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 2019

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

Prepared by: DEP, Bureau of Water Supply

1. Introduction

The 2017 Filtration Avoidance Determination (FAD) requires the New York City Department of Environmental Protection (DEP) Stream Management Program (SMP) to continue data collection and analysis for the Esopus Creek Watershed Turbidity/Suspended-sediment Study ("the Study") initiated in 2016. The 2017 FAD further requires the SMP to submit biennial status reports on the Study findings. This is the first biennial status report and covers the period from the Study inception through 2018.

1.1 Study Overview

A collaborative 10-year Study between DEP and the U.S. Geological Survey (USGS) is underway to characterize suspended-sediment and turbidity source dynamics in the Catskill System of the New York City Water Supply, and to evaluate the efficacy of stream sediment turbidity reduction projects (STRPSs). Esopus Creek is the primary source of water to the Ashokan Reservoir and serves as the representative model fluvial system to investigate suspended-sediment and turbidity source dynamics at the basin to sub-basin scales. Stony Clove Creek is the largest tributary to Esopus Creek and serves as an experimental sub-basin system to investigate suspended-sediment and turbidity source dynamics at the reach to sub-basin scales, and STRP efficacy. The Study investigates and monitors hydrology, suspended-sediment, turbidity and geomorphology at multiple spatial scales to examine the physical conditions and causal processes influencing stream turbidity and suspended-sediment yield in the New York City Watershed.

Per the 2017 FAD, DEP submitted a Study design report detailing research objectives and methods in January 2017, which was revised in July 2017. DEP will continue to revise the Study design to incorporate modifications in methods and scope based on the first two years of the Study.

The Study started in July 2016 with the registration of a five-year agreement between DEP and USGS. USGS is responsible for (1) monitoring and analyzing stream discharge, suspended-sediment, and turbidity, and (2) pilot testing suspended-sediment fingerprinting as a source-sediment characterization technique. DEP is responsible for (1) research project coordination and reporting, (2) stream channel geologic and geomorphologic sediment source investigations, and (3) funding design, construction and monitoring of STRPs in the Stony Clove sub-basin through an agreement between DEP and the Ulster County Soil and Water Conservation District (UCSWCD). Additionally, DEP funds the Ashokan Watershed Stream Management Program (AWSMP), which further supports this Study.

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

- Using the Esopus Creek watershed as a model fluvial system, continue to characterize how watershed sub-basins vary in terms of suspended-sediment yield/turbidity. How do these differences change under a range of flow conditions and over time? How can characterization of this variability inform stream management strategies?

- Using the Stony Clove as a sample sub-basin, characterize how different stream reaches vary in terms of suspended-sediment yield/turbidity within the same sub-basin. What are the reach level conditions and processes that lead to those heterogeneous yields?
- Using the reach level characterization in the Stony Clove sub-basin, evaluate the effectiveness of strategically located STRPs. To what extent can suspended-sediment yield/turbidity associated with these sources, channel conditions and processes be sustainably managed within the stream system?

1.2 Study Area

The upper Esopus Creek watershed refers to the section of Esopus Creek above the Ashokan Reservoir in the south-central Catskill Mountains of New York State (Figure 1). The 26 mile course of the creek flows “clockwise” in a sweeping arc from the headwaters at Winnisook Lake on Slide Mountain to the Ashokan Reservoir through the Ulster County towns of Shandaken and Olive. Esopus Creek at the Ashokan Reservoir drains 192 mi^2 and is representative of the mountainous watersheds that supply water to the Ashokan and Schoharie Reservoirs comprising the Catskill System. The upper Esopus Creek watershed is a mostly forested (>90%), high relief terrain with a maximum elevation of 4,180 feet above sea level (asl) at Slide Mountain to 585 feet asl at the Ashokan Reservoir (Figure 2). There are 21 peaks with elevations ranging from 3,000 to 4,180 feet asl. As a result, the fluvial network is a high energy, coarse sediment-dominated mountain stream system with naturally and anthropogenically exacerbated erosion from flood discharge. Although storm event precipitation is the primary driver of flood hydrology, on a seasonal basis, rainfall induced snowmelt discharge has produced some of the biggest floods in the upper Esopus Creek watershed. Average annual precipitation is 47 inches.

The fluvial network includes 10 primary contributing sub-basin streams that supply water to Esopus Creek (Table 1; Figure 1). The Study monitoring network includes eight of the 10 sub-basin streams, excluding Fox Hollow and Peck Hollow.

The Catskill Mountain bedrock in the Study area is composed of a repeating sequence of sandstones, shales and, at higher elevations, conglomerates. Pleistocene glaciation mantled this bedrock with fine-grained sediment in glacial till and lacustrine (lake) deposits. The post-glacial fluvial system will continue to process this glacial legacy sediment for many thousands of years. The water quality response to this geomorphic processing is the episodically chronic to acute high turbidity levels observed in Catskill streams.

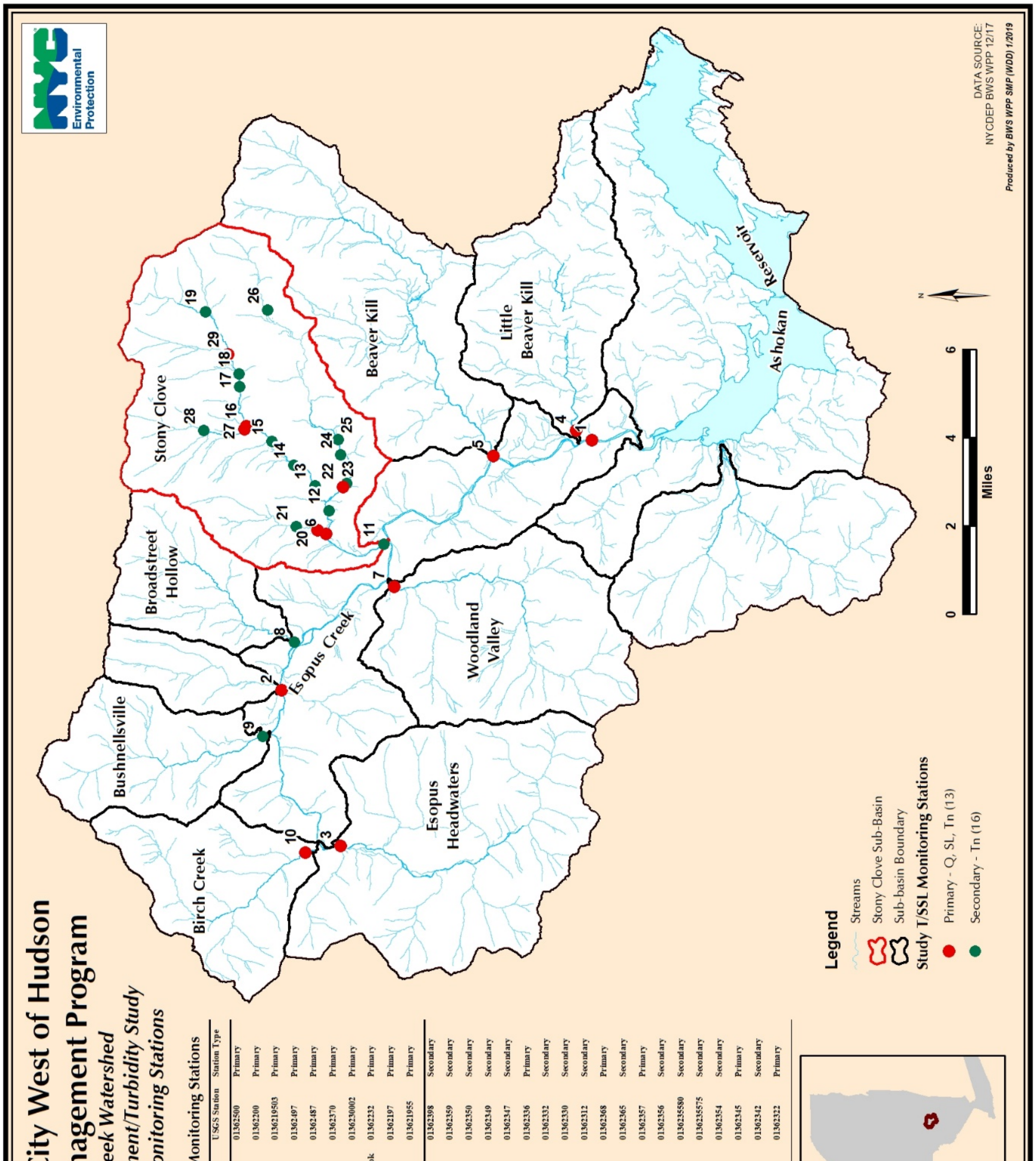

Figure 1. Upper Esopus Creek watershed study area with USGS water quality monitoring stations.

