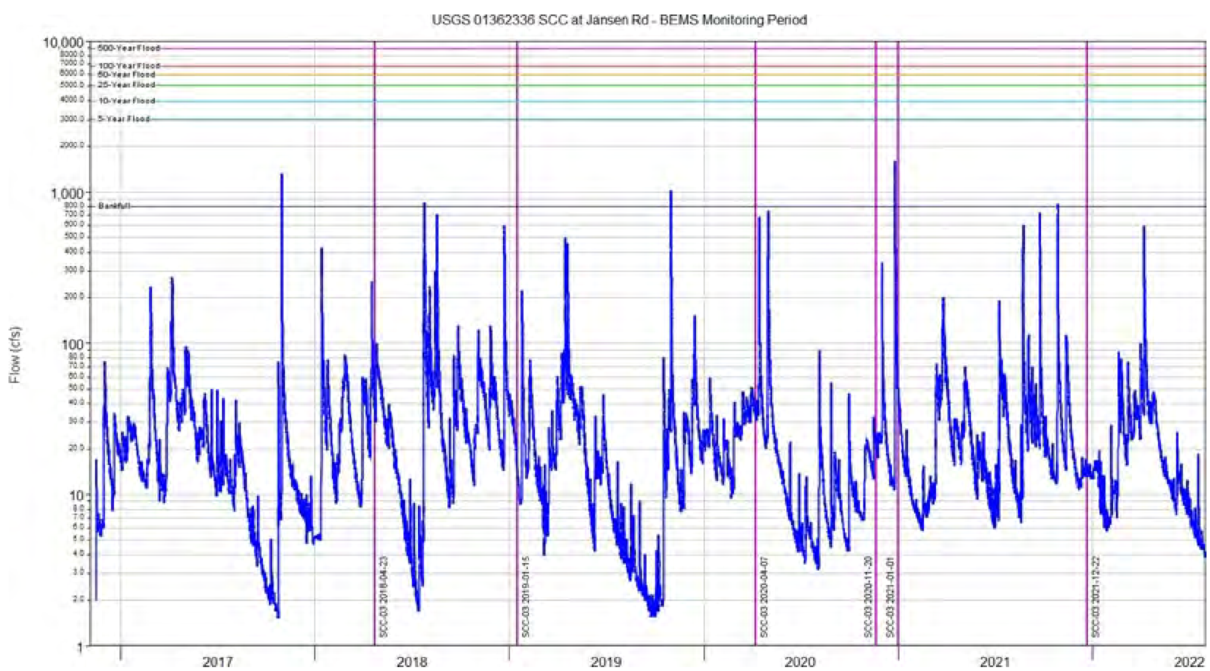

Figure 4.25 USGS Stony Clove Creek monitoring station 01362336 hydrograph for water years 2017 through partial 2022. SCC-03 BEMS site topographic survey dates are identified to show hydrology that would influence detected geomorphic change. Source: SLR Consulting, 2023

An important driver of geomorphic change at the SCC-03 site is that it exists within a generally aggradational setting as the steeper, more confined valley upstream transitions to a lower gradient and wider valley bottom. The aggradational setting makes the site prone to dramatic shifts in channel alignment. The reach has a history of cross-valley floor channel migration through avulsions, lateral erosion, and reportedly through past channel modifications by previous landowners. SCC-03 was an actively adjusting reach over the course of the monitoring period through mid-2022. BEMS and STRP design investigations found that thick deposits of lacustrine sediment underly the alluvium across the entire valley bottom and high terraces. The channel erosion into the right valley margin high glacial legacy terrace triggers rotational slump mass failures that expose lacustrine sediment and force this sediment into the active channel margin. The result of the surficial geology and the dynamic fluvial geomorphology is spatially and temporally variable erosional contact with this primary turbidity producing sediment.

Figures 4.26 through 4.31 excerpted from the BEMS report depict some of the available results for the period between November 2020 and December 2021. The use of UAS to obtain high resolution orthophotographs (Figure 4.26 to 4.28) that can be converted to point cloud elevation data for SfM derivation of topographic surfaces, such as DEMs, allows for DEM differencing to generate raster files of topographic difference that represent geomorphic adjustment through erosion and deposition (Figure 4.29 to 4.30). Channel cross-section and longitudinal profiles can be exported from the DEMs to assist in measuring geomorphic change (Figure 4.31). Table 4.10 presents the DEM differencing results as coarsely estimated volumetric budgets for SCC-03, prior to construction as an STRP. This set of figures and the table of geomorphic change detection results illustrates the potential utility of the BEMS data for tracking geomorphic change that can inform turbidity reduction management efforts.

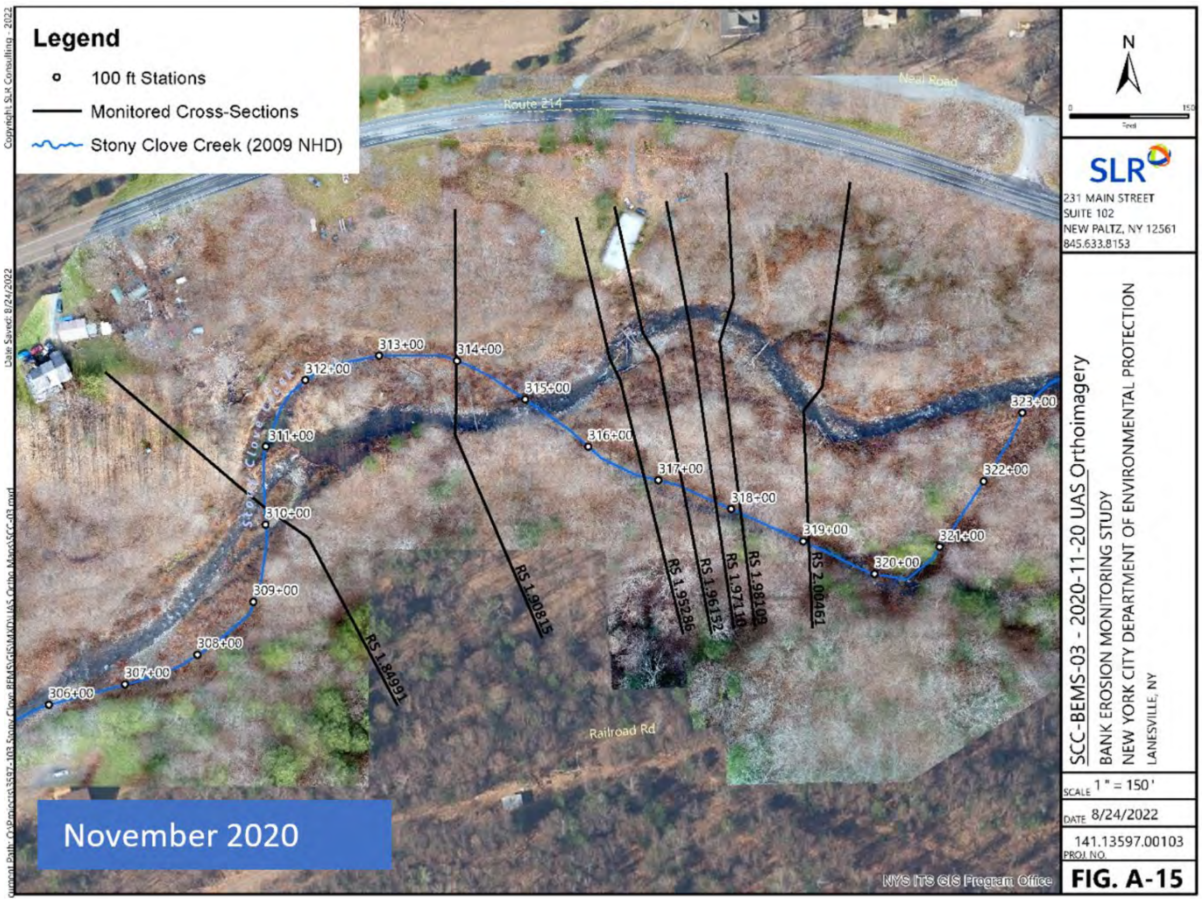

Figure 4.26 SCC-03 November 11, 2020 orthophoto used for SfM derivation of a digital topographic surface for morphologic monitoring and geomorphic change detection. Source: SLR Consulting, 2023.

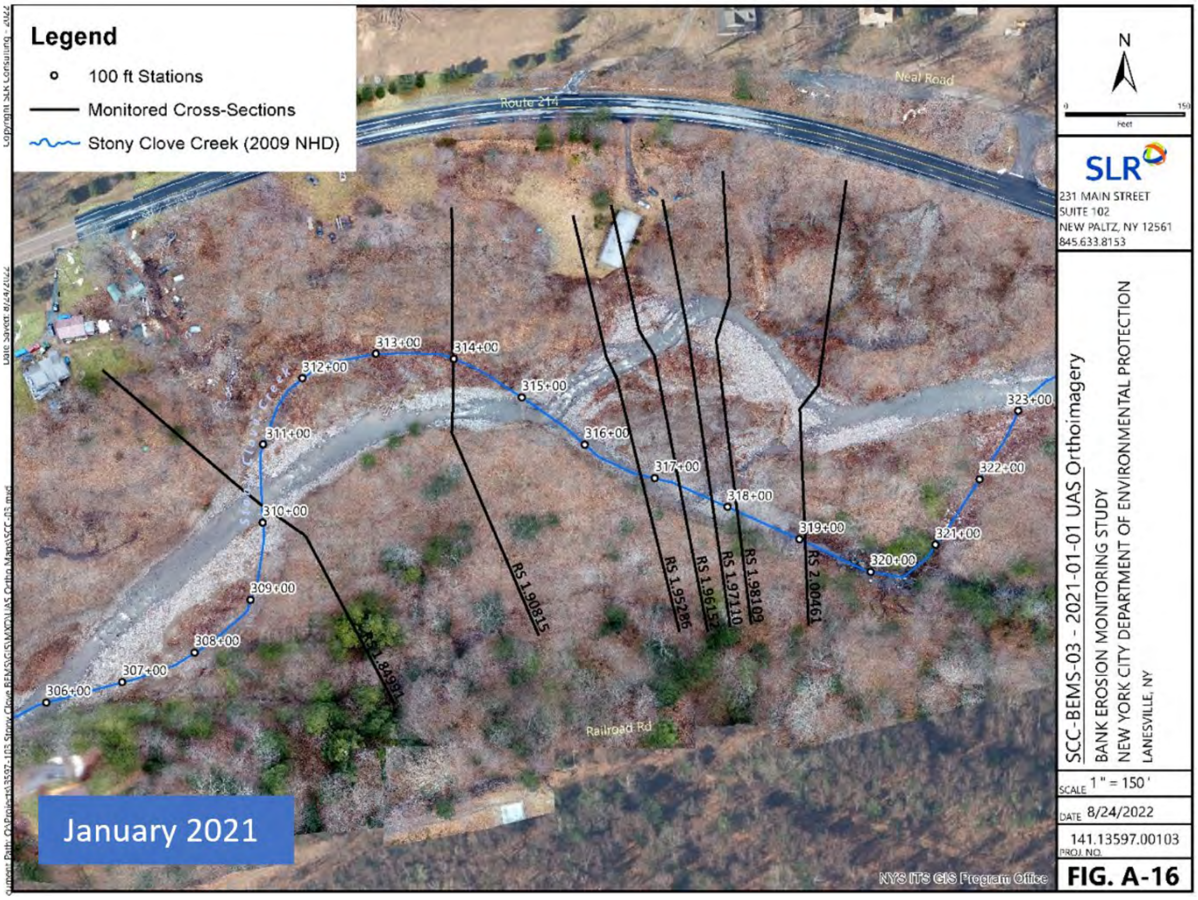

Figure 4.27 SCC-03 January 1, 2021 orthophoto used for SfM derivation of a digital topographic surface for morphologic monitoring and geomorphic change detection following the December 25, 2020 flood. Source: SLR Consulting, 2023.

Figure 4.28 SCC-03 December 22, 2021 orthophoto used for SfM derivation of a digital topographic surface for morphologic monitoring and geomorphic change detection. Source: SLR Consulting, 2023.

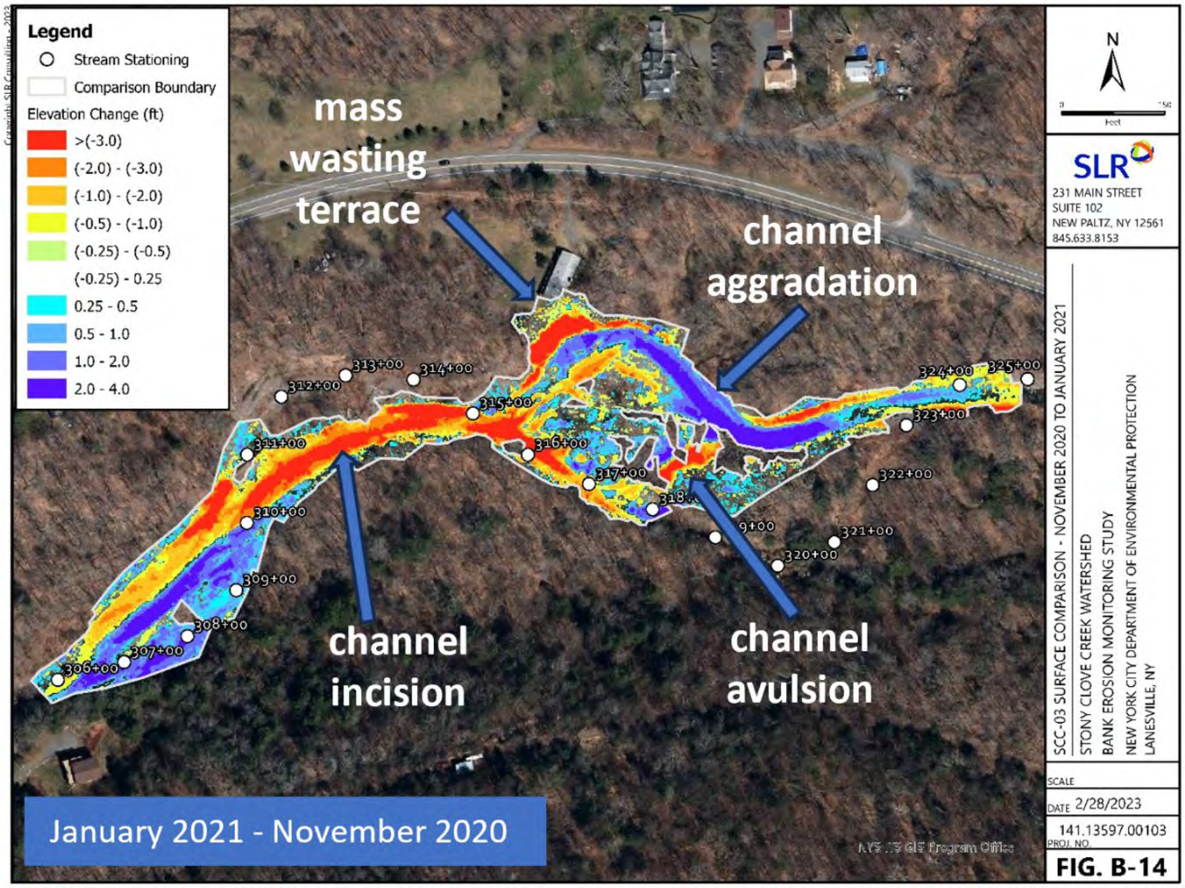

Figure 4.29 SCC-03 Geomorphic change detection using the January 2021 and November 2020 DEMs. The surface elevation change from negative (erosion) to positive (deposition) is color-coded as shown in the legend. This measured geomorphic change is associated with the December 25, 2020 flood. The background image is the April 2021 Orthoimagery available from the NYS GIS Clearinghouse. Source: SLR Consulting, 2023.