Figure 2. The upper Esopus Creek watershed looking south across the Stony Clove sub-basin toward Slide Mountain in the background.

Table 1. Upper Esopus Creek and primary contributing streams listed from upstream to downstream.

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

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

2. Study Goals and Objectives

This research aims to improve understanding of the fluvial geomorphic process-response relationship (e.g. erosion-turbidity) in a Catskill System watershed necessary to effectively site and implement STRPs. The Study objectives listed below are to quantify and characterize (1) the upper Esopus Creek watershed sub-basin to basin scale suspended-sediment/turbidity source dynamics, and (2) the Stony Clove reach to sub-basin scale suspended-sediment/turbidity source dynamics and STRP efficacy.

Discharge and water quality monitoring, and suspended-sediment source characterization in the upper Esopus Creek watershed.

Objective 1: Monitor suspended-sediment and turbidity over a range in discharge at three Esopus Creek locations and five tributary sub-basins, and monitor turbidity only at an additional two tributary sub-basins.

- All ten monitoring stations in the upper Esopus Creek watershed are installed and operational. Monitoring station locations include pre-existing stations and new stations.
- **Primary** monitoring stations are those where stream discharge, suspended-sediment concentration (SSC), and turbidity are measured (Figure 3). **Secondary** monitoring stations are those where only turbidity is measured (Figure 4).
- Suspended-sediment sampling, 15-minute interval turbidity and discharge monitoring cover most of USGS water years 2017 and 2018 (October 1, 2016 to September 30, 2018) and include some moderate flood events.

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

- USGS successfully monitored turbidity and sampled SSC at primary stations with the goal of collecting samples through the range in turbidity levels measured at each station to develop SSC-turbidity relationships.
- USGS recommends a minimum of two years of data collection before regression equations are developed. Initial review by USGS indicates adequate SSC and turbidity data is available to develop those equations. USGS plans to develop the first set of regression equations in 2019.

Objective 3: Estimate suspended-sediment loads and yields at eight locations within the upper Esopus Creek watershed

- USGS will calculate suspended-sediment load and yield for each sediment monitoring location after finalizing the sediment-discharge rating curves.

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

- UCSWCD and DEP advanced suspended-sediment source mapping using stream feature inventory (SFI) methods for four streams from 2017 to 2018.

- DEP and USGS will evaluate potential regression relations among discharge, suspended-sediment, turbidity, and geomorphic conditions after 2020 when sufficient quality assured data will be available.

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

Objective 1. Monitor suspended-sediment and turbidity over a range in discharge at two Stony Clove Creek locations and four tributary sub-basins, and monitor turbidity only for several stream reaches within the Stony Clove sub-basin.

- Six primary and 14 secondary monitoring stations in the Stony Clove watershed are installed and operational.
- Sediment sampling, turbidity and discharge monitoring covered most of USGS water year 2017 and 2018 and included some moderate flood events.

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

- In 2018, DEP developed a suspended-sediment source characterization SFI protocol that was used to map Stony Clove sub-basin sediment sources. DEP will map sediment source in the four water quality monitored Stony Clove Creek tributaries in 2019.
- DEP established eight reach-scale bank erosion monitoring sites (BEMS) between 2016 and 2018 for annual to biennial recurring topographic surveys. Investigation at these sites also includes geomorphic evaluation, stream bank sediment sampling, and hydraulic modeling.
- With support from DEP and AWSMP, USGS initiated a pilot suspended-sediment fingerprinting study in 2017 that is scheduled to be completed in 2019.

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

- In January 2019, DEP nominated three prioritized stream reaches (and two alternate reaches) that had measurable reach-scale turbidity contributions.

Objective 4. Evaluate the effectiveness of individual and combined STRPs from the reach scale to the sub-basin scale in the Stony Clove sub-basin, and the basin scale in the upper Esopus Creek watershed.

- USGS and DEP will report on the status of this objective in the first five-year Study findings report due November 30, 2022. This objective requires multiple years of monitoring data representing as broad a range of hydrologic conditions as possible.
- In 2018, USGS initiated this research objective by re-examining the sub-basin scale turbidity-discharge relationship for the primary monitoring station on Warner Creek (01362357). Preliminary assessment detects changes in the relationship first established following construction in 2013 of the only STRP in Warner Creek to date. Work will continue in 2019 and 2020 to examine the sub-basin scale relationship for the

downstream Stony Clove Creek primary monitoring station, which encompasses all eight STRPs constructed from 2012 to 2016. This will set a new baseline condition for evaluating future STRPs at the sub-basin scale.

- The limited amount of pre-construction monitoring limits reach scale evaluation for individual STRPs constructed prior to the start of the Study. The current monitoring network includes upstream/downstream monitoring station placement to capture before/after water quality data for the three proposed STRPs planned for construction in 2020 and 2021.

Figure 3. Primary water quality monitoring station 01362322 for Myrtle Brook in the Stony Clove watershed. Primary stations monitor stream discharge and turbidity at 15-minute intervals and use automated and manual sampling for suspended-sediment concentration across a range of discharge conditions.

Figure 4. Secondary water quality monitoring station 01362365 on Ox Clove Creek in the Stony Clove watershed. Secondary sites monitor turbidity at 15-minute intervals.

3. Discharge and Water Quality Monitoring

3.1 Monitoring Network

Tables 2 and 3 provide details on the 29 primary and secondary monitoring stations established for the Study area and in operation for most of the Study period. Results from the first two years of the current Study suggest the monitoring design has been successful in measuring SSC and turbidity. The 20 Stony Clove sub-basin monitoring stations delineate water quality monitoring reaches for five streams: Stony Clove Creek, Ox Clove Creek, Warner Creek, Hollow Tree Brook, and Myrtle Brook (Figure 5 and Table 4). The water quality monitoring reaches segment the monitored streams into distinct suspended-sediment loading and turbidity production sections. Suspended-sediment source characterization investigations in the Stony Clove sub-basin will yield predictive geomorphic source metrics for each water quality monitoring reach.

Table 2. Upper Esopus Creek watershed USGS monitoring stations listed from upstream to downstream.

Station name	USGS station ID	Station type	Measurements
Esopus Cr bl Lost Clove @ Big Indian	0136219503	Primary	Discharge, SSC, Turbidity
Birch Cr @ Big Indian[1]	013621955	Primary	Discharge, SSC, Turbidity
Bushnellsville Creek at Shandaken	01362197	Secondary	Estimated Discharge, Turbidity
Esopus Cr @ Allaben[1]	01362200	Primary	Discharge, SSC, Turbidity
Broad Street Hollow Brook at Allaben	01362232	Secondary	Estimated Discharge, Turbidity
Woodland Cr abv mouth @ Phonecia[1]	0136230002	Primary	Discharge, SSC, Turbidity
Stony Clove Cr blw Ox Clove @ Chichester[1]	01362370	Primary	Discharge, SSC, Turbidity
Beaver Kill @ Mt Tremper	01362487	Primary	Discharge, SSC, Turbidity
Little Beaver Kill at Beechford nr Mt Tremper[1]	01362497	Primary	Discharge, SSC, Turbidity
Esopus Cr at Coldbrook[1]	01362500	Primary	Discharge, SSC, Turbidity

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

Table 3. Stony Clove sub-basin USGS monitoring stations listed from upstream to downstream.

Station name	USGS station ID	Station type	Measurements
Stony Clove Cr @ Edgewood	01362312	Secondary	Estimated discharge*, Turbidity
Myrtle Br @ SR 214 @ Edgewood	01362322	Primary	Discharge, SSC, SSL, Turbidity
Stony Clove Cr nr Lanesville	01362330	Secondary	Estimated discharge, Turbidity
Stony Clove Cr @ Wright Rd nr Lanesville	01362332	Secondary	Estimated discharge, Turbidity
Stony Clove Cr @ Jansen Rd @ Lanesville	01362336	Primary	Discharge, SSC, SSL, Turbidity
Hollow Tree Br @ SR 214 @ Lanesville	01362345	Primary	Estimated discharge, SSC, SSL, Turbidity
Hollow Tree Br @ Lanesville[1]	01362342	Secondary	Discharge, Turbidity
Stony Clove Cr @ Lanesville	01362347	Secondary	Estimated discharge, Turbidity
Stony Clove Cr abv Moggre Rd nr Chichester	01362349	Secondary	Estimated discharge, Turbidity
Stony Clove Cr @ Chichester	01362350	Secondary	Estimated discharge, Turbidity
Warner Cr blw Silver Hollow Notch nr Edgewood	01362354	Secondary	Estimated discharge*, Turbidity
Warner Cr nr Carl Mountain nr Chichester	0136235575	Secondary	Estimated discharge*, Turbidity
Warner Cr in Silver Hollow nr Chichester	0136235580	Secondary	Estimated discharge, Turbidity
Warner Cr @ Silver Hollow Rd nr Chichester	01362356	Secondary	Estimated discharge, Turbidity
Warner Cr nr Chichester	01362357	Primary	Discharge, SSC, SSL, Turbidity
Stony Clove Cr @ Silver Hollow Rd, Chichester	01362359	Secondary	Estimated discharge, Turbidity
Ox Clove @ Chichester	01362365	Secondary	Discharge, Turbidity
Ox Clove nr mouth @ Chichester	01362368	Primary	Estimated discharge, SSC, SSL, Turbidity
Stony Clove Cr blw Ox Clove @ Chichester[1]	01362370	Primary	Discharge, SSC, SSL, Turbidity
Stony Clove Cr abv SR 214 @ Phoenicia	01362398	Secondary	Estimated discharge, Turbidity

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

Table 4. Stony Clove watershed water quality monitoring reaches delineated by USGS water quality monitoring stations. Stream lengths rounded to the nearest foot.