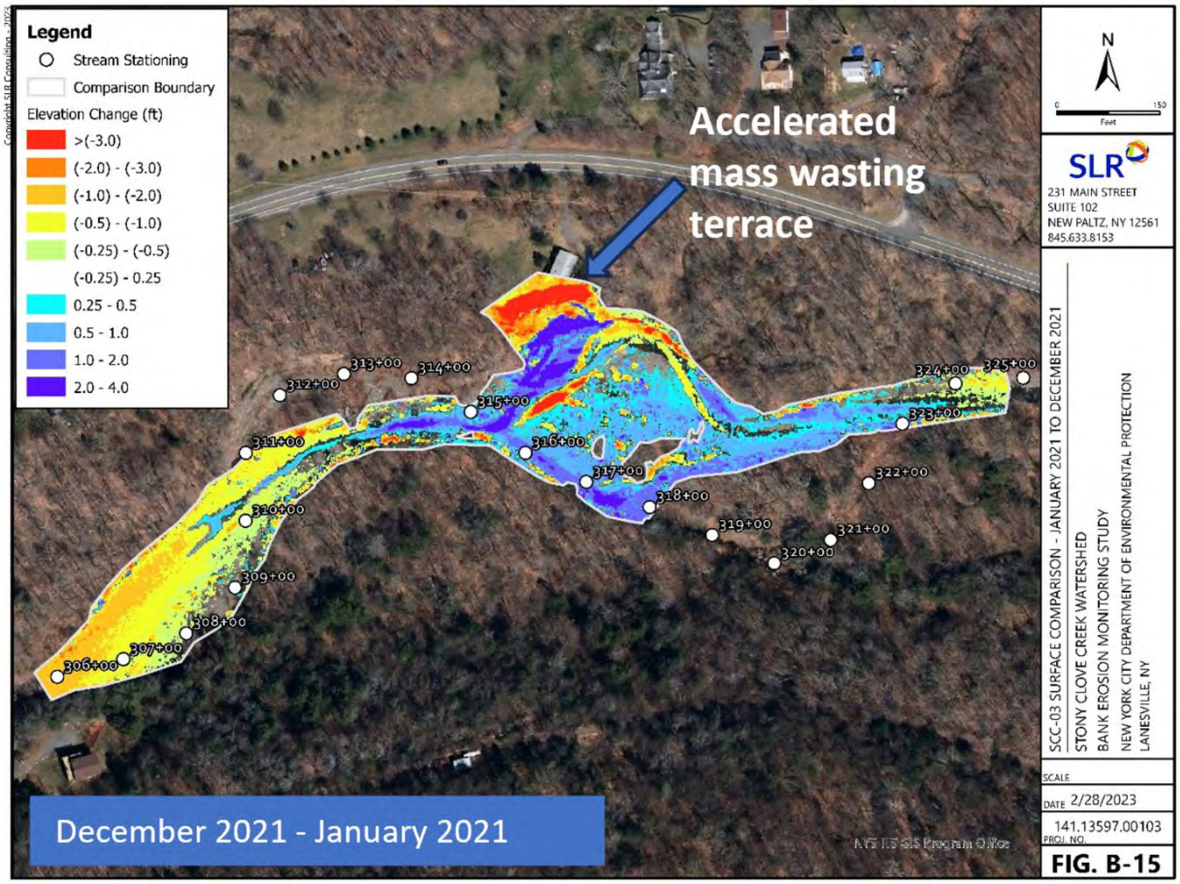

Figure 4.30 SCC-03 geomorphic change detection using the December 2021 and January 2021 DEMs. The surface elevation change from negative (erosion) to positive (deposition) is color-coded as shown in the legend. This measured geomorphic change is for the year following the December 25, 2020 flood. The background image is the April 2021 Orthoimagery available from the NYS GIS Clearinghouse. Source: SLR Consulting, 2023.

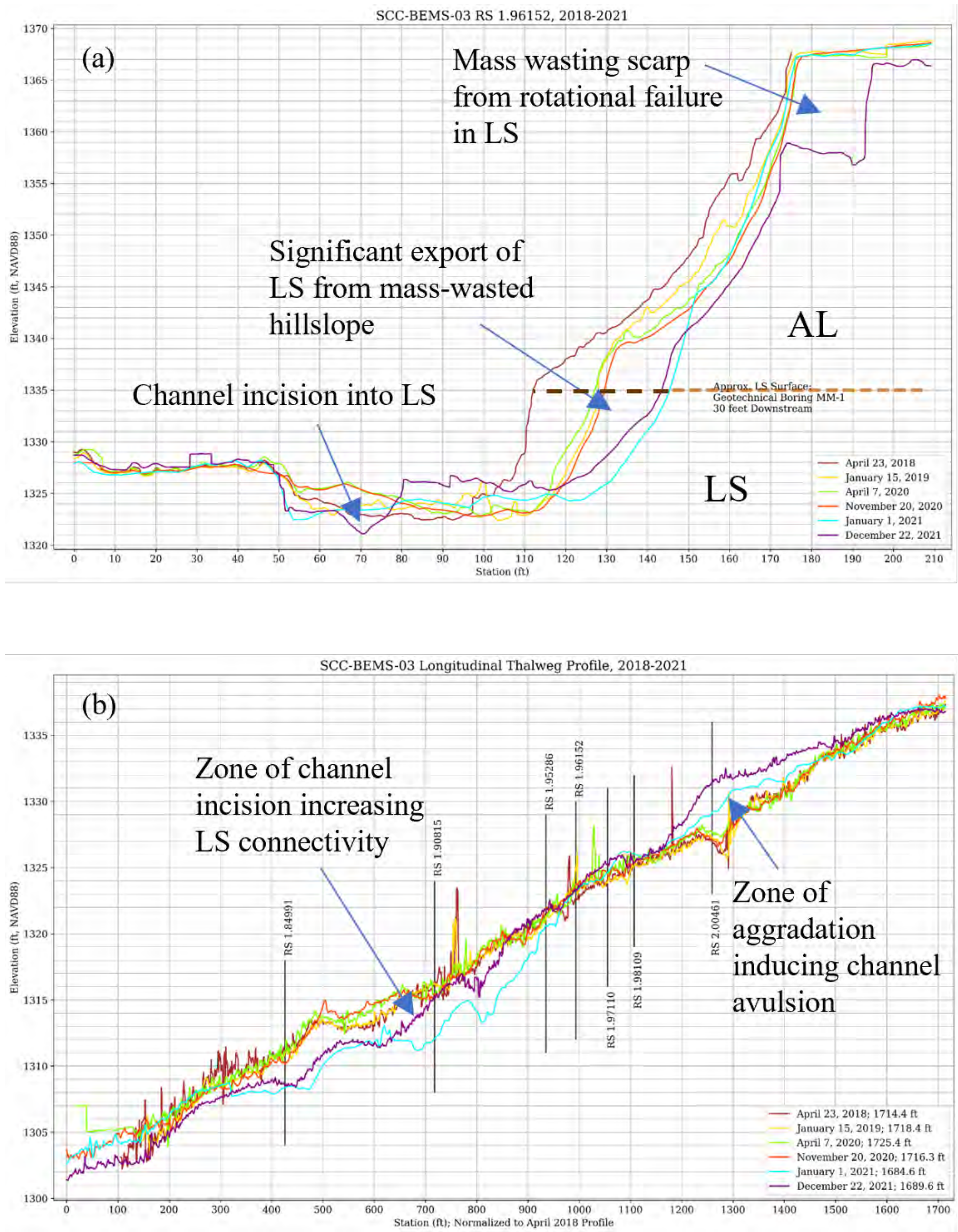

Figure 4.31 SCC-03 channel cross-section and longitudinal profiles cut from DEMs for geomorphic change detection. Source: adapted from SLR Consulting, 2023.

Table 4.10 Example of volumetric estimates of erosion and deposition (cubic yards) at BEMS site SCC-03 and the net gain/loss in sediment between topographic surveys.

Time Period	Elapsed (months)	Erosion (CY)	Deposition (CY)	Net Gain/Loss (CY)
April 2018 – January 2019	8	1147	735	-412
January 2019 – April 2020	16	945	1146	+201
April 2020 – November 2020	7	590	408	-182
November 2020 – January 2021	2	6013	3438	-2574
January 2021 – December 2021	11	3234	2860	-374

Stream bank sediment sampling

There are no updates to DEP's mid-term report stream bank sediment sampling results. Multiple bulk samples were taken at each BEMS location to document the grain size distribution of the SS source units exposed within the study area. The primary objective for the analysis was to obtain estimates of the percentage of fine-grained sediment (silts and clays) in each source that contributes to suspended sediment. The samples were submitted to Independent Material Testing Labs in Plainville, Connecticut, or to Atlantic Testing Labs in Highland, New York, for gradation and hydrometer analyses. The stream bank sediment sample fine sediment content results for AL, LS and GT are presented in Figure 4.32. The boxplots show the substantial difference in fine sediment content among the three primary SS sources – LS, GT, and AL.

The 14 LS samples have the highest percent fines, ranging from an outlier low of 83.7% up to 99.9% and a mean of 96%. The four GT samples range from moderate to high (30-51%) with a mean of 50.5%. The seven AL samples represent the low-end with a range of 0.6% to 12.7% and a mean of 5.3%. It takes very little erosion of LS to exceed the SS contributions of GT and AL. This data supports the assumption that LS is the primary target for STRP sediment dysconnectivity.

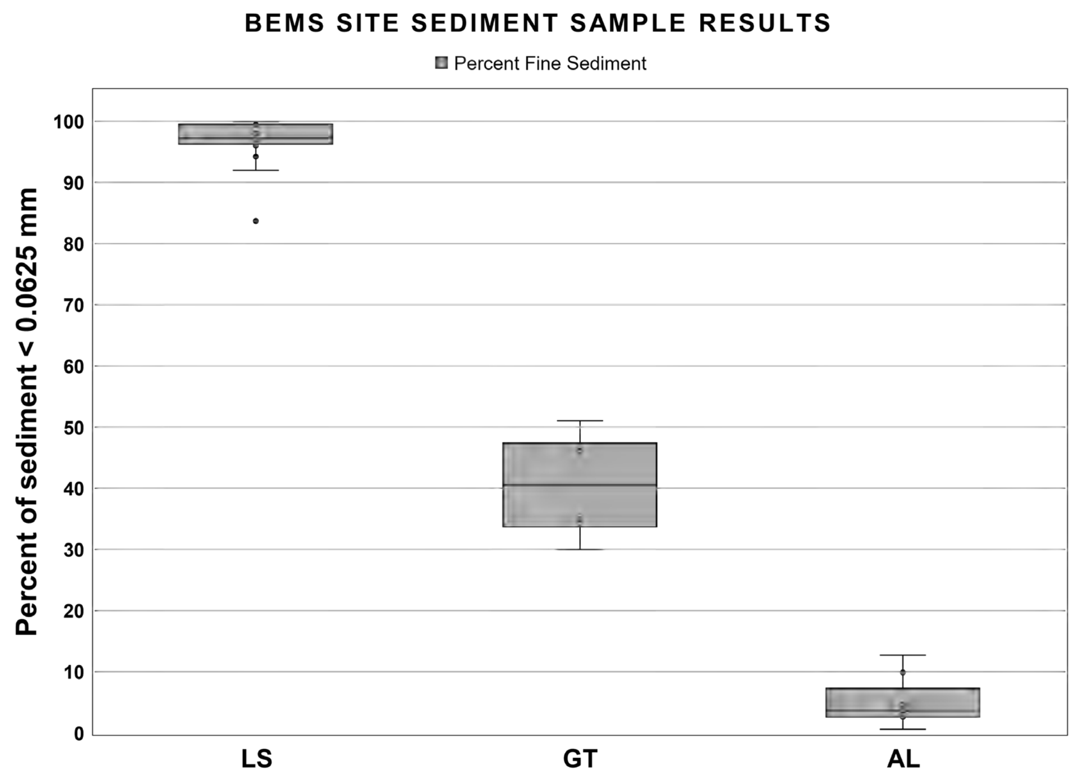

Figure 4.32 BEMS site stream bank sediment sample results for LS (14 samples), GT (4 samples), and AL (7 samples).

Streambed sediment sampling

In 2021, DEP and SLR initiated streambed sediment sampling to estimate percent fine sediment stored in channel alluvium. Sampling started with use of track hoe excavators at the Warner Creek and Stony Clove Creek STRPs in 2021 and 2022, respectively. DEP and SLR with support from the SUNY Ulster Watershed Conservation Corp and USGS conducted additional sediment sampling for grain size distribution analysis in the Stony Clove Creek and Woodland Creek sub-basins. Track hoe excavators were not available, so the method used hand dug excavations sufficient to collect up to 5.1 ft^3 (33-gallon trash can) of sediment that was field-sieved down to medium gravel and sent off to a certified lab for further gradation analysis.

The preliminary results are in Table 4.11, showing the grain-size distribution for the 35 samples collected at 32 locations. The table includes the percentage of particle size distribution by sampled weight for the following grain-size classes: clay/silt, sand, gravel, cobble and boulder. The fine sediment fraction comprising just silt and clay is a very small percentage (typically less than 1%) in these gravel and cobble dominated streams. There is some indication that sampling methods do matter. The samples collected by track hoe excavators and then sub-sampled by hand, tended to have higher percent fine composition. All of the 2023 samples were collected from depositional bar features (e.g. point bars, mid-channel bars) that are mobile features that can represent the bedload fraction during bed mobilizing events. These results are still under review and are considered provisional. DEP and USGS will review the existing data for use in the sediment budget development as part of the planned 2024 to 2026 geomorphologic investigations led by USGS.