WQM Reach	Length (ft)	Downstream station[1]	Upstream station[1]	STRP[2]	Drainage area[3] (mi^2)
SC_WQM_01	840	None	01362398	F	32.3
SC_WQM_02	8,855	01362398	01362370	F	32.3 - 30.9
SC_WQM_03	3,589	01362370	01362359	T	30.9 - 26.6
SC_WQM_04	3,875	01362359	01362350	F	26.2 - 16.8
SC_WQM_05	4,003	01362350	01362349	T	16.8 - 15.9
SC_WQM_06	4,121	01362349	01362347	T	15.9 - 14.3
SC_WQM_07	3,894	01362347	01362336	F	14.3 - 8.8
SC_WQM_08	5,420	01362336	01362332	F	8.8 - 7.9
SC_WQM_09	1,608	01362332	01362330	T	7.9 - 7.4
SC_WQM_10	9,498	01362330	01362312	F	7.4 - 2.2
SC_WQM_11	8,763	01362312	None	F	2.2 - 0
WC_WQM_01	2,822	None	01362357	F	9.1 - 8.6
WC_WQM_02	978	01362357	01362356	T	8.6 - 8.5
WC_WQM_03	4,619	01362356	013623558	F	8.5 - 7.3
WC_WQM_04	2,100	0136235580	0136235575	F	7.3 - 6.9
WC_WQM_05	22,792	0136235575	01362354	F	6.9 - 2.4
WC_WQM_06	16,837	01362354	None	F	2.4 - 0
OC_WQM_01	1,106	None	013623682	F	3.9 - 3.8
OC_WQM_02	3,320	013623682	01362365	F	3.8 - 3.1
OC_WQM_03	2,270	01362365	None	F	3.1 - 0
HTB_WQM_01	407	None	01362345	F	4.4
HTB_WQM_02	5,807	01362345	01362342	F	4.4 - 1.9
HTB_WQM_03	1,473	01362342	None	F	1.9 - 0
MB_WQM_01	180	None	01362322	F	2
MB_WQM_02	4,098	01362322	None	F	2.0 - 0

[1]If "None" is listed for upstream or downstream stations, these are the upper or lower monitoring reaches for each stream.

[2] "F" denotes that an STRP is not currently located in a monitoring reach; "T" denotes that an STRP is located in a monitoring reach.

[3]Drainage area ranges are for the downstream to upstream extents of each monitoring reach; if "0", then that represents the upstream extent of the monitored drainage area. Single values are for the very short downstream reaches.

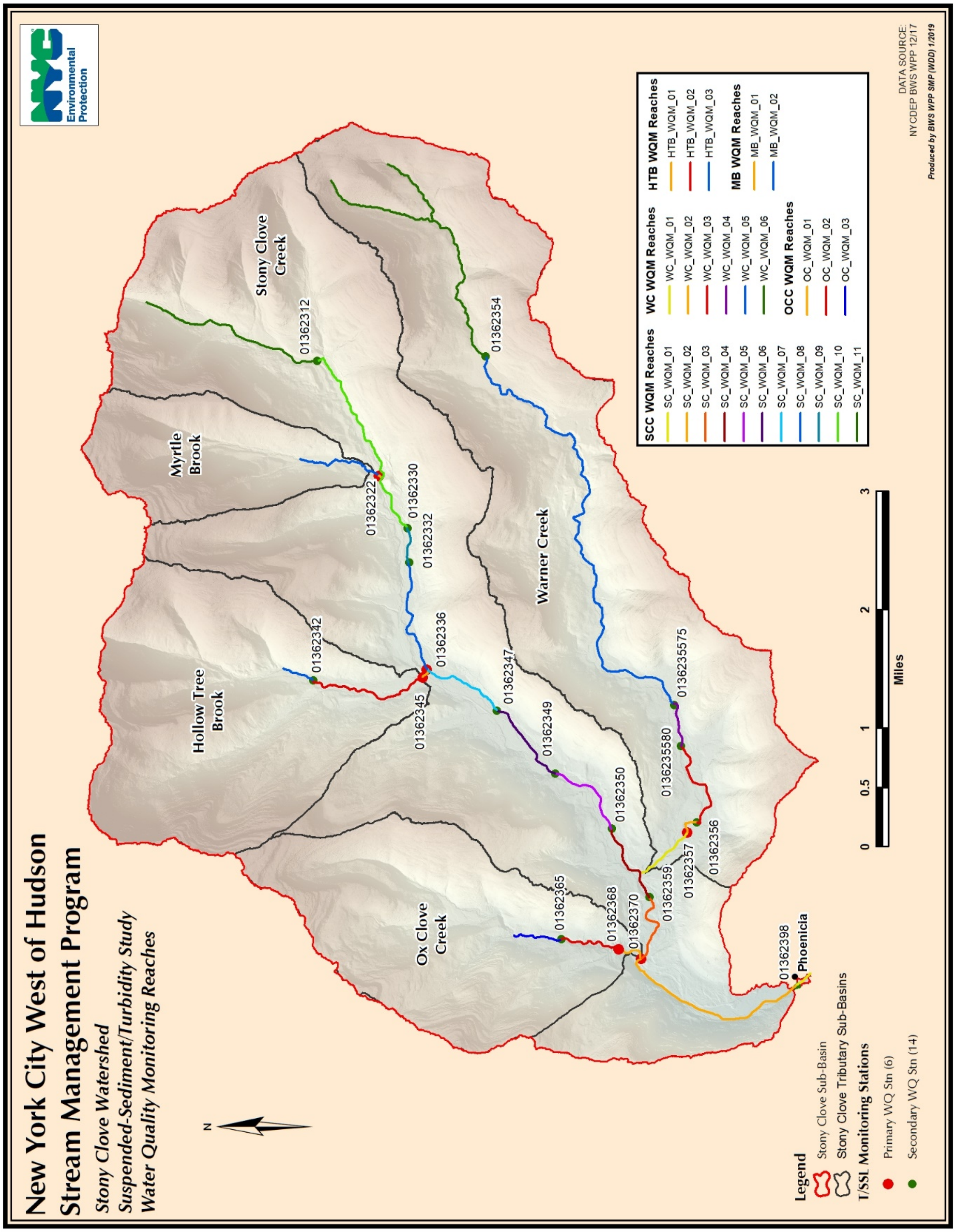

Figure 5. Stony Clove Watershed USGS water quality monitoring stations and water quality monitoring reaches.

3.2 Stream Discharge Monitoring

Stream discharge measurement and stage-discharge rating curve development by USGS is ongoing at all primary stations. USGS also measures stream discharge at three of the secondary stations to calibrate discharge estimates at the stations. These measurements are made under high and low discharge conditions.

DEP analyzed the continuous discharge and peak annual discharge record for Esopus Creek at Coldbrook station (01362500) and the Stony Clove Creek at Chichester station (01362370) for the first two water years of the Study period to evaluate the potential for geomorphic response to hydrologic conditions. The magnitude, duration and flow energy of discrete flood events directly influences the geomorphic process-response relationship that produces stream turbidity. This preliminary analysis examines only the flood magnitude, expressed as a magnitude-frequency recurrence interval derived through flood frequency analysis. Subsequent analysis will examine other metrics associated with duration and energy.

A commonly assumed threshold discharge for fluvial geomorphic work is the “bankfull discharge” (or channel forming flow), a frequently recurring moderate flood condition that over decadal time scales performs most of the work in shaping the stream channel and conveying sediment. Bankfull discharge typically has a magnitude-frequency recurrence interval of 1.2 to 2-years and is often approximated by the 1.5-year recurrence interval discharge ($Q_{1.5}$). Erosion, sediment transport and deposition can occur at flows less than $Q_{1.5}$; however, such conditions are likely to be localized and not effective over the fluvial network scale.

There is no standard magnitude-frequency threshold for “excess” fluvial geomorphic work; however, for the purpose of this analysis, DEP sets the threshold at the 10-year recurrence interval discharge (Q_{10}). Flood events exceeding this threshold can result in potential systemic geomorphic responses triggered by headcut migration, channel avulsions, planform changes, and mass wasting at channel-hillslope coupled reaches. As with the $Q_{1.5}$, such geomorphic adjustments can happen at lower discharges.

Figures 6 and 7 show this analysis, specifically the hydrographs for each station depicting the lower ($Q_{1.5}$) and upper (Q_{10}) discharge thresholds with Q_5 depicted for reference as an intermediate threshold. The frequency-magnitude values were determined by computing a Log-Pearson Type III flood frequency analysis for each gage covering the annual peak flows for a 21-year period of 1997 to 2018.

The period 2009-2011 included several high magnitude discharge events capable of system-scale process-response conditions (e.g. high impact on channel morphology and suspended-sediment load/turbidity). Many of the STRPs constructed in the Stony Clove sub-basin from 2012 to 2016 were to treat stream instabilities caused or exacerbated by the high magnitude events during this period. Since October 2012, there have been no events recorded at either station that would typically cause significant geomorphic impacts to the fluvial system. The first two years of the Study show a continued pattern of low to moderate geomorphic impact hydrology. The fluvial geomorphic system is in an extended recovery period from the disruptive disturbance of the prior unusually high frequency-high magnitude events.

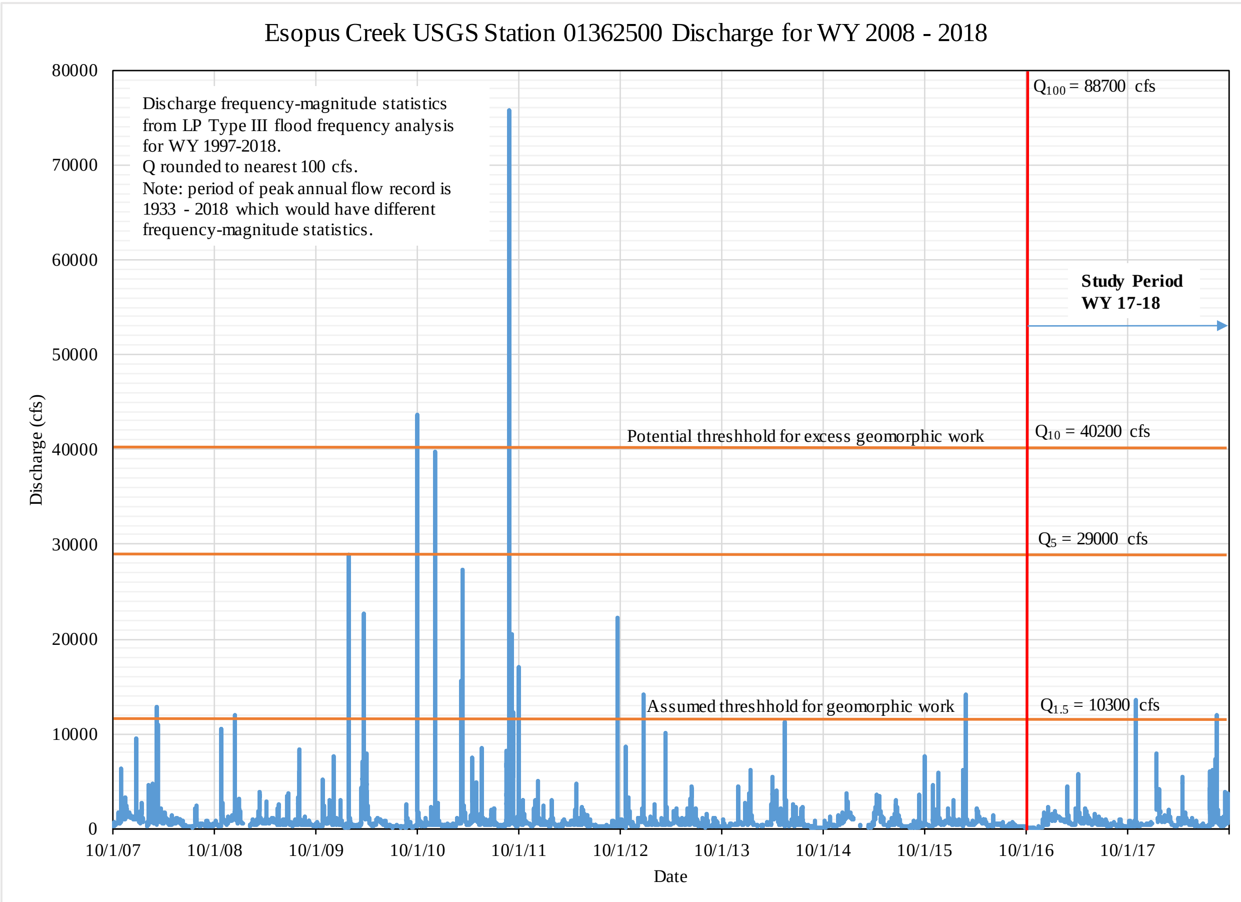

Figure 6. Hydrograph with referenced flood magnitude-frequency thresholds for Esopus Creek at Coldbrook, NY USGS gage station for the period 10/1/2007 to 9/30/2018.

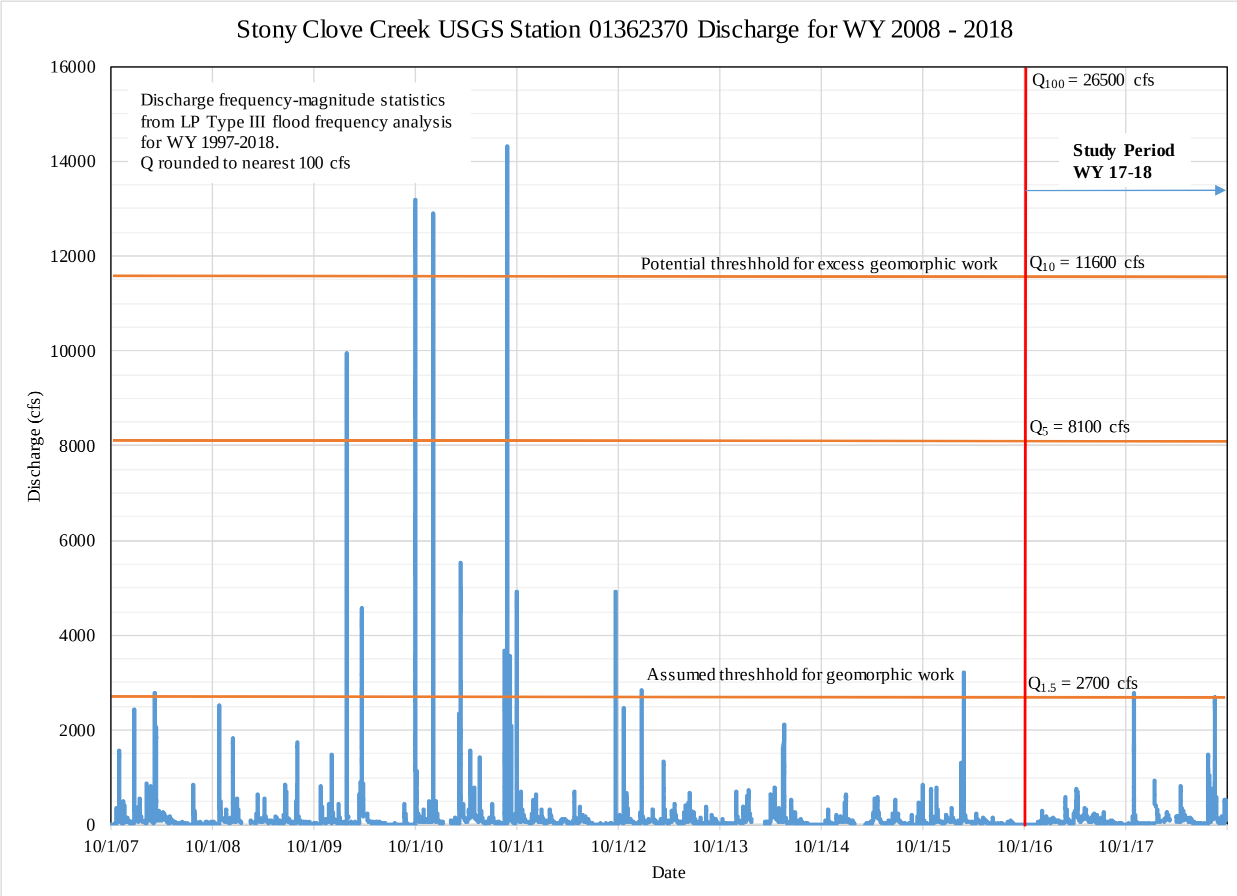

Figure 7. Hydrograph with referenced flood magnitude-frequency thresholds for Stony Clove Creek below Ox Clove at Chichester, NY USGS gage station for the period 10/1/2007 to 9/30/2018.