Table 4.11 Provisional streambed sampling results as percentage of total sampled mass.

Sample ID	Stream	Clay/Silt	Sand	Gravel	Cobble	Boulder	Sample Mass (kg)
HTB-SB-01.1	Hollow Tree Brook	1.00%	90.0%	9.0%	0.0%	0.0%	25.00
HTB-SB-01.2	Hollow Tree Brook	0.69%	17.1%	51.7%	30.5%	0.0%	203.71
HTB-SB-02	Hollow Tree Brook	0.54%	15.2%	24.3%	54.7%	5.2%	166.28
MB-SB-01	Myrtle Brook	0.45%	9.9%	31.7%	40.1%	17.9%	225.70
OCC-SB-01	Ox Clove Creek	0.71%	18.5%	46.2%	34.6%	0.0%	194.38
OCC-SB-02	Ox Clove Creek	0.38%	12.1%	27.3%	48.8%	11.4%	187.91
SCC-SB-01	Stony Clove Creek	0.45%	12.1%	37.6%	49.9%	0.0%	109.12
SCC-SB-02	Stony Clove Creek	0.33%	3.7%	62.7%	29.7%	3.6%	196.17
SCC-SB-02.1	Stony Clove Creek	0.90%	38.1%	60.0%	1.0%	0.0%	65.89
SCC-SB-03	Stony Clove Creek	0.99%	32.8%	48.7%	3.8%	13.7%	201.62
SCC-SB-04	Stony Clove Creek	0.53%	18.0%	69.9%	11.6%	0.0%	102.01
SCC-SB-05.1	Stony Clove Creek	0.71%	29.9%	24.0%	25.0%	20.4%	218.85
SCC-SB-05.2	Stony Clove Creek	0.41%	13.7%	21.2%	40.1%	24.6%	240.39
SCC-SB-06	Stony Clove Creek	0.26%	6.4%	28.4%	48.4%	16.5%	203.28
SCC-SB-07	Stony Clove Creek	0.21%	17.7%	33.4%	39.8%	8.8%	230.57
SCC-SB-08	Stony Clove Creek	0.52%	12.0%	30.6%	56.9%	0.0%	125.70
SCC-SB-09	Stony Clove Creek	0.39%	12.3%	42.9%	31.2%	13.3%	198.67
SCC-SB-10	Stony Clove Creek	0.37%	11.7%	35.8%	52.1%	0.0%	195.85
WC-SB-01	Warner Creek	0.36%	9.2%	50.1%	40.4%	0.0%	206.04
WC-SB-02	Warner Creek	0.64%	19.9%	43.6%	28.7%	7.2%	223.62
WC-SB-03	Warner Creek	0.99%	18.1%	42.5%	15.2%	23.2%	260.34
WC-SB-04	Warner Creek	0.50%	13.3%	34.2%	47.7%	4.3%	211.49
WC-SB-05	Warner Creek	0.52%	8.9%	14.8%	66.2%	9.6%	215.97
WVC-SB-01	Woodland Creek	0.17%	9.2%	21.8%	57.8%	11.0%	214.50
WVC-SB-02	Woodland Creek	0.21%	8.9%	17.9%	58.4%	14.6%	214.56
WVC-SB-03	Woodland Creek	0.30%	11.6%	22.7%	47.5%	17.9%	241.61
WVC-SB-04	Woodland Creek	0.34%	22.4%	32.7%	44.6%	0.0%	217.84
WC-BEMS-02.1	Warner Creek	1.00%	26.1%	50.3%	22.6%	0.0%	213.75
WC-BEMS-02.2	Warner Creek	1.10%	25.1%	50.9%	22.9%	0.0%	188.36
WC-BEMS-02.3	Warner Creek	0.80%	13.7%	22.5%	58.6%	4.3%	256.57
WC-BEMS-02.4	Warner Creek	0.90%	20.6%	43.5%	35.1%	0.0%	222.69
SCC-BEMS-03.1	Stony Clove Creek	0.80%	12.2%	27.3%	39.4%	20.5%	303.17
SCC-BEMS-03.2	Stony Clove Creek	2.10%	33.2%	33.7%	31.2%	0.0%	224.20
SCC-BEMS-03.3	Stony Clove Creek	2.10%	16.4%	51.5%	23.4%	7.0%	213.35
SCC-BEMS-03.4	Stony Clove Creek	1.30%	17.5%	26.0%	41.1%	14.1%	286.80

4.6 Sediment and Turbidity Reduction Projects Monitoring

A primary goal of the study is to evaluate STRP efficacy on measurably reducing turbidity and SSC at a range of spatial, temporal and hydrologic scales. STRPs disconnect a stream channel from primary turbidity production sources exposed in eroding streambeds, banks and adjacent hillslopes. Individually and collectively, they test the role of reach scale processes on sub-basin to basin scale turbidity production and SS flux. A set of the USGS stream monitoring stations is used in the study to monitor and evaluate the performance of the STRPs in mitigating turbidity.

DEP funds STRPs through design contracts with engineering consultants and program contracts with county SWCDs. Additional federal funding for STRPs constructed between 2012 and 2016 was provided by the USDA Natural Resource Conservation Service and one project was supported by the Federal Emergency Management Agency.

The study focuses STRP evaluation on the Stony Clove sub-basin. Though not part of this study scope, STRP evaluation in other sub-basins is also performed by USGS, DEP, the AWSMP and Cornell University (Wang et al., 2021). USGS is collaborating with the AWSMP on evaluating STRP efficacy in the Woodland Creek sub-basin using methods similar to this study. In addition to the work documented in Wang et al. (2021) and discussed in the mid-term study report, USGS and DEP collaborated on a presentation at the 2023 SEDHYD conference in St. Louis, MO that resulted in a published paper (Siemion et al., 2023) that investigated the impact of the December 2020 flood on the STRP-influenced Tn-Q and SSC-Q relationship in the Stony Clove sub-basin. The paper is attached as Appendix A to this report.

4.6.1 STRP Implementation

Table 4.12 lists the 14 STRPs constructed through 2023, linking a number designation to the project name used in prior FAD reports. The Roman numeral designations are used for consistency with the published scientific journal articles usage (Wang et al., 2021; Siemion et al., 2023). Table 4.13 provides details on the treated stream lengths, SS source conditions, STRP practices and costs. As of 2023, STRPs treated a total stream length of 16,030 feet for a total cost of $14,047,691. The Stony Clove STRPs included as part of this study treated a length of 11,630 feet for a total cost of $9,957,060. Figure 4.33 shows the locations of the Stony Clove sub-basin STRPs evaluated in this report.

All STRP treated stream reaches were selected based on ranking the magnitude of monitored erosional contact with turbidity source sediment, the potential for disproportionate turbidity production, landowner support, and for the projects constructed between 2012 and 2016 in coordination with the USDA Emergency Watershed Protection Program following the 2011 Tropical Storm Irene flood. Three of the STRPs constructed in the Stony Clove sub-basin between 2021 and 2022 were selected as part of the study using upstream/downstream turbidity monitoring data, and geomorphic mapping and monitoring data (DEP, 2019b; DEP, 2022). Two nearly contiguous STRPs were completed in the Beaver Kill sub-basin in 2017 and two STRP was constructed in the Woodland Creek sub-basin in 2018 and 2022. The most recent STRP was constructed in the Esopus Creek headwaters tributary stream Elk-Bushkill in 2023.

All STRPs disrupted some version of channel-hillslope connectivity and sediment input from glacial legacy sources, yet each treated reach had unique connectivity configurations and sediment composition (Table 4.13). The practices used included channel realignment where feasible, grade and planform control to limit erosional adjustment, in-stream structures to influence hydraulics, stabilization of hillslopes, enhancing floodplain connectivity and riparian zone revegetation.

Table 4.12. STRPs completed in the UEC sub-basins between 2012 and 2023.

Stream Project ID	Stream Project Name
STRP I	Stony Clove Creek at Chichester Site 1
STRP II	Warner Creek Site 5
STRP III	Stony Clove Creek at Chichester Sites 2&3
STRP IV	Stony Clove Creek at Lanesville
STRP V	Stony Clove Creek at Stony Clove Lane
STRP VI	Stony Clove Creek-Warner Creek Confluence
STRP VII	Stony Clove Creek at Wright Road (channel)
STRP VIII	Stony Clove Creek at Wright Road (hillslope)
STRP IX	Beaver Kill at Van Hoagland Road 1
STRP X	Beaver Kill at Van Hoagland Road 2
STRP XI	Woodland Creek at Wilmot Way
STRP XII	Warner Creek Site 1
STRP XIII	Warner Creek Site 2
STRP XIV	Stony Clove Creek abv Jansen Road
STRP XV	Panther Kill Stream Restoration
STRP XVI	Elk-Bushkill Stream Restoration

Table 4.13 STRPs completed in the UEC sub-basins. [GT = glacial till; LS = lacustrine sediment; STRP practices: 1 = channel realignment; 2 = grade control; 3 = planform control with revetment or bioengineering; 4 = in-stream hydraulic structures; 5 = restoring floodplain connectivity/disconnecting from hillslope; 6 = hillslope stabilization through regrading/improving drainage/restoring vegetation cover; 7 = riparian planting]

Stream Project	Stream Length (ft)	Year	Problem/SS Source	Practices Implemented	Total Cost
Stony Clove Creek (STRP I)	650	2012	Channel-hillslope erosion / LS	1, 2, 3, 4, 5, 6, 7	$1,020,369
Warner Creek (STRP II)	800	2013	Channel-hillslope erosion / LS	1, 2, 3, 4, 5, 6, 7	$495,465
Stony Clove Creek (STRP III)	1,350	2013	Channel-hillslope erosion / LS+GT	1, 2, 3, 4, 5, 6, 7	$1,415,113
Stony Clove Creek (STRP IV)	1,700	2014-2015	Channel-hillslope erosion / GT	1, 2, 3, 4, 5, 7	$301,789
Stony Clove Creek (STRP V)	455	2014	Channel-hillslope erosion / LS+GT	2, 3, 4, 5	$540,146
Stony Clove-Warner Creeks confluence (STRP VI)	1,300	2014-2015	Channel-hillslope erosion / LS+GT	2, 3, 4	$1,585,454
Stony Clove Creek (STRP VII, VIII)	2,675	2015-2016	Channel-hillslope erosion / LS+GT	1, 2, 3, 4, 5, 6	$1,802,985
Beaver Kill (STRP IX, X)	1,300	2017	Channel-hillslope erosion / GT	1, 2, 3, 4, 5, 6, 7	$1,383,408
Woodland Creek (STRP XI)	1,350	2018	Channel-terrace erosion / LS	1, 2, 3, 4, 5	$1,075,795
Warner Creek (STRP XII)	540	2021	Channel-terrace erosion/LS	1, 2, 3, 4, 5, 6, 7	$373,342
Warner Creek (STRP XIII)	560	2021	Channel-terrace erosion/LS	1, 2, 3, 4, 5, 6, 7	$373,342
Stony Clove Creek (STRP XIV)	1,600	2022	Channel-terrace erosion/LS	1, 2, 3, 4, 5, 6, 7	$2,049,055
Panther Kill (STRP XV)	450	2022	Channel-terrace erosion/LS	1, 2, 3, 4, 5, 6, 7	$501,528
Elk-Bushkill (STRP XVI)	1,300	2023	Channel-terrace erosion/LS	1, 2, 3, 4, 5, 7	$1,129,900

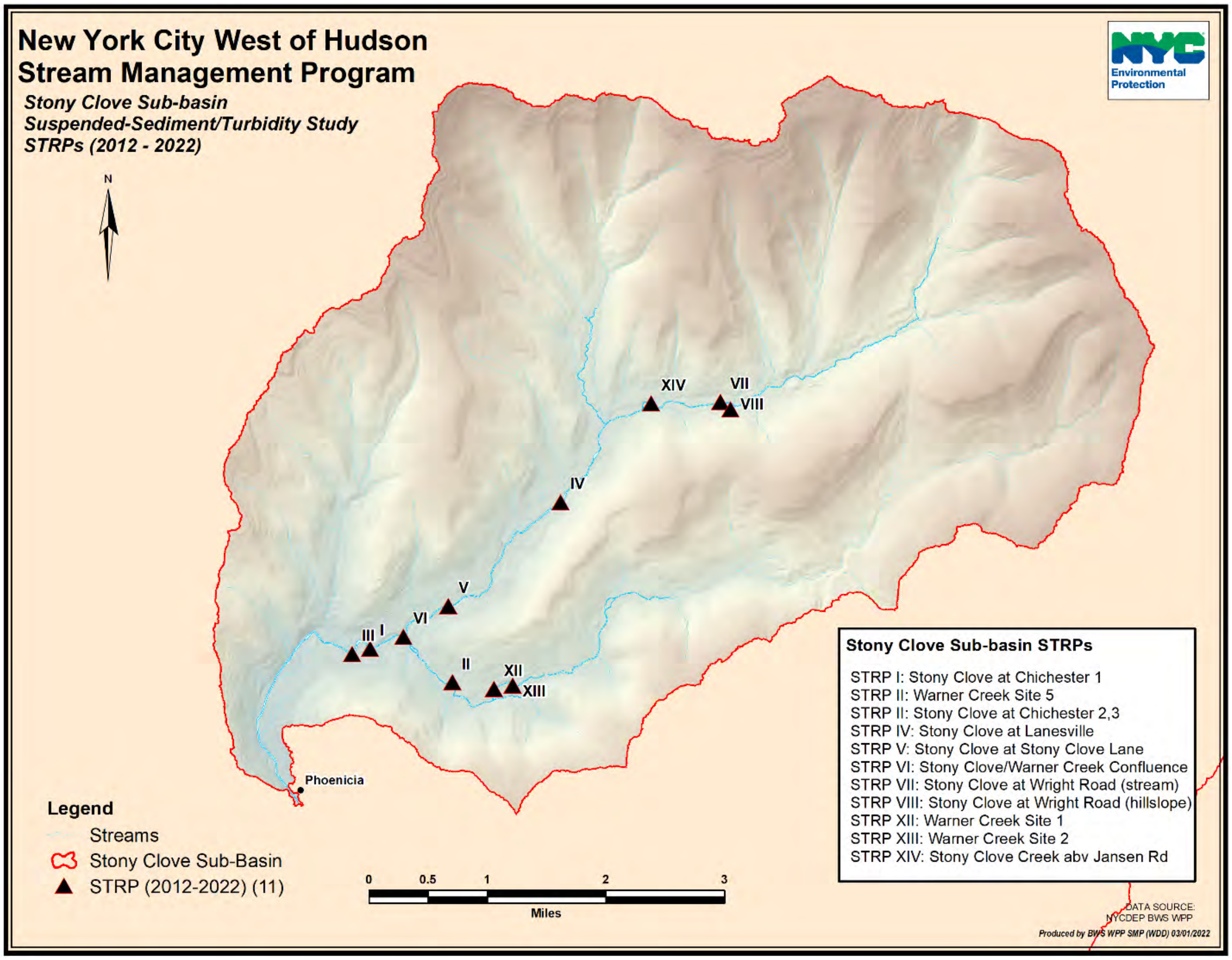

Figure 4.33 Stony Clove sub-basin STRPs constructed between 2012 and 2022. Note that number designations replace version presented in 2022 mid-term study report.

4.6.2 STRP Turbidity and SS Monitoring: Water Years 2017-2023

Past research by USGS and DEP concluded that cumulative STRPs in the Stony Clove sub-basin reduce turbidity and SS flux and yield for a limited range of streamflow for a short monitoring period following implementation (Siemion et al., 2016). Wang et al. (2021) used dynamic linear modeling (DLM) and physical-based distributed parameter modeling to investigate the effects of STRPs I, II, III and VI in the Stony Clove sub-basin and the effects of STRP II in Warner Creek. Results of the analysis suggest measurable decreases in the streamflow-SSC relation coincident with the timing of the stream projects. The December 25, 2020 flood in the UEC watershed resulted in an order of magnitude increase in SSC per unit streamflow at the outlet of the Stony Clove Creek sub-basin that persisted for three months throughout the range in streamflow, that persisted for at least one year at high streamflow following the flood, and resulted in large increases in mapped bank erosion throughout the Stony

Clove Creek sub-basin (DEP, 2022; Siemion et al., 2023). However, relatively small increases in sediment concentration per unit streamflow were measured and less erosion was noted from stream reaches where STRP were constructed.

Streamflow Conditions

Figure 4.34 depicts an update of the monitored hydrology in Stony Clove Creek, Warner Creek and Woodland Creek for water years 2011 to 2023. The period before STRP construction in the Stony Clove sub-basin was more hydrologically active, and thus geomorphically active, than the period from water year 2013 through water year 2020 (Figure 4.34). The December 25, 2020 flood in water year 2021 was a significant hydrologic forcing event in the Stony Clove sub-basin that yielded a prolonged elevated turbidity production response. Subsequent hydrologic vents in water years 2022 and 2023 did not exceed the 2-year recurrence interval.

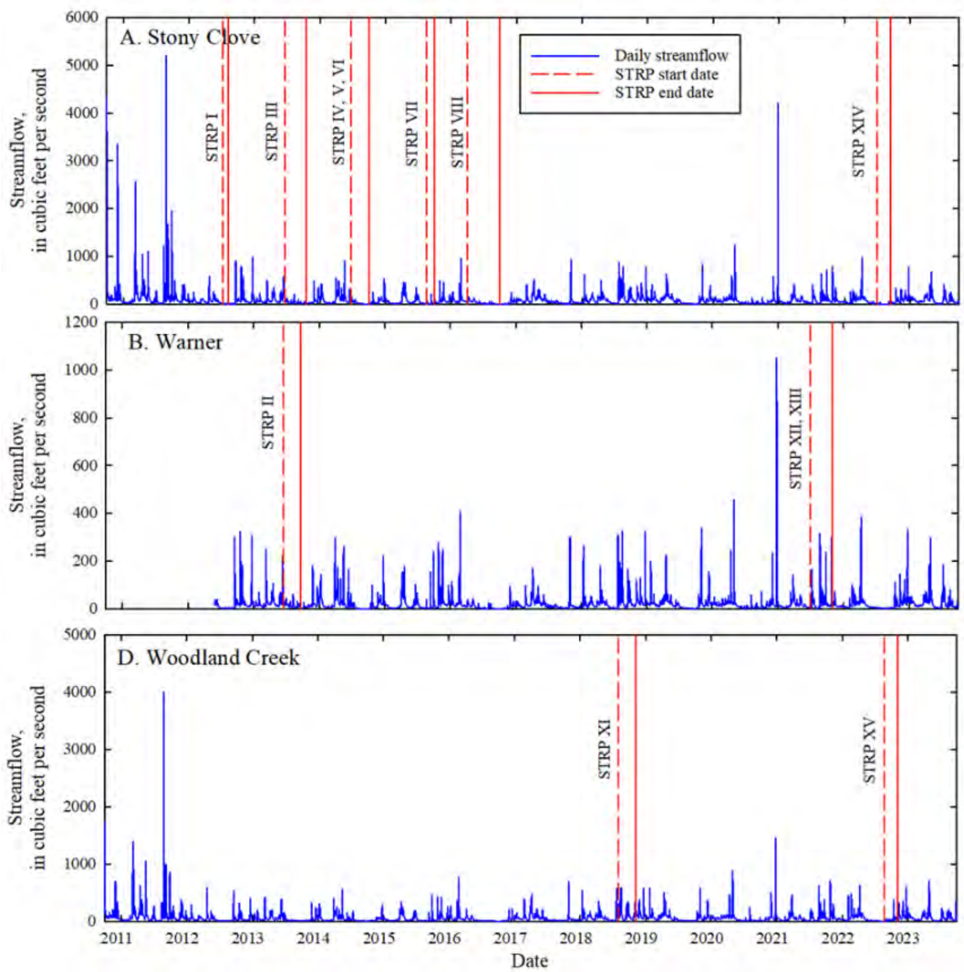

Figure 4.34 Streamflow was greater in the period before stream STRPs were constructed than the post-construction period through water year 2020 in Stony Clove Creek (and presumably Warner Creek, a tributary to Stony Clove Creek). Source: USGS

Effects of STRP on Turbidity

Daily mean turbidity as a function of daily mean streamflow at Stony Clove Creek at Chichester (01362370) was an order of magnitude lower during the relatively geomorphically stable water years 2022-2023 than the pre-STRP geomorphically active water years 2010-2011 (Figure 4.35). The 2022-2023 observations are similar to those of Siemion et al. (2016) for the 2012-2014 period immediately after the construction of STRPs. The 2022-23 results at Stony Clove Creek at Chichester incorporate the effects of all previous STRP constructed in the sub-basin as well as the effects of geomorphically significant floods and subsequent geomorphic recovery of the stream channels.

With this report, USGS has provided a new approach to presenting and analyzing the turbidity-streamflow relations in the Stony Clove sub-basin to facilitate STRP evaluation and to accommodate increased understanding of the system dynamics. Daily mean turbidity as a function of daily mean streamflow for Stony Clove Creek at Chichester (01362370) was subset into six distinct time periods with similar hydrogeomorphic conditions (Figure 4.36):

(1) an initial period of repeated high magnitude streamflows prior to STRP construction (October 1, 2010 to July 10, 2012),

(2) a period of relatively stable conditions after construction of STRP I and II, but including STRP III to VII (October 15, 2013 to October 28, 2017),

(3) a period of elevated turbidity after a storm with peak streamflows approximating a 1.5-year return interval (October 29, 2017 to February 28, 2018),

(4) a period of a period of relatively stable conditions between geomorphically significant streamflows (March 1, 2018 to December 23, 2020),

(5) a period of elevated turbidity after a storm with peak streamflows approximating a five to 20-year return interval (December 24, 2020 to September 30, 2021), and

(6) a final period of relatively stable conditions (October 1, 2021 to September 30, 2023).

An approximate order of magnitude decrease in daily mean turbidity per unit streamflow was measured from the initial geomorphically active pre-STRP period to the relatively stable period. This decrease was observed by both Siemion et al. (2016) and Wang et al. (2021) using different data analysis techniques, though it remains unclear how much of this decrease was directly attributable to the STRP and how much resulted from natural recovery of the stream channels after the period of high magnitude streamflow events. The subsequent time periods in Figure 4.36 show a pattern of increased turbidity per unit streamflow after high magnitude streamflow events followed by periods of lower turbidity per unit streamflow during relatively stable hydrogeomorphic conditions. An important observation is that even after the high magnitude streamflow events of October 29, 2017 and December 25, 2020, turbidity associated with low to moderate streamflows does not reach the levels it did during the period of repeated high magnitude streamflows prior to STRP construction. This suggests the STRPs have been successful in disconnecting the streams from chronic sources of fine sediment in the project reaches.

Two STRPs were completed in Warner Creek during 2021 between reach scale monitoring sites 0136235580 and 01362356. This provides an opportunity to use a Before After Control Impact (BACI) type of analysis to investigate the effects of the STRPs on turbidity because there is sufficient data from both upstream and downstream of the project. The construction period as well as the period of elevated turbidity after the December 25, 2020 storm are not included in the data shown in Figure 4.37. This was done to remove potential effects of the construction period and to focus the analysis on periods with similar hydrogeomorphic conditions. An important benefit of a BACI analysis is that natural variation between sites and time periods can be accounted for. There was a downward shift in the daily mean turbidity-daily mean streamflow relation from the before to after STRP period at 0136235580 upstream of the STRPs. Thus, only a downward shift in the relation at the below STRPs site greater than that observed at the upstream of the project site would imply reduction of turbidity resulting from the STRPs. Preliminary results suggest there was no measurable decrease in turbidity at lower streamflows that can be attributed to the 2021Warner Creek STRPs. However, it does appear that there was a decrease in turbidity at moderate to near bankfull streamflows at the downstream site that could be attributable to the STRPs. Additional data and a detailed statistical analysis completed for DEP's final study FAD report in 2027 will be needed to verify this.

The AWSMP funded the monitoring of a 2022 STRP constructed in the Panther Kill tributary to Woodland Creek. Like the 2021 Warner Creek STRP, the Panther Kill STRP monitoring included data collection both above and below, and before and after construction (Figure 4.37). Downward shifts in the streamflow-turbidity were noted at both monitoring sites from the before to after construction periods. The downward shift at the downstream monitoring site was greater than that of the upstream site through the range in monitored streamflows suggesting the STRP effectively reduced sediment production in the treated reach. The post-project monitoring period was less than one year and thus limits the evaluation.

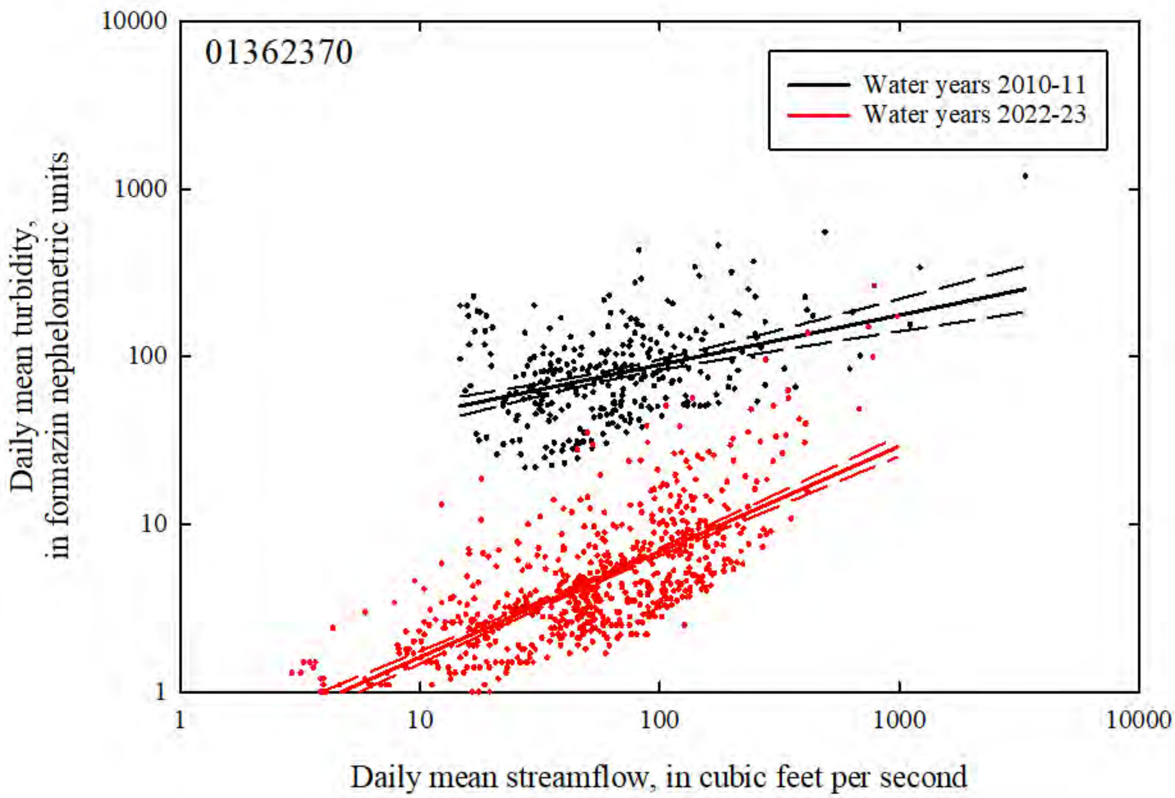

Figure 4.35 Daily mean turbidity as a function of daily mean streamflow at Stony Clove at Chichester (01362370) was an order of magnitude lower during water years 2022-23 than the water years 2010-11 pre-STRP period. Source: USGS