3.3 Suspended-sediment Monitoring

Automated samplers collect point suspended-sediment samples during storms at predetermined changes in stage and manually at cross-sections during both storms and low stream discharge conditions. USGS uses the cross-section samples to calibrate and ensure the representativeness of the point samples. Sample collection occurs throughout the range in discharge and turbidity values. Periods of high discharge and turbidity are targeted for more frequent sampling because this is when most suspended-sediment is transported. The total number of point samples collected during the first two years of the study averaged more than 50 per primary station and were representative of the range of monitored discharge. USGS also collected four to five cross-section samples at each primary station. Particle size is measured on a subset of suspended-sediment samples from each primary station, generally when turbidity values exceed 200 formazin nephelometric units (FNU).

Esopus Creek Watershed Monitoring

The following are median SSC values for point samples at each primary station for the current Study period:

- Beaver Kill and Birch Creek: greater than 100 mg/L, the highest of any of the Esopus Creek tributaries
- Woodland Creek: 57 mg/L
- Stony Clove Creek: 42 mg/L
- Little Beaver Kill: 27 mg/L
- Esopus Creek: 28 mg/L at Lost Clove, 44 mg/L at Allaben, 88 mg/L at Coldbrook

The notable change evident in this data is that Stony Clove Creek no longer has the highest median SSC. A previous investigation by USGS covering 2010-2012 reported that Stony Clove Creek had the highest median SSC, by a considerable margin over all other monitored streams, and it accounted for up to 40% of the suspended-sediment load measured at the Esopus Creek at Coldbrook station (McHale & Siemion, 2014). This dramatic shift in suspended-sediment contributions indicate (1) the potential SSC reduction efficacy of the Stony Clove watershed STRPs; and (2) the transient nature of the geomorphic process-response dynamics that influence suspended-sediment flux (the amount of sediment transported over time) and turbidity in the glacially conditioned Catskill Mountain watersheds.

USGS successfully collected point samples for several storm events during 2017-2018. Data from all of the storms sampled in 2018 are still undergoing USGS data review. USGS collected samples during a bankfull discharge event at most Esopus sub-basin primary stations on October 29-30, 2017. Maximum SSC in point samples ranged from 504 mg/L at Little Beaver Kill to 3,200 mg/L at Woodland Creek.

Stony Clove Sub-basin Monitoring

The following are median SSC values for point samples at each primary station for the current Study period:

- Ox Clove and Warner Creek: greater than 55 mg/L, the highest of the Stony Clove tributaries
- Hollow Tree Brook and Myrtle Brook: less than 30 mg/L
- Stony Clove Creek: decreased from 100 mg/L at the upstream Jansen Road station to 42 mg/L at the downstream Chichester station

This is the first fully analyzed annual median SSC data for the Stony Clove sub-basin primary stations and it provides a baseline for subsequent comparison. From this data, it is clear that Ox Clove Creek, Warner Creek and the upper Stony Clove Creek have active erosional sources contributing suspended-sediment.

USGS successfully collected point samples for several storm events during 2017-2018. Data from all of the storms sampled in 2018 are still undergoing USGS data review. Maximum SSC in point samples at most Stony Clove watershed primary stations were measured during a large storm on October 29-30, 2017 and ranged from 301 mg/L at Hollow Tree Brook at SR 214 in Lanesville to 2,770 mg/L at Stony Clove Creek Below Ox Clove at Chichester.

3.4 Turbidity Monitoring

All primary and secondary monitoring stations measure turbidity at 15-minute time intervals. Turbidity data from Stony Clove primary stations is finalized through the 2018 water year. Turbidity data from Esopus Creek primary stations is finalized through the 2017 water year and will be finalized in 2019 through the 2018 water year. Turbidity data from secondary stations varies and will be finalized as soon as possible.

Esopus Creek Watershed Monitoring

Daily mean turbidity exceeded 100 FNU at all Esopus watershed monitoring stations except for Broadstreet Hollow Brook, Bushnellsville Creek, and Little Beaver Kill (Figure 8). Woodland Creek had the greatest daily mean turbidity. Greater frequency and duration of moderate turbidity values may indicate chronic sources of turbidity in sub-basins. Woodland Creek, Broadstreet Hollow Brook, Birch Creek, Stony Clove Creek, and Beaver Kill all had more frequent and longer lasting moderate turbidity values.

Maximum 15-minute turbidity values at Esopus Creek stations were all greater than 900 FNU except for Broadstreet Hollow (419 FNU) and Little Beaver Kill (403 FNU). These results suggest that Woodland Creek and Beaver Kill were the greatest sources of turbidity from tributaries to the upper Esopus Creek during water years 2017 and 2018 (Table 5). Birch Creek and Stony Clove Creek had turbidity values lower than Woodland Creek and Beaver Kill, but higher than the other tributaries and the mainstem station located furthest upstream (Esopus Creek below Lost Clove at Big Indian). Little Beaver Kill and Bushnellsville Creek had the lowest turbidity values of the tributaries. Turbidity values increased in a downstream direction along the mainstem of Esopus Creek.

As with the SSC data, the change in relative turbidity levels from the sub-basins across the Esopus Creek watershed highlights the potential efficacy of the Stony Clove sub-basin STRPs as well as the value of multi-year monitoring to track watershed scale changes in turbidity conditions that can inform future STRP implementation. The most recent STRPs implemented in the Esopus Creek watershed during the Study period were in the two highest turbidity-contributing basins – Beaver Kill and Woodland Creek.

Stony Clove Sub-basin Monitoring

Daily mean turbidity exceeded 100 FNU at the Stony Clove Creek at Jansen Road at Lanesville station, Warner Creek near Chichester, and Stony Clove Creek below Ox Clove at Chichester monitoring stations (Figure 9). Warner Creek near Chichester had the greatest daily mean turbidity. Warner Creek near Chichester and Ox Clove at Chichester had more frequent and longer lasting moderate turbidity values than other primary monitoring stations.

Provisional turbidity monitoring results for the combined primary and secondary monitoring stations for the current Study period demonstrate the success in observing reach scale variations in turbidity (Figures 10-12). It is important to note that USGS is still reviewing this provisional data and values may change. DEP includes this provisional data to illustrate that it is feasible to identify the upstream extent of turbidity production (e.g. station 01362336 on Stony Clove Creek in Figure 10 and station 0136235585 on Warner Creek in Figure 11); and quantitatively differentiate downstream variation in turbidity that can be used for subsequent causal process-response analysis. Figure 12 depicts stations in Ox Clove, Hollow Tree Brook and Myrtle Brook and shows that the relatively high turbidity in Ox Clove is produced downstream of station 01362365. Future reports will analyze the geomorphic factors influencing the downstream variations in turbidity in the Stony Clove sub-basin.

Maximum 15-minute turbidity values at the Stony Clove basin primary stations ranged from 256 FNU at Hollow Tree Brook to 1,090 FNU at Stony Clove Creek at the Jansen Road station. The turbidity exceedance results suggest that Warner Creek was the greatest tributary source of turbidity to Stony Clove Creek during water years 2017 and 2018 (Table 6). Ox Clove was a secondary tributary source; Hollow Tree Brook and Myrtle Brook produced little turbidity.

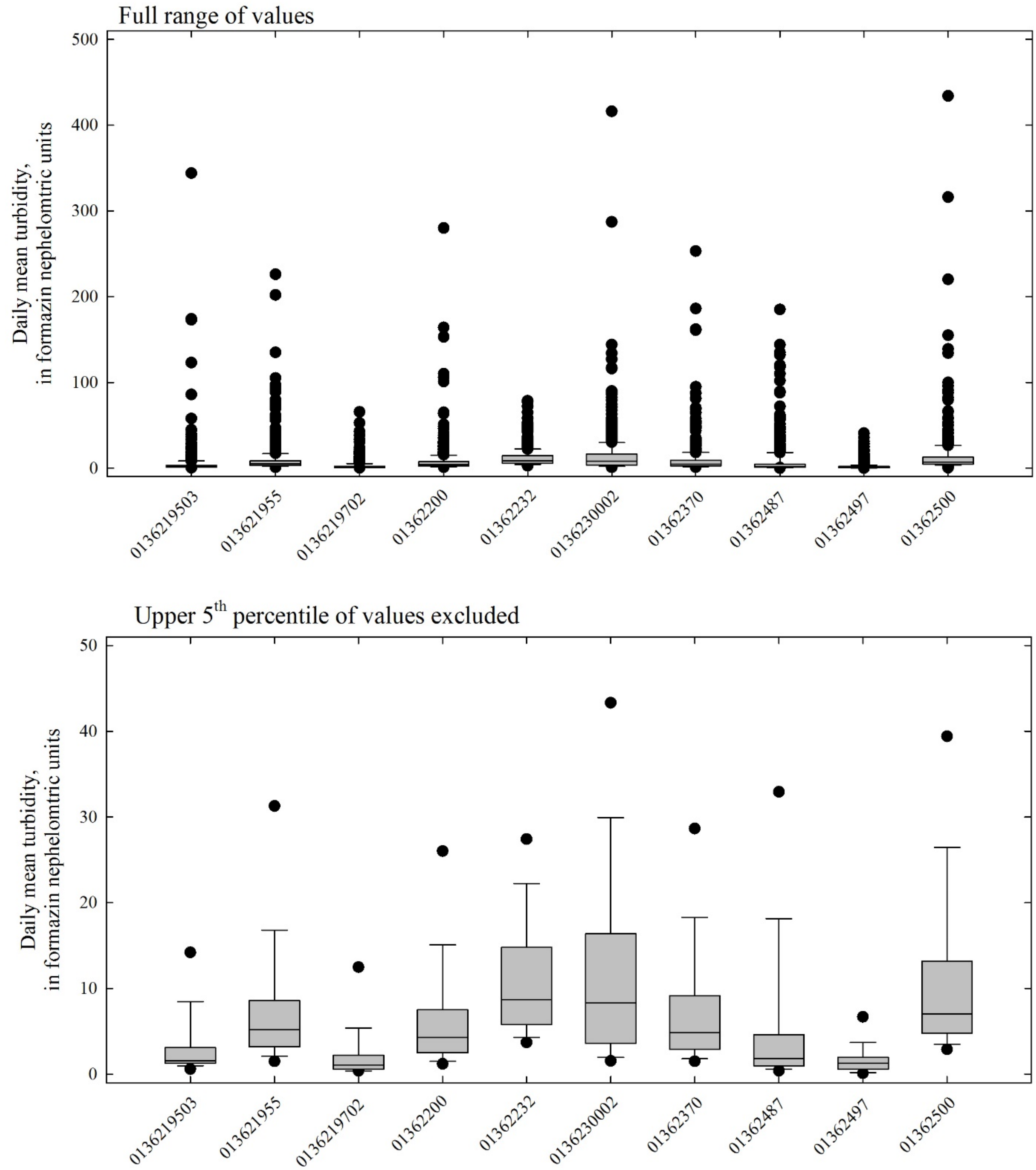

Figure 8. Upper panel, box plots of the full range in daily mean turbidity at Esopus sub basin monitoring stations and lower panel, box plots of daily mean turbidity at Esopus sub basin monitoring stations excluding the upper 5th percentile of values. USGS station numbers along the x-axis; refer to Table 2 for station stream names.

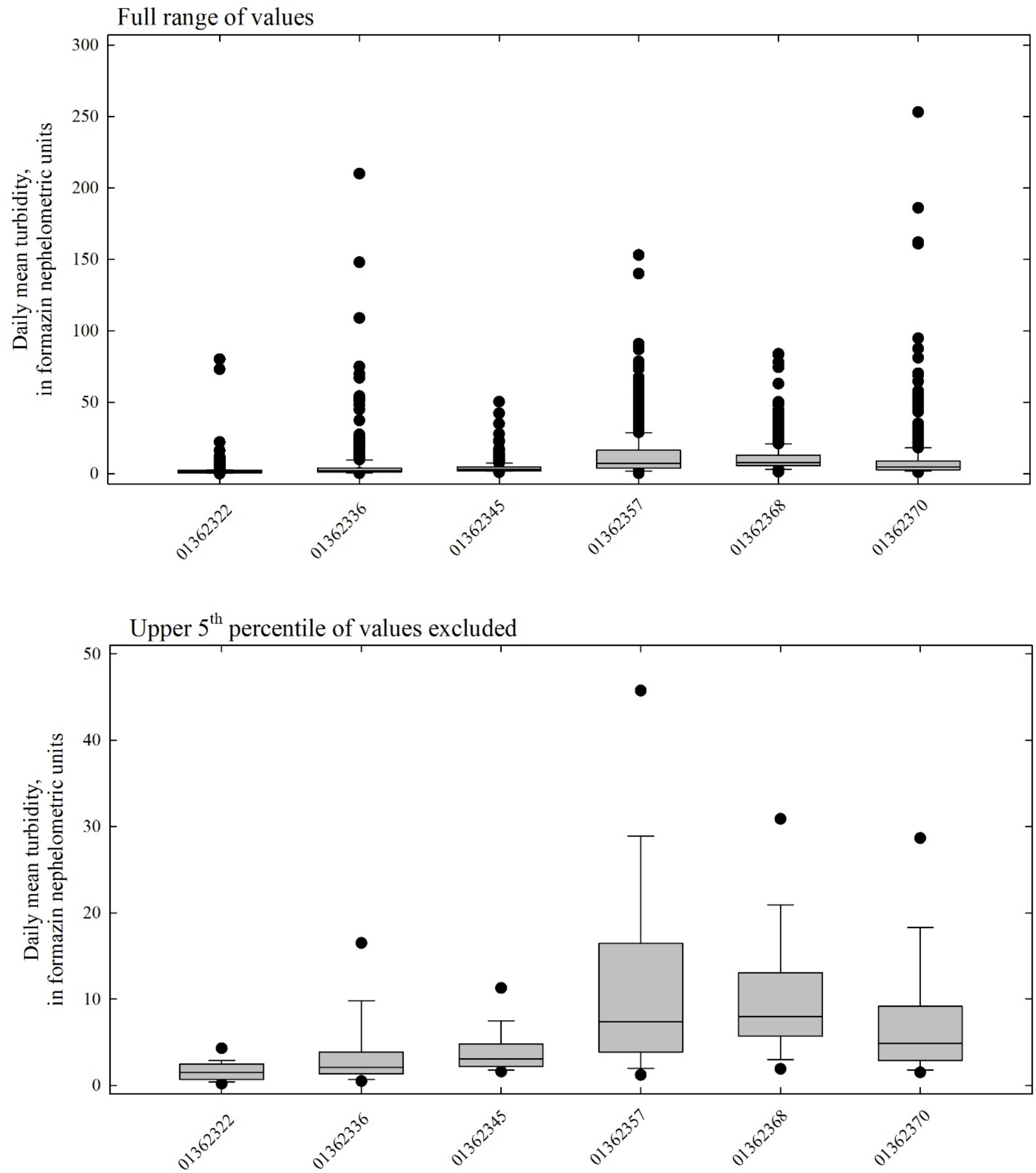

Figure 9. Upper panel, box plots of the full range in daily mean turbidity at Stony Clove sub basin monitoring stations and lower panel, box plots of daily mean turbidity at Stony Clove sub basin monitoring stations excluding the upper 5th percentile of values. USGS station numbers along the x-axis; refer to Table 3 for station stream names.