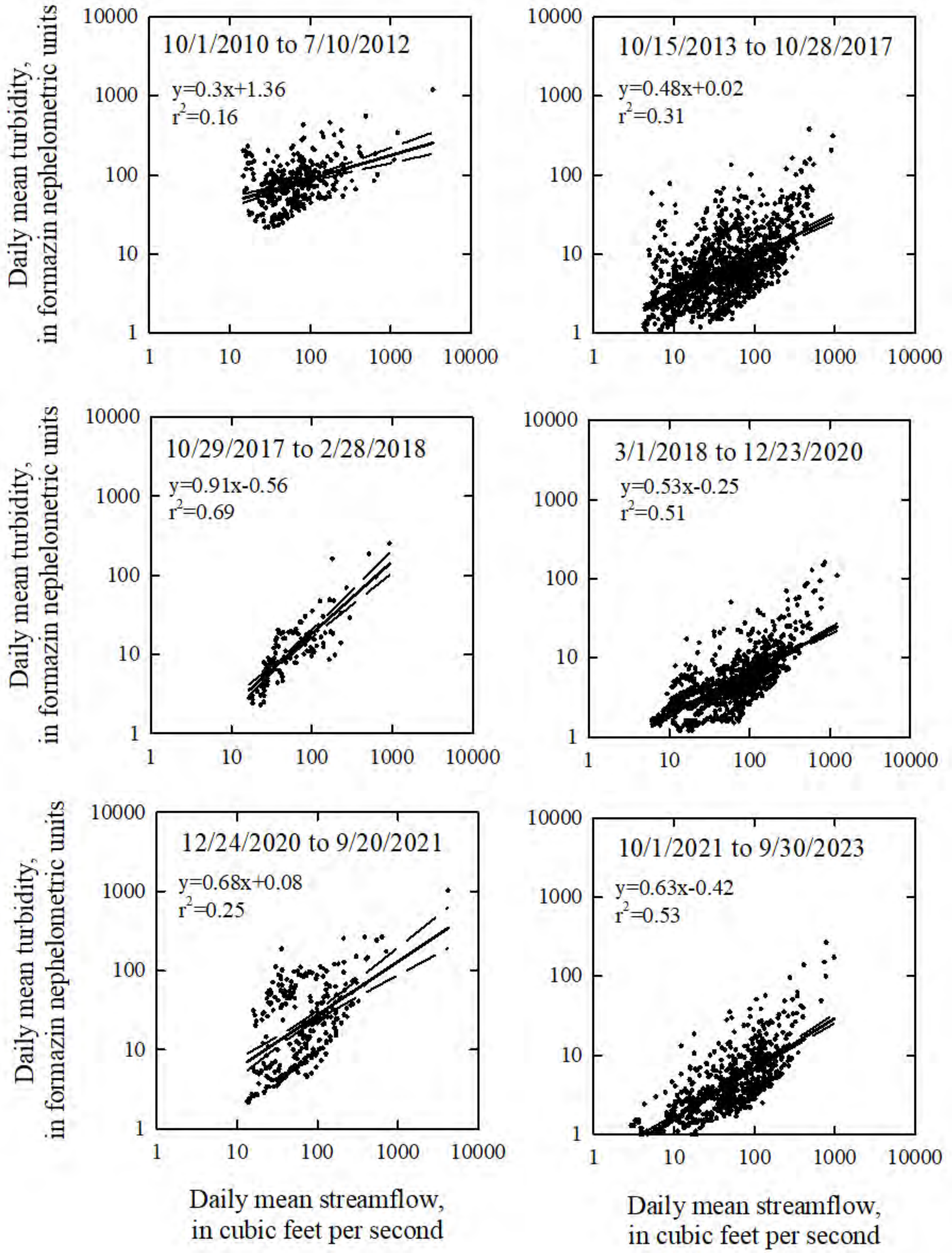

Figure 4.36 Daily mean turbidity as a function of streamflow at Stony Clove at Chichester (01362370) subset into time periods representing similar hydrogeomorphic conditions spanning 10/1/2010 to 9/30/2023. Source: USGS

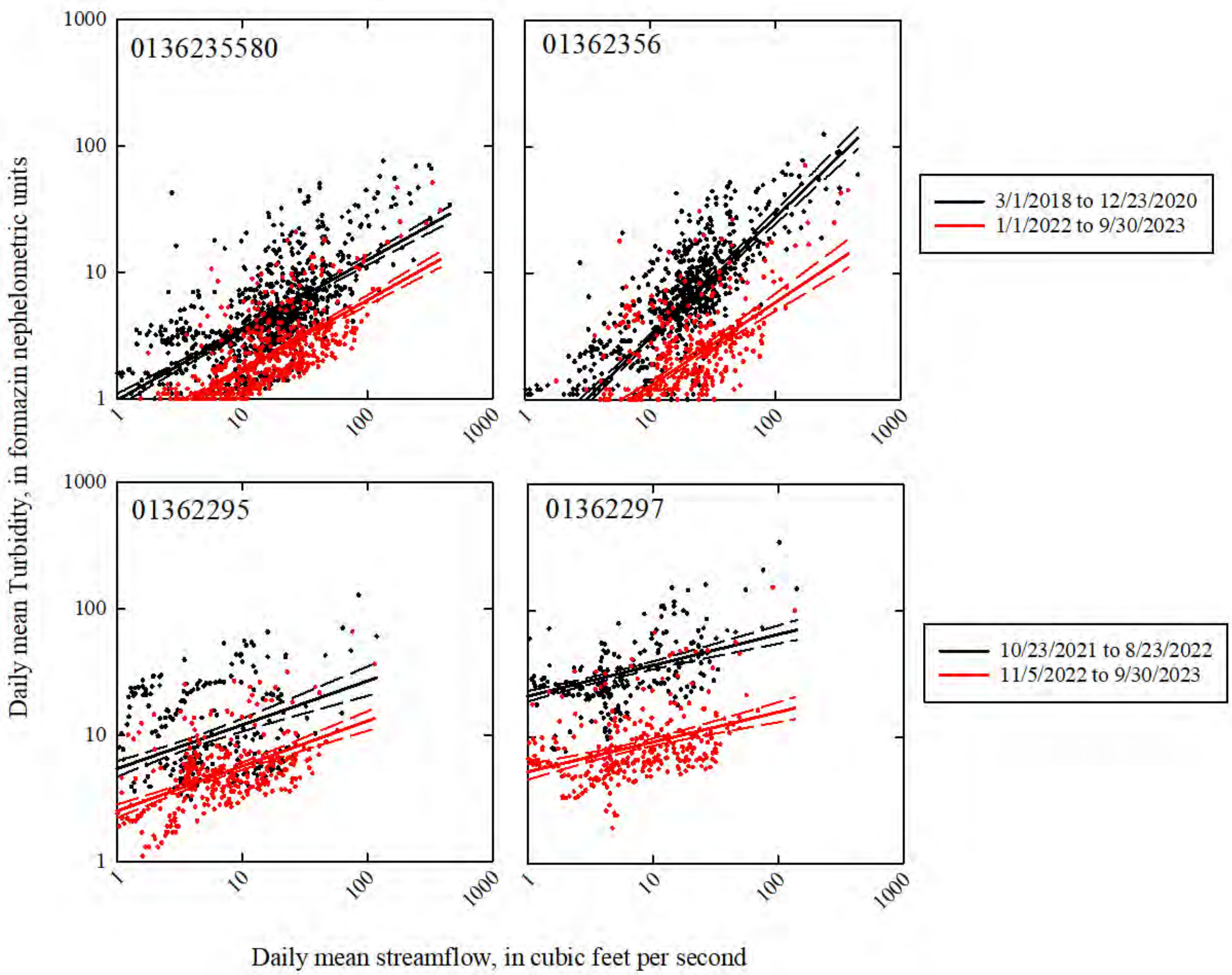

Figure 4.37 Daily mean turbidity as a function of streamflow before and after STRP at Warner Creek above the 2021 STRP (0136235580), Warner Creek below the 2021 STRP (01362356), Panther Kill above the 2022 STRP (01362295), and Panther Kill below the 2022 STRP (01362297). Source: USGS

5. Discussion

DEP's 2022 mid-term study FAD report provided categorized discussion on turbidity production monitoring results in the UEC and Stony Clove sub-basins, turbidity reduction through STRPs, and the suitability of the conceptual framework. The discussion below is not as extensive as the mid-term report which offered preliminary answers to the posed research questions. DEP's final study report in November 2027 will provide the concluding answers to those questions, to the extent feasible. The following discussion is focused on evaluating whether the previous findings still hold with the addition of two more water years of data.

The results of the first seven years of stream monitoring, turbidity source characterization and STRP implementation continue to provide information to guide turbidity reduction strategies. The results also continue to support many of the conceptual model assumptions about the drivers and controls of turbidity production and the hypothesized outcomes of turbidity reduction efforts through STRP implementation.

The USGS study monitoring network demonstrates that it is sufficient to help the AWSMP use an adaptive strategy to inform and implement stream turbidity reduction efforts. The two biggest loaders of turbid streamflow to the Ashokan Reservoir over the course of the study are Stony Clove Creek and Woodland Creek followed by Beaver Kill, though there is variation year-to-year. DEP's mid-term study report discussed the measurable and significant reduction in Stony Clove sub-basin turbid streamflow following the implementation of STRPs between 2012 and 2016 sufficient to make it no longer the consistently highest producer of turbidity. The December 2020 flood was powerful enough to reset Stony Clove as a top-level producer. Within the Stony Clove sub-basin, Ox Clove Creek and Hollow Tree Brook are the more turbid prone streams since the December 2020 flood. A planned STRP in Hollow Tree Brook at BEMS site HTB-01 will address the current biggest turbidity production hot spot in the Stony Clove sub-basin and is expected to substantially reduce turbidity production at flows below bankfull discharge.

The next level down in monitored turbid streamflow loading in the UEC includes the Birch Creek and Broadstreet Hollow Brook. These are followed by the Esopus Creek headwaters and Bushnellsville Creek. Esopus Creek headwaters can generate a lot of turbid streamflow based on its drainage area and access to GLS, yet it tends to clear up relatively quickly following flood events. Little Beaver Kill has a uniquely low turbidity production record through water year 2023, attributable to the very limited contact with GLS. Esopus Creek below the headwater monitoring station also contributes to turbidity production but the monitoring network is not set up to identify the discrete production locations between the two downstream stations. Further geomorphic investigation into the mainstem Esopus Creek is recommended to update the potential turbidity source connectivity.

The monitoring data shows annual variations changing ranking order in turbidity production levels, yet on average, this grouping of watershed turbidity production has been mostly consistent throughout the study. These results can guide where AWSMP will focus assessment and treatment targeted to reduce stream turbidity.

The mid-term report described how big floods force enough geomorphic adjustment in the stream corridor landscape to increase erosional contact locally and systemically with glacial legacy sediment and can supply most of a multi-year suspended sediment load in just one event. The erosional contacts, if extensive enough and include contact with glacial lake sediment, can function as hot spot turbidity production sources that generate measurable turbidity across a range of flows. Flooding in the Stony Clove sub-basin continues to provide an excellent illustration of the role of big floods on influencing turbidity production at the event to annual time scale. The December 2020 flood disrupted a monitored apparent trend of decreasing turbidity production in the Stony Clove watershed (water years 2016 to 2020), effectively providing an experimental disturbance that disrupted the post-2011 period natural and STRP-assisted geomorphic recovery (Wang et al., 2021; DEP, 2022; Siemion et al., 2023). The remainder of water year 2021 was characterized by non-disruptive flood hydrology, allowing a period of vegetative recovery and minor sediment resorting to begin the process of geomorphic recovery that continued into water year 2023. The Stony Clove primary and secondary monitoring stations, SFI data and BEMS findings continue to support this supposition.

The current preliminary results also continue to support the previous preliminary findings that strategically disconnecting the channel from these sources through STRPs can measurably reduce turbidity at the watershed scale for flows below hydrogeomorphic forcing thresholds and can reduce the scale and duration of post-flood turbidity production, or suspended sediment loading (Wang et al., 2021; Siemion et al., 2023). Big floods also limit the STRP efficacy in a turbidity prone landscape that can readily produce new erosion hot spots or reactivate treated turbidity sources. Continued stream monitoring data collection and analysis through water year 2026 may further quantitatively define the STRP efficacy limits.

6. Conclusions

The preliminary results of the study show that turbidity production in the UEC watershed landscape is both sensitive to flooding disturbances causing reach scale acute and chronic turbidity production, and resilient through intrinsic geomorphic post-disturbance recovery processes, assisted by strategic STRP placement.

The geomorphic connectivity conceptual framework guiding data acquisition and analysis is proving to be useful for explaining turbidity production at a range of spatial, temporal and hydrologic scales. USGS has successfully completed the first seven water years of monitoring streamflow, turbidity and SS while DEP with SLR support continued to quantitatively characterize temporally varying geomorphic connectivity to turbidity/SS sources in the Stony Clove sub-basin.

Preliminary results of STRP monitoring continue to indicate that for the observed range of streamflow conditions through water year 2023, the Stony Clove sub-basin STRPs are still effective in reducing turbidity and SSC even after a 10 to 25-year recurrence interval flow in late December 2020, though their reduction impact has diminished in the context of new turbidity sources significantly controlling spatial and temporal turbidity production.

DEP expects that the concluding three years of monitoring, source characterization and STRP implementation and evaluation will complete a robust data set that can be used by USGS, DEP, program partners and other researchers to investigate and analyze turbidity production and reduction potential through management in a glacially conditioned mountain stream system.

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Appendix A

SEDHYD 2023 Conference Proceedings Paper:

Siemion, J., Davis, W.D., Bonville, D.B. 2023. Effects of a large flood on sediment and turbidity reduction projects in the Esopus Creek watershed, NY. Proceedings of the 2023 SEDHYD Conference, St. Louis, Missouri.

Effects of a large flood on sediment and turbidity reduction projects in the Esopus Creek watershed, NY

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Abstract

On December 24-25, 2020, 7.3 to 14.6 cm of rain fell on a large snowpack in the upper Esopus Creek (UEC) watershed in the Catskill Mountains of New York. The resulting flood had an annual exceedance probability (AEP) of 4 to 20% (recurrence intervals of 25 to 5 years) in streams across the watershed, resulted in substantial geomorphic adjustments in some stream channels, and transported the highest sediment concentrations observed since stream restoration projects in the UEC began in 2012. The largest flooding occurred in the Stony Clove Creek subbasin of the UEC which contains 8 sediment and turbidity reduction projects.

The UEC is the primary water source for the Ashokan Reservoir, part of New York City's unfiltered water-supply system. A network of 16 turbidity-only and 13 suspended sediment and turbidity monitoring stations has been in operation within the UEC since October 2016. One of the primary purposes of this monitoring network is to investigate changes in suspended-sediment concentrations (SSC) and turbidity resulting from sediment and turbidity reduction projects (STRPs) implemented in tributaries to the UEC between 2012 and 2018. During the 2 to 8 years following the installation of the projects and prior to the 2020 flooding, declines in SSC and turbidity were measured at all monitoring sites although there were no flows that exceeded a 50% AEP flood. The flood of December 2020 had a 4-percent AEP at the subbasin outlet (Stony Clove Creek below Ox Clove at Chichester NY, USGS station number 01362370) and provided an opportunity to assess the effectiveness of the STRP following a large flood.

An order of magnitude increase in suspended-sediment concentration per unit discharge was measured at the outlet of the Stony Clove Creek subbasin following the flood. Increased SSC persisted for 3 months throughout the range in discharge and for at least 1 year at high discharges following the flood. The concentration-discharge relation returned to near pre-flood levels at low discharges but continued to remain above pre-flood levels at high discharges for more than 1 year. Mapped bank erosion increased in all Stony Clove subbasins following the flood and increases in stream contact with clay-rich glacial till and lacustrine sediments were greater relative to increases in contact with alluvium. Large increases in sediment concentration were observed where contact with glacial lacustrine material also increased. Minor increases in sediment concentration per unit discharge were measured from stream reaches where STRP were constructed and substantially less erosion was noted within those reaches relative to non-STRP reaches, though some breaches in revetments were noted.

Introduction

Low-frequency, high-magnitude floods can transport disproportionately high suspended-sediment loads (Hicks et al., 2000; Mano et al., 2009; Yellen et al., 2014) and cause substantial geomorphic adjustments in stream channels (Dethier et al., 2016; Gartner et al., 2015; Magilligan et al., 2015). Increases in suspended-sediment loads from these rare events can approach an order of magnitude or more (Hicks et al., 2000; Yellen et al., 2014) and single events can account for a majority of the annual suspended-sediment loads (Mano et al., 2009; Mukundan et al., 2013). New and reactivated erosion resulting from these events can result in mass wasting where the channel is in contact with hillslopes and increased sediment inputs for months to years after the event (Dethier et al., 2016). Even relatively short duration events can have significant and pervasive effects if the magnitude of the event is large enough (Magilligan et al., 2015).

Large storms in the Ashokan Reservoir watershed have resulted in suspended-sediment concentrations (SSC) that remain above pre-storm levels for up to two years (McHale and Siemion, 2014). The Ashokan Reservoir, located in the Catskill Mountains of New York, USA, is part of the New York City unfiltered water supply system. The system provides drinking water to more than 9 million users each day. Suspended-sediment concentration and turbidity are principal water quality concerns in Esopus Creek, the primary tributary to the Ashokan Reservoir. An estimated 80% of the suspended-sediment load was transported to the Ashokan Reservoir in 4% of the time from 2003 to 2011 (Mukundan et al., 2013). Extended periods of high turbidity can require chemical treatment of the water supplied by the Ashokan Reservoir or result in a temporary loss of reservoir use.

Between 2012 and 2016 eight sediment and turbidity reduction projects (STRPs) were implemented in Stony Clove Creek, a subbasin of the Esopus, to decouple the stream channel from glacial legacy sediment (NYCDEP, 2022; Wang et al., 2021). The source of suspended sediment to upper Esopus Creek is primarily fine sediment stored in channel alluvium and discrete locations of channel contact with glacial legacy sediment (NYCDEP, 2022). The fine sediment is composed primarily of clay minerals (Effler et al., 1998; Gelda et al., 2009). The reach scale erosion into the glacial legacy sediments is similar to other steep, glaciated basins in the region and can yield suspended sediment long after the event leading to chronic turbidity production (Dethier et al., 2016; Underwood et al., 2021; Yellen et al., 2014). The locations for implementation of STRPs in the Stony Clove subbasin were based on observed sources of turbidity after a series of floods in 2010 and 2011. Analysis of SSC and turbidity monitoring results through September 2020 found the STRPs were effective at reducing SSC and turbidity at the subbasin scale and possibly at the Ashokan Reservoir watershed scale (NYCDEP, 2022; Siemion et al., 2016; Wang et al., 2021).

A National Weather Service Public Information Statement estimated 7.3 to 14.6 cm of rain fell on a large snowpack in the Esopus Creek watershed between December 24 and 25, 2020. The resulting peak discharges on the Esopus Creek and its tributaries had annual exceedance probabilities (AEP) ranging between 4 and 20% (Graziano and Siemion, 2022). The AEP and peak runoff were much greater in Stony Clove Creek than in other Esopus Creek subbasins. The event runoff damaged monitoring equipment and highway infrastructure and resulted in substantial erosion and other geomorphic adjustments in some stream channels and adjacent hillslopes. The event also resulted in the highest SSC and turbidity measured at most monitoring locations in the Esopus Creek watershed since the runoff associated with the remnants of

Hurricane Irene in 2011. SSC and turbidity remained above pre-event conditions for months after the flood.

The December 2020 flood caused an order of magnitude increase in SSC throughout the Stony Clove Creek subbasin and provided an excellent opportunity to assess the resilience of STRPs in the Stony Clove subbasin that had not previously experienced a peak discharge with an AEP greater than 50%. This study sought to answer the following questions:

1) Were the STRPs able to prevent the stream from reconnecting with glacial legacy sediment within the project reaches?
2) If the STRP reaches did not revert to sediment sources, then what were the sources of the suspended sediment within the subbasin?

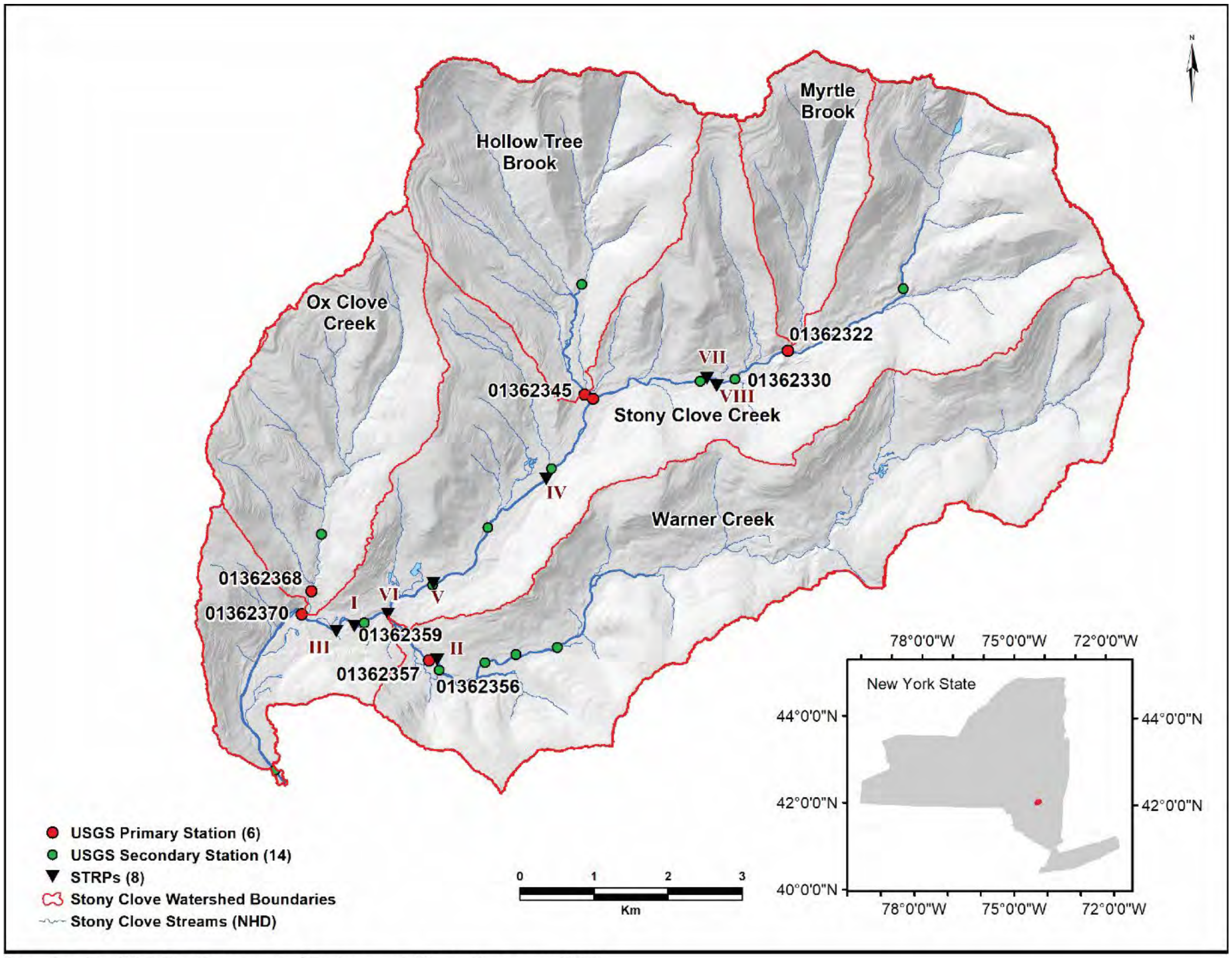
Methods and Site Description

Site Description

The upper Esopus Creek is a 497 km^2, mountainous, mostly forested watershed located in the east-central Catskill Mountains in New York. Stony Clove Creek is the largest tributary to the Esopus Creek, with a subbasin draining an area of 83.9 km^2 (Figure 1). Surficial geology of this region of the Catskill Mountains is primarily a complex distribution of Pleistocene glacial and proglacial deposits variably covered or replaced in stream valleys by Holocene alluvium and colluvium (Cadwell and Skiba, 1986; Davis et al, 2009; Rich, 1935). Glacial legacy sediment in the study area can be classified into three suspended sediment (turbidity) source categories: 1) pro-glacial lake deposits primarily composed of lacustrine clay and silt (referred to as lacustrine sediment hereafter), 2) silt/clay-rich glacial tills (referred to as glacial till hereafter), and 3) glacial meltwater deposits which are typically more coarse grained than the lacustrine and till deposits (NYCDEP, 2022; Rich, 1935). The focus of this study is on the silt and clay sized sediments that may be transported to the Ashokan Reservoir. It is assumed that the coarser-grained meltwater deposits may be entrained locally but are not a major contributor to reservoir loading. Colluvium derived from mass-wasted glacial legacy sediment is an additional fluvial sediment source along hillslope-confined channel reaches. Holocene stream bank alluvium is the most ubiquitous potential source of suspended sediment yet is poor in silt and clay content relative to glacial legacy deposits (NYCDEP, 2022). There are other suspended sediment sources such as road runoff and soil erosion, however, limited sediment fingerprinting (Staub et al, 2022) and extensive field observations during flood conditions indicate that sources in contact with the channel and in-stream storage of fine sediment account for most of the sediment in suspension.

There were 6 primary monitoring stations in the Stony Clove watershed where stream discharge, SSC and turbidity were monitored, as well as 14 secondary monitoring stations where turbidity was monitored (Figure 1). These monitoring stations were arranged to provide data at 1) the outlet of the Stony Clove subbasin, 2) the outlets of the 4 primary tributaries to Stony Clove Creek, and 3) upstream and downstream of each STRP (Figure 1). In addition, there was extensive geomorphic mapping in the Stony Clove subbasin before and after the December 2020 flood. This analysis focuses on SSC, turbidity and channel geomorphic response at 4 STRPs constructed in the Stony Clove and 1 in Warner Creek, a tributary to Stony Clove (Figure 1). The analysis is confined to the geomorphic response at 3 additional STRPs where water quality data were not available because of equipment damage during the flood.

The analysis focuses on STRP I, III, VII, and VIII in Stony Clove Creek, and on STRP II in Warner Creek (Figure 1). STRP I and III were implemented within one monitoring reach and treated the largest exposure of glacial legacy sediment in Stony Clove Creek. STRP VII and VIII were implemented within one monitoring reach approximately 10 km upstream of STRP I and III. STRP II treated the largest exposure of glacial legacy sediment in Warner Creek. The STRPs were designed to disconnect the channel from glacial legacy sediment sources. The STRP work included channel realignment, grade control with constructed riffles or steps, planform control with revetment or bioengineering, in-stream hydraulic structures (e.g., cross vanes), restoring stream connectivity to the floodplain, disconnecting channels from hillslopes, hillslope stabilization through regrading/improving drainage/restoring vegetation cover, and riparian planting (Figure 2).



Base from New York City Department of Environmental Protection 1 meter DEM
Universal Transverse Mercator, Zone 18N
North American Datum of 1983

Figure 1. Map of the study area showing locations of Stony Clove Creek, Stony Clove Creek subbasins, U.S. Geological Survey (USGS) water-quality monitoring stations, and sediment and turbidity reduction projects (STRPs), New York, USA. Roman numerals refer to specific STRPs.

Figure 2. Images of Warner Creek from before (2012, left) and after (2013, right) construction of sediment and turbidity reduction project II (STRP II).

Field Methods

Discharge at primary monitoring stations was reported at 15-minute intervals according to methods in Sauer and Turnipseed (2010) and Turnipseed and Sauer (2010). Discharge for Hollow Tree Brook at State Highway 214 at Lanesville NY (USGS station number 01362345) was estimated from an upstream station as described in Siemion (2023). Turbidity was measured at 15-minute intervals with Forest Technology Systems DTS-12 turbidity probes (Wagner et al., 2006). Water samples were collected for analysis of SSC according to methods in Edwards et al. (1999) throughout the range in discharge and turbidity from 2010 through 2021 (Siemion et al., 2016; Siemion et al., 2021) at Stony Clove Creek below Ox Clove at Chichester, NY, and from 2016 through 2021 at all primary locations. More than 300 samples were collected at the Stony Clove primary monitoring station from 2010 to 2021. At the 6 primary monitoring locations, automated pumping samplers were used to collect point samples during storms at predetermined rates of change in stream stage and channel cross-section samples were collected using the equal-width-increment (EWI) method by either wading at the measurement section or from a nearby bridge using depth integrating, isokinetic samplers appropriate for the observed conditions (U.S. Geological Survey, 2006). Cross-section and point samples were analyzed for SSC at either the USGS Ohio-Kentucky-Indiana Water Science Center or the Cascades Volcano Observatory sediment laboratories using methods described in Guy (1969). Paired cross-section and point sample concentrations were used to correct any bias in point sample concentrations. Turbidity-SSC regression equations were developed for each primary monitoring station to estimate SSC at 15-minute intervals (Siemion et al., 2021). Discrete and regression-derived continuous water-quality data are available through the USGS National Water Information System (U.S. Geological Survey, 2016).

Sources of suspended sediment were investigated in the field through a comparative analysis of channel-reach mapping before and after the December 2020 flood at four of the five monitored streams in the Stony Clove subbasin (NYCDEP, 2022). Data were only recorded where erosional features in contact with the stream were observed. Hollow Tree Brook was not assessed prior to the flood and had only limited post-flood mapping to assess a significant new source of sediment. The section of Stony Clove Creek below the most downstream monitoring location (USGS station number 01362370) was not mapped after the flood so was not included in the comparative analysis. Total assessed channel length for comparing pre- and post-flood was 18.25 kilometers (NYCDEP, 2022). Mapping included using GPS instruments (Trimble Geo-

XH), capable of centimeter to meter scale resolution, to record the spatial extents of bank erosion. Alluvium, glacial till, and lacustrine sediment were identified in the field by sediment size distribution and erodibility characteristics. Alluvium was identified as a stream sorted unconsolidated deposit composed principally of sand to small boulder size material with interstitial finer grained sediment. Glacial till was identified as an unsorted and typically over-consolidated aggregation of sediment ranging in size from clay to boulders with coarser sediment embedded in a dense silt-clay matrix. Lacustrine sediment was identified as stratified and cohesive layers of clay, silt and some sand deposited subaqueously in impounded glacial meltwater. Lacustrine sediment is commonly exposed along the toe of eroding stream banks and as distinct layers in mass wasting hillslopes. Points collected in the field were subsequently concatenated in a GIS platform into line and area features defined by similarity in point attributes. The same personnel conducted the stream mapping before and after the flood to help minimize subjective bias in feature mapping.