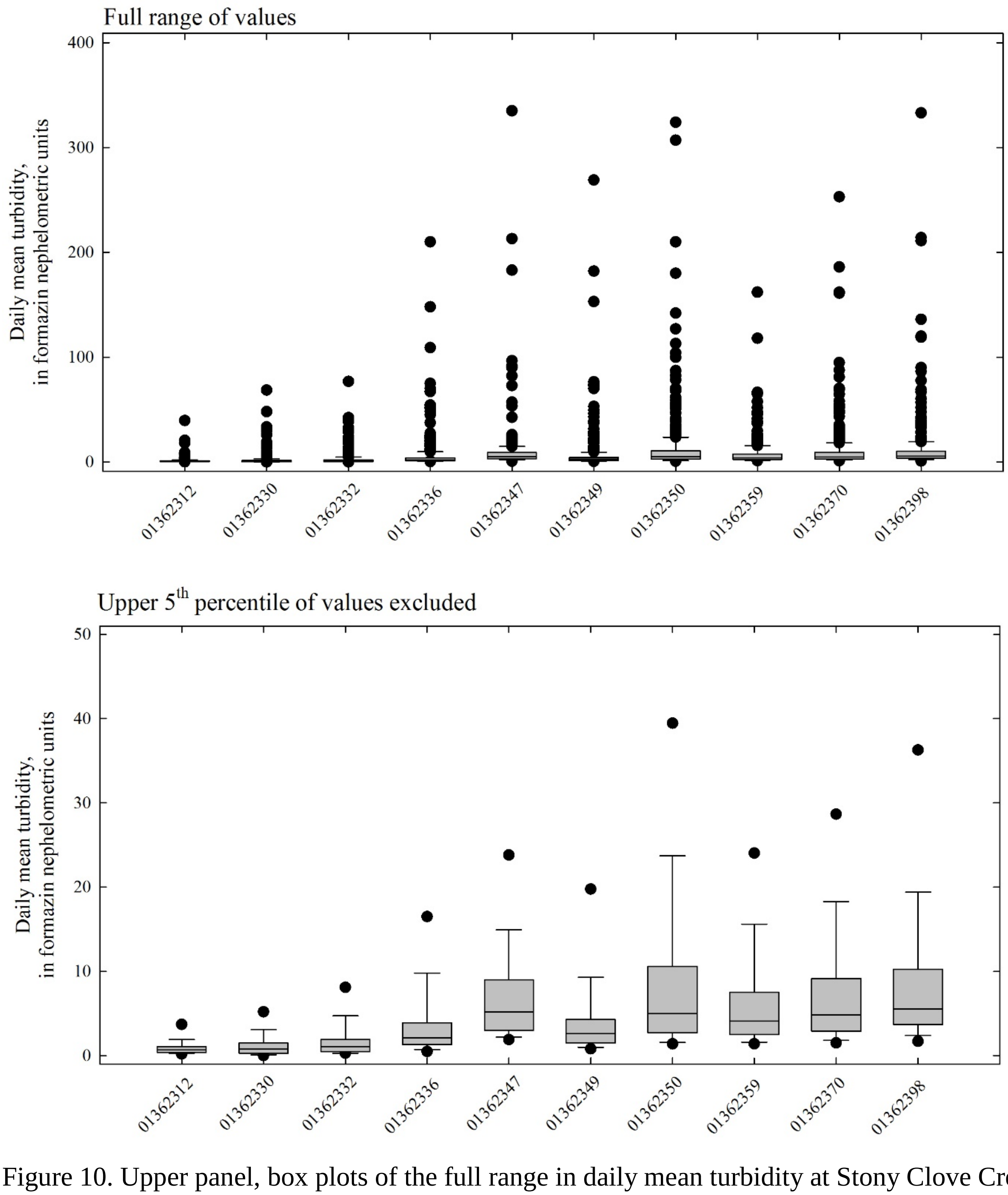

Figure 10. Upper panel, box plots of the full range in daily mean turbidity at Stony Clove Creek reach monitoring stations and lower panel, box plots of daily mean turbidity at Stony Clove Creek reach monitoring stations excluding the upper 5th percentile of values. USGS station numbers along the x-axis; refer to Table 3 for station stream names.

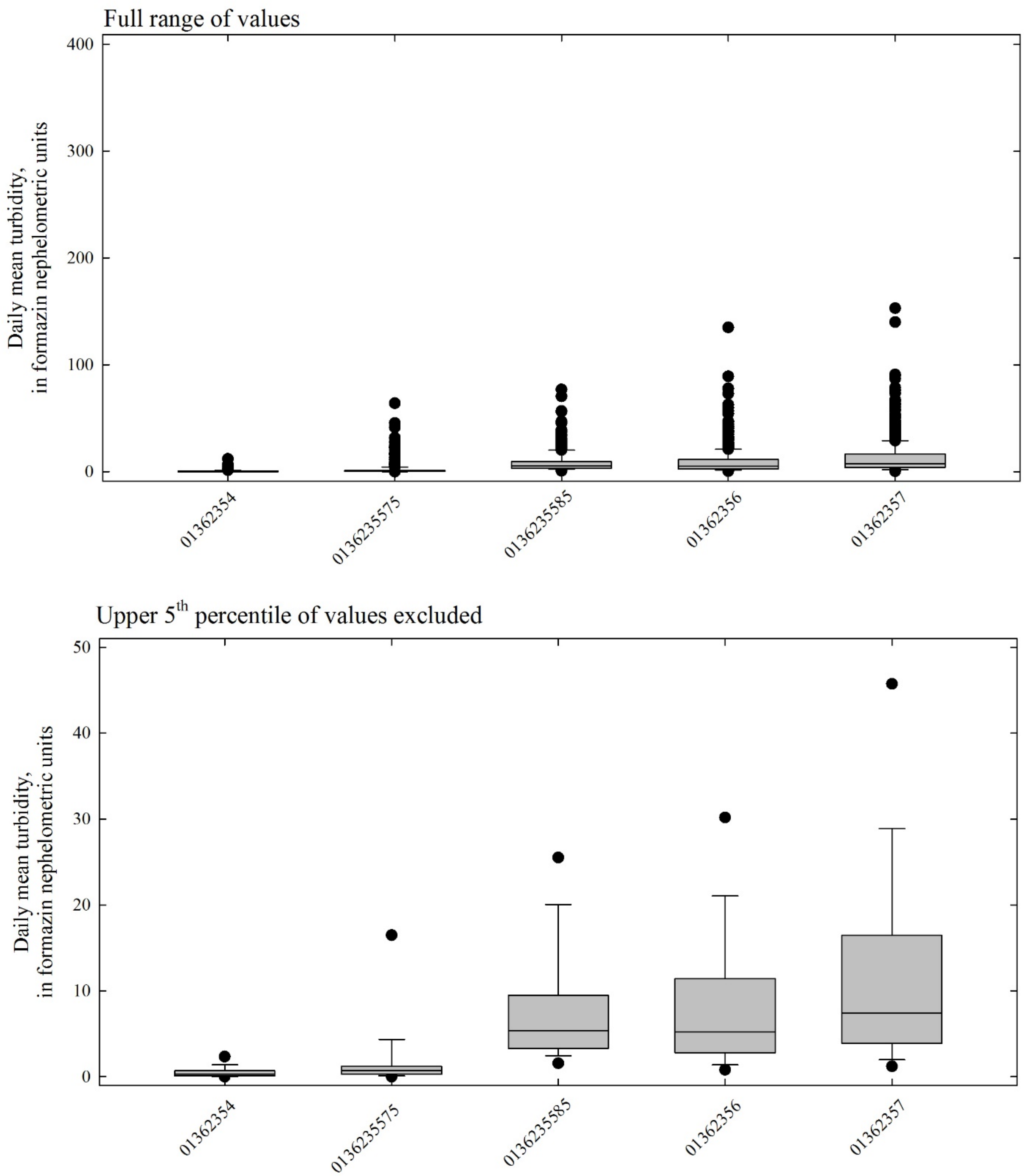

Figure 11. Upper panel, box plots of the full range in daily mean turbidity at Warner Creek reach monitoring stations and lower panel, box plots of daily mean turbidity at Warner Creek reach monitoring stations excluding the upper 5th percentile of values. USGS station numbers along the x-axis; refer to Table 3 for station stream names.