Statistical Methods

Sediment source geomorphic metrics were derived from field mapped data. A streambank erosion index (EI_{Bnk}) representing the percentage of the channel length in contact with erodible sediment was computed as the mapped bank erosion length divided by the total length of assessed stream channel. Bank erosion was classified into three sediment contact categories to represent whether the mapped bank erosion included contact with alluvium, glacial lacustrine or glacial till. Dominance of lacustrine sediment or glacial till was determined based on the relative proportion by mapped length.

All statistical analyses were conducted in the R statistical environment using the dplyr, dataRetrieval, compute.es, effect, multcomp, pastecs, WRS2, and car packages (R Core Team, 2013). Discharge and water-quality data at the subbasin scale from the Stony Clove Creek below Ox Clove at Chichester monitoring station (USGS station number 01362370) were divided into 4 time periods for analysis: October 1, 2020-December 23, 2020 (pre-flood), December 24, 2020-March 31, 2021 (post-flood 1), April 1, 2021-September 30, 2021 (post-flood 2), and October 1, 2021-March 31, 2022 (post-flood 3). The analysis was conducted on data from Stony Clove Creek (USGS station number 01362370) for 3 months prior to the December 2020 flood and 3 time periods post-flood; and 3 months pre- and post-flood at tributary streams Ox Clove (01362368), Warner Creek (01362357), Hollow Tree Brook (01362345), and Myrtle Brook (01362322). The non-parametric Kruskal-Wallis test was used to test for significant differences in SSC between multiple time periods before and after the December 2020 flood. The relation between discharge and SSC was analyzed using an analysis of covariance (ANCOVA) on log10 transformed data to control for the effects of discharge between time periods. Levene's test was used to test the assumption of similar variance between experimental conditions (Levene, 1960). An analysis of variance was used to check that the covariate did not vary significantly across levels of the predictor variable. The ANCOVA was run using daily mean SSC or turbidity as the dependent variable, daily mean discharge as the covariate, and a time factor that separated the dataset into 4 time periods. The ANCOVA was re-run to test the assumption of homogeneity of regression slopes by including the interaction of the time factor and the covariate. The assumptions were not met in any of the ANCOVA analyses, so a robust ANCOVA (Wilcox, 2005) was used.

Results

Changes in Suspended-Sediment Concentration or Turbidity

Discharge and water-quality data at the subbasin scale from the Stony Clove below Ox Clove at Chichester monitoring station (USGS station number 01362370) were analyzed to determine if there were significant differences in the relation between discharge and SSC for the pre- and 3 post-flood periods. The non-parametric Kruskal-Wallis test indicated daily mean SSC was different in at least one of the time periods tested. Robust ANCOVA tests were conducted between consecutive time periods to investigate changes in the slope and intercept of the daily mean discharge-SSC regression equations (Figure 3, Table 1). There was a significant decrease in slope and increase in the intercept ($\rho < 0.05$) from the pre-flood period to the post-flood 1 period. The result was approximately an order of magnitude increase in SSC per unit discharge from the pre- to post-flood 1 period through the range in discharge monitored during the periods. The slope significantly increased, and the intercept significantly decreased during the two subsequent post-flood periods. This indicates SSC decreased at lower discharges during the latter two post-flood periods but remained above pre-flood values at high discharge.

Table 1. Slope, intercept, adjusted coefficient of determination, and residual standard error for regression equations for daily mean discharge-daily mean turbidity regression equations (01362322, 01362345, and 01362368) and daily mean discharge-daily mean suspended-sediment concentration (SSC) (USGS station numbers 01362357 and 01362370). All slopes were significant at the $\rho < 0.05$ level except for Hollow Tree Brook [n = number of mean daily pairs in regression; r^2 = adjusted coefficient of determination; rse = residual standard error].

Monitoring Location (USGS station number)	Time Period	Slope	Intercept	n	r^2	rse
Stony Clove (01362370)	10/1/2020-12/23/2020	0.72	-1.0	84	0.58	0.19
Stony Clove (01362370)	12/24/2020-3/31/2021	0.49	0.95	98	0.48	0.21
Stony Clove (01362370)	4/1/2021-9/30/2021	1.02	-0.86	183	0.68	0.24
Stony Clove (01362370)	10/1/2021-3/31/2022	1.23	-1.45	182	0.70	0.24
Ox Clove (01362368)	10/1/2020-12/23/2020	0.48	0.22	82	0.60	0.17
Ox Clove (01362368)	12/24/2020-3/31/2021	0.13	1.78	84	0.17	0.16
Warner Creek (01362357)	10/1/2020-12/23/2020	0.73	-0.73	84	0.48	0.24
Warner Creek (01362357)	12/24/2020-3/31/2021	0.40	0.90	98	0.37	0.22
Hollow Tree Brook (01362345)	10/1/2020-12/23/2020	-0.07	0.92	84	0.01	0.13
Hollow Tree Brook (01362345)	12/24/2020-3/31/2021	0.12	2.31	98	0.03	0.20
Myrtle Brook (01362322)	10/1/2020-12/23/2020	0.74	-0.72	38	0.68	0.20
Myrtle Brook (01362322)	12/24/2020-3/31/2021	0.97	-0.02	73	0.54	0.39

A paired sample t-test of reach scale data indicated a significant ($p<0.05$) increase in daily mean turbidity during the first 3 months after the flood (post-flood 1 period) through the stream reach where STRP I and III were constructed (Figure 4). Prior to the flood, the mean difference from above to below the reach was 11 Formazin Nephelometric Units (FNU). The mean difference post flood period 1 was 24 FNU, which equates to an estimated 23 mg/L increase using the turbidity-SSC regression equation from Stony Clove Creek below Ox Clove at Chichester (USGS station number 01362370) (Siemion et al., 2021). There was also a statistically significant decrease in turbidity of 1.46 FNU through the STRP VII and VIII reach during post-flood period 1 equating to an approximate decrease of 1.4 mg/L using the turbidity-SSC regression equation from Stony Clove at Jansen Road (USGS station number 01362336) 1.5 km downstream. Prior to the flood there was an increase in turbidity of 1.3 FNU through the STRP VII and VIII reach. There was a significant decrease in turbidity of 14.2 FNU through the STRP II reach in Warner Creek during post flood period 1, equating to a change in SSC of approximately 9.7 mg/L using the turbidity-SSC regression equation for Warner Creek (USGS station number 01362357).

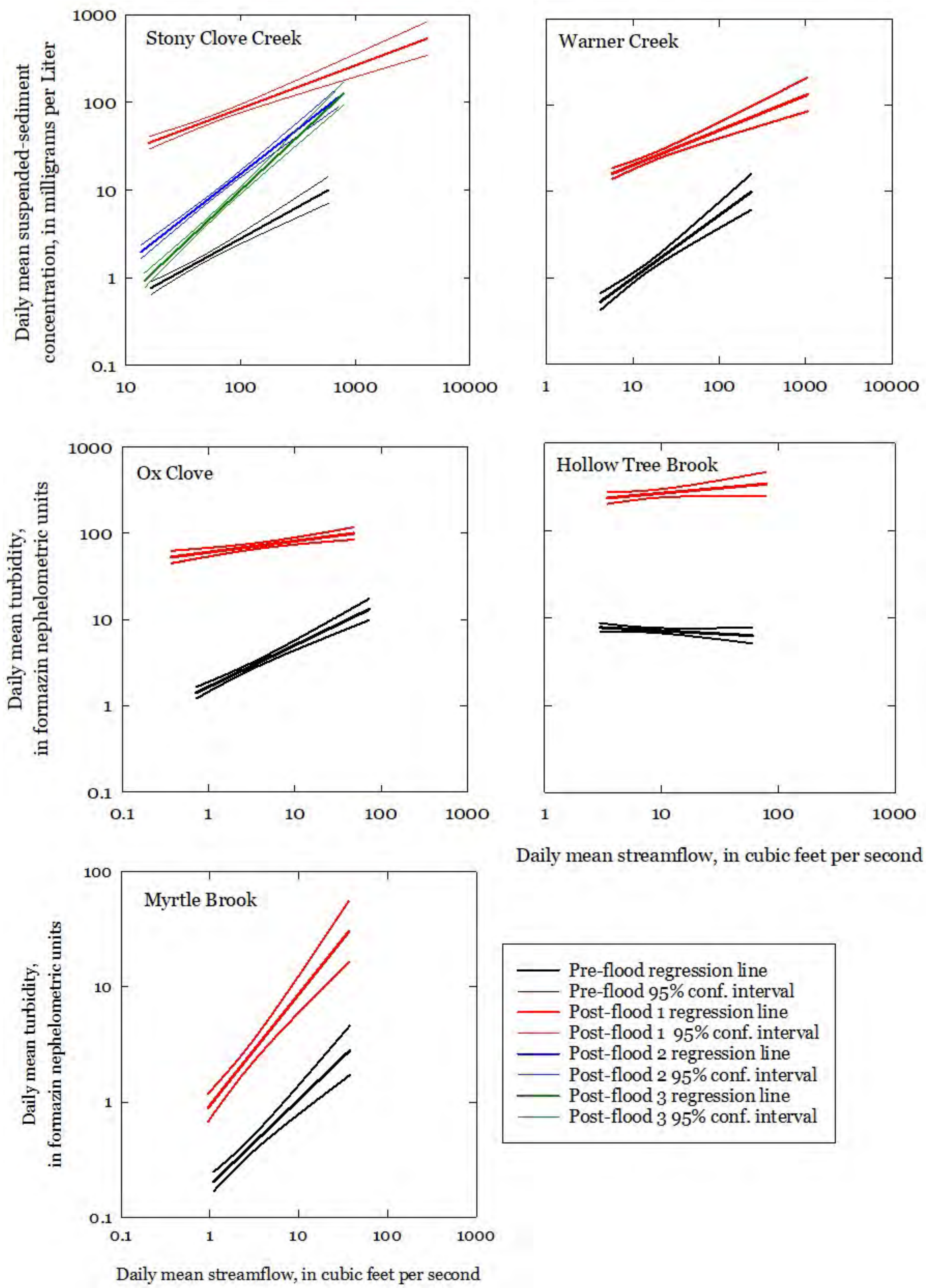


Figure 3. Daily mean suspended-sediment concentration or turbidity as a function of daily mean discharge at Stony Clove Creek (USGS station number 01362370) for 3 months prior to the December 2020 flood and 3 time periods post-flood; and 3 months pre- and post-flood at tributary streams Ox Clove (01362368), Warner Creek (01362357), Hollow Tree Brook (01362345), and Myrtle Brook (01362322).

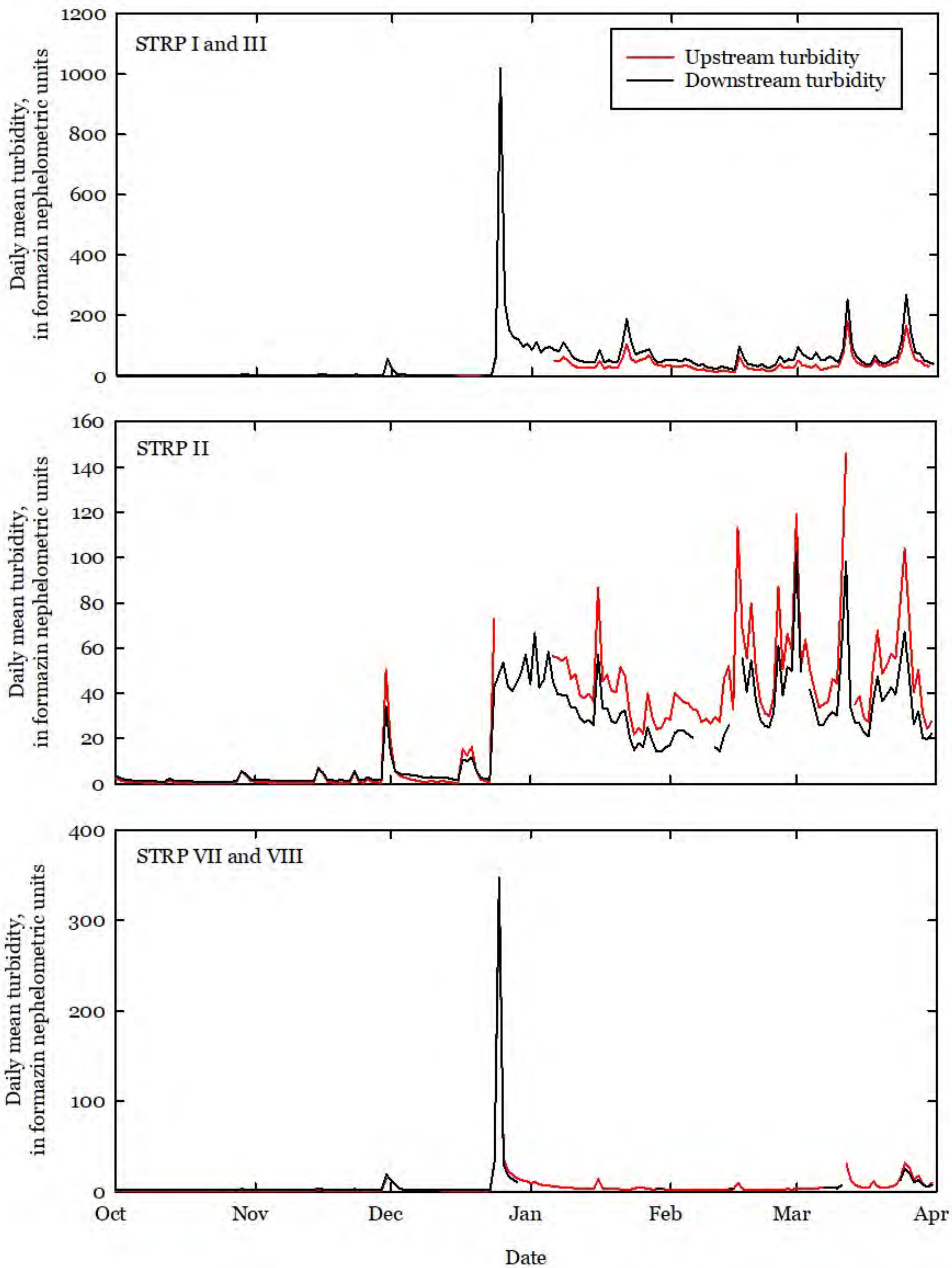


Figure 4. Daily mean turbidity upstream and downstream of sediment and turbidity reduction projects (STRPs) for 3 months prior to the December 2020 flood and 3 months post-flood.

There were significant changes in SSC per unit discharge at each of the tributaries to Stony Clove Creek from the pre-flood to the post-flood periods (Figures 1 and 3). The discharge-SSC relation for Warner Creek (USGS station number 01362357) was based on daily mean discharge-daily mean SSC. The discharge-SSC relations at Ox Clove, Hollow Tree Brook, and Myrtle Brook (USGS station numbers 01362368, 01362345, and 01362322, respectively) were based on daily mean discharge-daily mean turbidity because daily mean SSC was not available for those monitoring stations during the study period. The slope of the discharge-SSC relation significantly decreased and intercepts significantly increased at Ox Clove and Warner Creek after the flood. The slope and intercept at Myrtle Brook both increased, though only the increase in slope was significant. The slope did not significantly increase while the intercept significantly increased at Hollow Tree Brook.

Geomorphic Changes

Combined bank erosion, hillslope erosion, and contact with glacial legacy sediment increased in all monitored streams because of the December 2020 flood (Figure 5). EI_{Bnk} increased by factors of 3.5 in Stony Clove Creek and up to 5.6 in Myrtle Brook. Erosional contact with glacial till or lacustrine sediment increased substantially in each mapped stream. A 248% increase in active bank erosion was measured in Stony Clove Creek; however, the alluvium to glacial legacy sediment ratio did not change as dramatically (0.32 for 2018; 0.37 for 2021). Ox Clove showed the greatest increase in contact with lacustrine sediment from 17% in 2019 to 52% in 2021, an order of magnitude increase in contact length. The amount of bank erosion in glacial till and lacustrine sediment decreased in Warner Creek, while the lacustrine sediment to glacial till ratio decreased markedly after the flood because there was a large increase in glacial till contact (Figure 5). Myrtle Brook had no mapped active contact with glacial till or lacustrine sediment prior to the December 2020 flood. However, 39% of the channel length was in contact with glacial till following the flood. Hollow Tree Brook was not mapped prior to the flood and limited post-flood mapping was conducted because of site access and logistical challenges. However, field observations indicate nearly 1 meter of downcutting of the Hollow Tree Brook channel took place during the flood with incision into lacustrine sediment material forming a "clay canal" (NYCDEP, 2022).

Pre- and post-flood mapping was conducted at each STRP. Increased contact with eroding alluvium was measured at 3 STRPs, with glacial till at 3 STRPs, and with lacustrine sediment at 2 STRPs (Table 2). The proportion of new bank erosion to stable banks in the STRPs was less than that observed throughout the mapped Stony Clove Creek and Warner Creek in non-STRP reaches. The mean increase in EI_{Bnk} in the STRPs was 8% with a range of 0 to 22% compared to a mean increase in EI_{Bnk} of 24% with a range of 19 to 28% for non-STRP reaches. Future contact with lacustrine sediment in the STRP reaches is possible at greater than bankfull discharge but is unlikely at lower discharge.

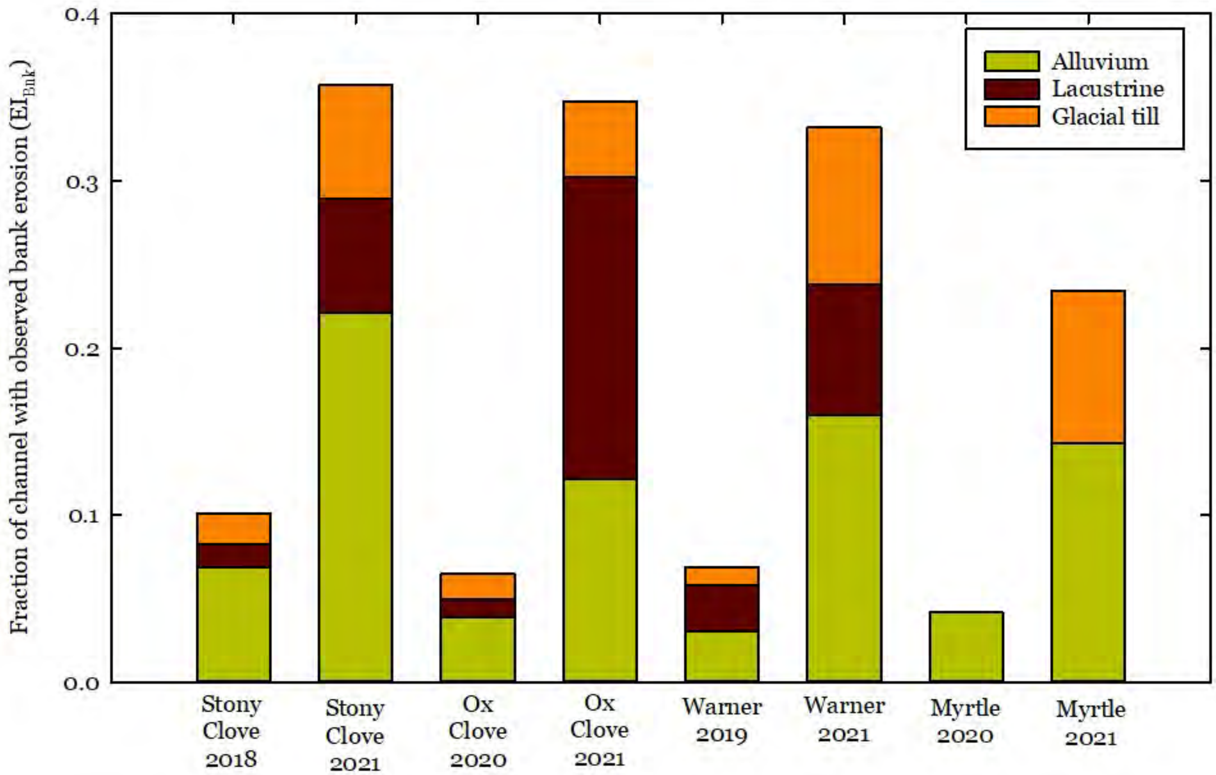


Figure 5. Pre- and post-flood observed bank erosion and associated sediments for non-sediment and turbidity reduction project (STRP) reaches on Stony Clove Creek and three tributaries. EI_{Bnk} = streambank erosion index.

Table 2. Change in erosional index following the flood and notes from stream feature inventories for sediment and turbidity reduction projects (STRPs) in the Stony Clove Creek subbasin [m = meters; AL = alluvium; LS = lacustrine sediment; Q = discharge; Q_{bf} = bankfull discharge; GT = glacial till; NONE = no contact with sediment sources].

STRP	STRP Length (m)	Sediment Source	Change in EI_{Bnk}	Notes
I	198	AL, LS	0.22	Breached revetment exposes construction fill and mass-wasted LS; contact only at $Q > Q_{bf}$
II	244	AL	0.17	Some breached revetment and erosion into fluvial terrace
III	411	LS, GT	0.11	Breached revetment along left channel margin; resumed contact with GT and LS is at $Q > Q_{bf}$
IV	518	GT	0.02	Expanded exposure of GT in right channel margin and numerous clustered exposures of GT in bed
V	139	NONE	0	Hillslope has exposed and mass wasting mix of GT and LS disconnected from channel by rock wall; slope runoff contributes suspended sediment
VI	396	AL, GT	0.12	Substantial increase in bank and bed erosional contact with GT; sheet pile grade control structures more exposed; headcut at upstream end of Warner Creek project reach
VII and VIII	815	NONE	0	Increased erosion into AL in reach between two treated sections; some increased in-channel deposition

Discussion

The December 2020 flood resulted in an order of magnitude increase in SSC per unit discharge at the Stony Clove Creek monitoring station near the outlet of the subbasin (Figures 1 and 3). This change was similar to the effects of the remnants of Hurricane Irene in 2011 on mountain streams of the northeast USA (Yellen et al., 2014). The 2020 flood exceeded stabilizing geomorphic thresholds along the channels and forced geomorphic adjustment throughout the Stony Clove subbasin resulting in large increases in the proportion of channel length in contact with glacial legacy sediment (Figure 5), similar to geomorphic adjustments caused by the remnants of Hurricane Irene in the northeast USA (Dethier et al., 2016). There was a significant increase in the intercept of the discharge-SSC relation during post flood period 1 (Table 1) and a corresponding increase in EI_{Bnk} (Figure 5). The concurrent decrease in slope of the discharge-SSC relation indicates the increase in SSC was proportionally greater during lower discharge and somewhat less at the higher discharge (Table 1; Figure 3). Although the rating returned close to pre-flood levels at lower discharges during post-flood periods 2 and 3, the concentration per unit discharge remained elevated at higher discharges(Figure 3). These results suggest that as the channels recovered after the flood, stream channel contact with new sediment sources decreased at lower discharge but continued at higher discharge.

These results indicate that the increase in sediment transport within the Stony Clove subbasin following the flood did not originate from the monitored STRP but rather from other reaches in the subbasin. Analysis of the upstream-downstream turbidity data from post-flood period 1 shows a statistically significant 23 mg/L increase through the STRP I and III reach, however the other monitored STRP reaches did not show a similar increase in concentration. The increase in concentration through the STRP I and III reach was far less than the 100 mg/L increase in sediment concentration measured at the outlet of the subbasin during the first 3 months post flood. Turbidity data were not available from all STRPs because of instrument damage resulting from the flood, leaving the possibility that the sediment originated from an unmonitored reach. However, the channel reach mapping conducted pre- and post-flood within the STRPs indicate that this is not the case (Table 2). Although there was bank erosion observed at nearly all STRPs after the flood (EI_{Bnk} 0 to 0.22), it was less than that measured throughout the Stony Clove and its tributaries (EI_{Bnk} 0.23 to 0.35) with little resumed contact with glacial till and lacustrine sediment. The increased contact with glacial legacy sediment within the STRPs was limited to breaches in revetment covering glacial legacy sediment. Furthermore, the breaches in the revetment within the STRPs were generally at or above bankfull discharge stage which would not account for the increase in sediment concentration through the range in discharge. Outside the STRPs there was a substantial increase in the amount of channel length in contact with clay rich glacial till and lacustrine sediment and sediment concentration per unit discharge increased by nearly an order of magnitude in the four tributary streams during the first 3-months post-flood (Figure 3).

The Ox Clove tributary had the largest increase in the proportion of channel length in contact with lacustrine sediment of any of the tributaries following the 2020 flood (Figure 5). The dominant suspended sediment source in Ox Clove shifted from alluvium to glacial legacy sediment and the stream showed the largest increase in SSC at low to moderate discharges of any of the tributaries (Figures 3 and 5). Indeed, Ox Clove became a chronic source of fine-grained suspended sediment after the flood, producing higher turbidity through the range in discharge (Figures 3 and 5) relative to pre-flood conditions. The contact with glacial legacy sediment in Warner Creek shifted from more easily erodible lacustrine sediment before the flood to glacial till after the flood. There was a significant increase in contact with glacial till in the bed and banks of Warner Creek a short distance upstream of the confluence with Stony Clove Creek where the stream incised nearly a meter into glacial till. Nonetheless, the increase in sediment concentration per unit discharge in Warner Creek was less than that of Ox Clove at low to moderate discharge. The difference in SSC between the two tributaries may be in part related to how contact with sediment sources changed in the two streams: in Ox Clove contact with lacustrine sediment increased while in Warner Creek contact with glacial till increased (Figures 3 and 5). The lacustrine sediment is more easily eroded and contains a greater percentage of fine sediment than the glacial till. Myrtle Brook experienced the greatest increase in erosional contact per unit of mapped stream channel length of any of the tributaries (Figure 5), yet it had the smallest response in sediment concentration per unit discharge because it has the least erosional contact with glacial till or lacustrine sediment (Figure 3 and 5). These results emphasize the importance of channel surficial geology on sediment concentration per unit discharge: the largest relative increase in EI_{Bnk} amongst the tributaries resulted in the smallest magnitude increase in sediment concentration because there was a limited amount of fine sediment with which the stream could contact. If Hollow Tree Brook had been mapped prior to the flood, it is likely that we would have measured a shift in the stream sediment source from alluvium to glacial legacy sediment like that observed in Ox Clove, based on field observations and the increase in sediment concentration per unit discharge (Figure 3 and Table 1).

The December 2020 flood provided a test of the resilience of STRPs installed throughout the Stony Clove subbasin. Although there was a significant increase in sediment concentration per unit discharge throughout the subbasin, the STRPs in the Stony Clove subbasin do not appear to be the primary source of that sediment. Substantial new erosional contact with glacial legacy sediment in stream reaches outside of the STRPs was more likely the source of the prolonged post-flood SSC increase. The December 2020 flood also demonstrated that the STRPs in the Stony Clove subbasin were able to experience a 4-20% AEP flood without reverting to chronic sediment sources even though these stream reaches were the largest sources of suspended sediment prior to treatment. This result is particularly important because New York City continues to invest in STRPs as part of the agreement with regulatory agencies to maintain the unfiltered status of the water supply. Finally, the flood also forced adjustment in stream reaches that are most likely to become new chronic sources of suspended sediment and therefore primary targets for additional STRP implementation. Several of these new reaches are being monitored for continued adjustment and entrainment of turbidity source sediment.

Conclusions

The 4-percent annual exceedance flood that occurred on December 24-25, 2020 in the Stony Clove Creek subbasin caused widespread erosion and order of magnitude increases in suspended-sediment concentration per unit discharge throughout the subbasin. A comparison of channel reach mapping before and after the flood showed an increase in erosional indices with all sediment source types throughout the subbasin. The relative proportions of alluvial versus glacial legacy sediment sources changed with increased contact with clay-rich glacial legacy sediment. The dominant sediment source in contact with the stream channel switched from alluvium to glacial legacy sediment in at least one tributary stream.

Study results show that the sediment and turbidity reduction projects (STRPs) in the Stony Clove Creek subbasin were resilient with regards to the flood, especially when compared to the entire subbasin. The STRPs prevented substantial stream channel contact with glacial sediments during and after the flood, though some breaches in revetment were noted during post flood stream surveys. All the tributary channels experienced substantial erosion. However Myrtle

Brook, which experienced the greatest increase in erodible channel length per unit of stream channel length of any of the tributaries, had the smallest response in suspended-sediment concentration because it has the least channel contact with glacial legacy sediment (Figure 5). This result emphasizes the importance of understanding the proximity of the channel to fine sediment sources and to anticipate future stream contact with fine sediment sources during and after large storms.

The majority of increased suspended sediment concentrations following the flood occurred during the first three months and then steadily decreased at low discharge, although elevated SSC and turbidity relative to pre-flood conditions were measured at high discharge in the Stony Clove Creek subbasin for more than 1 year following the flood (Figure 3).

The stream monitoring data (SSC, turbidity, and discharge) and stream reach mapping data were both essential to understand the sources and mechanisms responsible for the large increase in suspended-sediment concentrations and turbidity that occurred as a result of the flood.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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