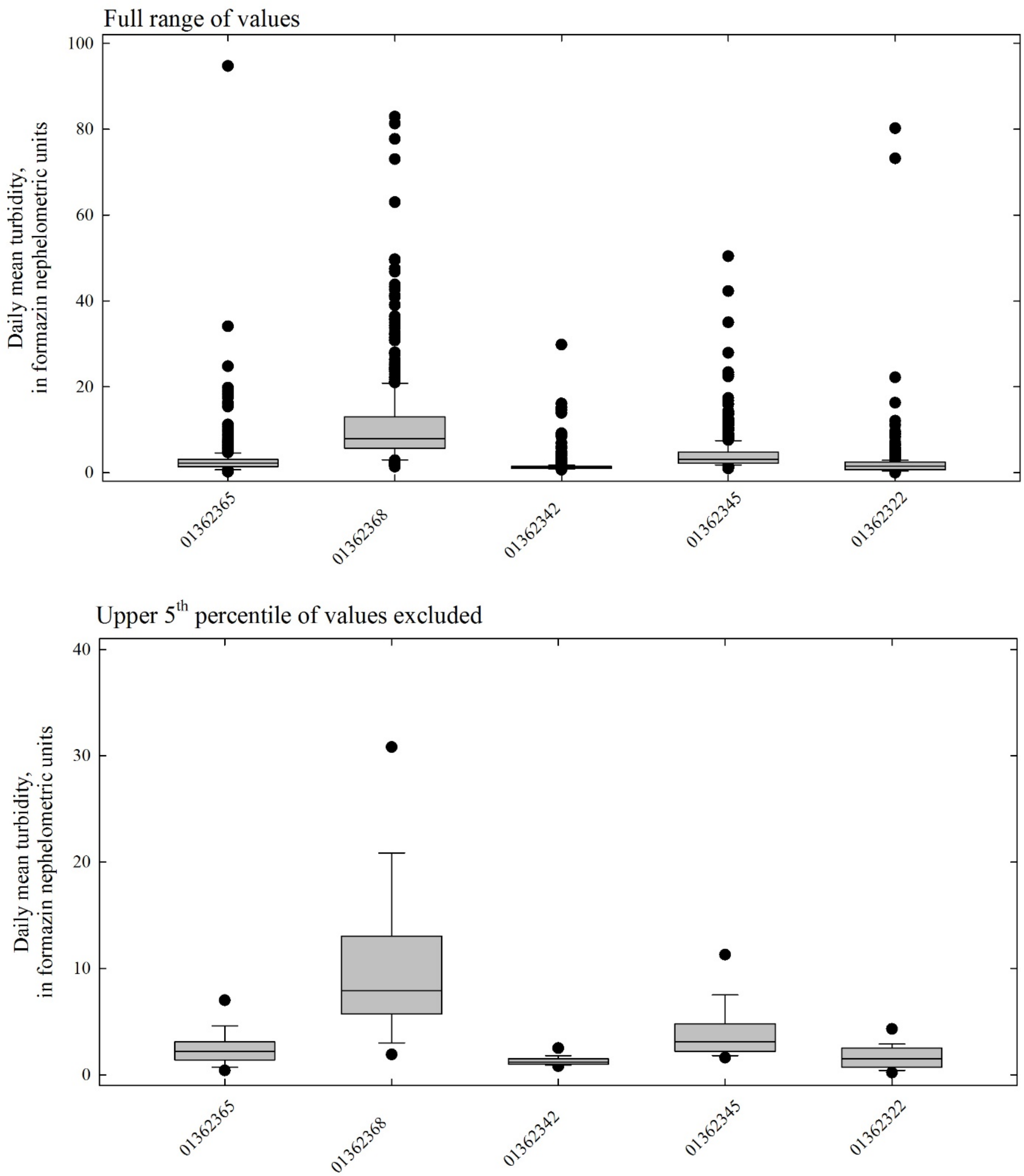

Figure 12. Upper panel, box plots of the full range in daily mean turbidity at Ox Clove, Hollow Tree Brook and Myrtle Brook reach monitoring stations and lower panel, box plots of daily mean turbidity at the same reach monitoring stations excluding the upper 5th percentile of values. USGS station numbers along the x-axis; refer to Table 3 for station stream names.

Table 5. Summary of 15-minute turbidity values from Esopus Creek sub-basin monitoring stations listed from upstream to downstream.

Station Name	USGS Station ID	Maximum	1% Exceedance	5% Exceedance	10% Exceedance	Median
Esopus Cr bl Lost Clove @ Big Indian	0136219503	>1,600	40	13	7	2
Birch Cr @ Big Indian	013621955	1,310	88	25	15	5
Bushnellsville Creek at Shandaken	0136219702	906	35	9	4	1
Esopus Cr @ Allaben	01362200	1,370	68	22	14	4
Broad Street Hollow Brook at Allaben	01362232	419	62	26	20	9
Woodland Cr abv mouth @ Phonecia[1]	0136230002	>1,600	123	44	28	7
Stony Clove Cr blw Ox Clove @ Chichester[1]	01362370	985	83	27	17	5
Beaver Kill @ Mt Tremper	01362487	1,120	104	32	14	2
Little Beaver Kill at Beechford nr Mt Tremper	01362497	403	21	5	3	1
Esopus Cr at Coldbrook	01362500	1,410	120	32	21	6

Table 6. Summary of 15-minute turbidity values from Stony Clove Creek monitoring stations listed from upstream to downstream.

Station Name	USGS Station ID	Maximum	1% Exceedance	5% Exceedance	10% Exceedance	Median
Stony Clove Cr @ Edgewood	01362312	950	10	3	2	1
Myrtle Br @ SR 214 @ Edgewood	01362322	712	12	4	3	1
Stony Clove Cr nr Lanesville	01362330	635	18	4	3	1
Stony Clove Cr @ Wright Rd nr Lanesville	01362332	614	25	7	3	1
Stony Clove Cr @ Jansen Rd @ Lanesville	01362336	1,090	59	17	9	2
Hollow Tree Br @ Lanesville	01362342	824	6	2	2	1
Hollow Tree Br @ SR 214 @ Lanesville	01362345	256	21	11	7	3
Stony Clove Cr @ Lanesville	01362347	1,520	140	25	16	5
Stony Clove Cr abv Moggre Rd nr Chichester	01362349	1,130	66	20	10	3
Stony Clove Cr @ Chichester	01362350	>1,600	123	33	19	4
Warner Cr blw Silver Hollow Notch nr Edgewood	01362354	124	6	2	1	<1
Warner Cr nr Carl Mountain nr Chichester	0136235575	281	30	13	4	1
Warner Cr in Silver Hollow nr Chichester	0136235580	587	65	26	17	5
Warner Cr @ Silver Hollow Rd nr Chichester	01362356	571	61	30	21	5
Warner Cr nr Chichester	01362357	885	85	45	30	7
Stony Clove Cr @ Silver Hollow Rd, Chichester	01362359	850	64	21	14	4
Ox Clove @ Chichester	01362365	1,020	20	6	4	2
Ox Clove nr mouth @ Chichester	01362368	1,600	69	26	20	8
Stony Clove Cr blw Ox Clove @ Chichester	01362370	985	83	27	17	5
Stony Clove Cr abv SR 214 @ Phoenicia	01362398	>1,600	133	30	18	5

4. Suspended-Sediment Source Characterization

4.1 Watershed Sources of Suspended-Sediment/Turbidity

Previous investigations conclude the fine-grained sediment that comprises much of the Pleistocene glacial and pro-glacial deposits is the originating source of the suspended-sediment that produces Catskill stream turbidity (Nagle, et al., 2007; McHale & Siemion, 2014). DEP used the Universal Soil Loss Equation and a range of sediment delivery ratios to estimate landscape erosion contributions to suspended-sediment in Esopus Creek (NYCDEP, 2008). The analysis showed that the majority of suspended-sediment observed in Esopus Creek is largely from sediment sourced from stream channel and stream adjacent hillslope erosional processes. Based on this information, the Study assumes stream channel erosion and mass wasting at channel-hillslope coupled stream reaches are the primary geomorphic processes to monitor in the upper Esopus Creek watershed. Together, DEP and USGS are testing the hypothesis that the geomorphic-turbidity process-response relationship can effectively be modified through STRP implementation that disrupts the connectivity of suspended-sediment flux to fluvial and hillslope morphological sediment sources.

The Study uses multiple methods to account for the assumed primary suspended-sediment source conditions and processes. These methods include (1) terrain interpretation using remote-sensed data in GIS; (2) baseline and repeat SFIs targeted to map spatial and temporal erosional contact with sediment sources; (3) repeat geomorphic assessment, topographic monitoring, and hydraulic modeling at select stream erosion sites; (4) further geologic sediment source investigation and interpretation; and (5) experimental use of suspended-sediment fingerprinting source-sediment identification. During the course of the 10-year Study, DEP and USGS will use these methods to derive and test potential predictive geomorphic metrics to help explain suspended-sediment flux through the system.

4.4 GIS Analysis of Watershed and Stream Channel Characteristics

The Study design report details several GIS-based tasks to obtain watershed and stream channel characteristics for potential geomorphic metric development. This section describes the status of each of these tasks and one newly proposed task.

Water Quality Monitoring Station Drainage Area Delineation

DEP used the coordinates for each primary and secondary monitoring station and the available 2009 1-meter digital elevation model (DEM) to compute the contributing drainage area for each station. (Table 4). USGS will calculate suspended-sediment yield for each monitoring station using these drainage area values.

Geomorphic Management Reach Delineation

The geomorphic management reach delineation attempts to segment the stream into relatively uniform sections based on contributing drainage area (segment breaks at tributary confluences), changes in valley width and/or slope, and often where major stream crossings occur. This task is complete for all SFI-mapped streams in the upper Esopus Creek watershed.

Historic Channel Alignment Analysis

Historic channel alignment analysis is a qualitative and/or quantitative measure of stream channel planform adjustment over time. Work to date includes digitizing stream channel centerlines for several years (1959 to 2016) for Stony Clove Creek and Warner Creek. DEP will digitize multi-year centerlines for the remaining monitored Stony Clove sub-basins in 2019 and develop potential metrics in 2019 to 2020.

Stream Channel Confinement Assessment

The stream channel confinement assessment uses remote-sensed data to measure stream-valley confinement conditions with methods detailed in Fryirs, et al (2015) to yield quantitative measures of channel-hillslope connectivity, an assumed significant source of suspended-sediment in the Stony Clove sub-basin. Work on this task started in 2018 and will continue into 2019.

Stream Channel Slope and Stream Power Assessment

Stream channel slope and stream power (product of slope and a reference discharge) are computed using the 2009 1-meter DEM and the corresponding 2009 stream channel centerline. This task is complete for Stony Clove Creek and Warner Creek. Work will continue for the other Stony Clove sub-basin monitored streams. DEP will test the value of stream power in spatially distributed modeling as a predictive metric for erosion and consequent suspended-sediment production.

DEM of Difference Assessment

The DEM of Difference method is a new GIS-based Study task introduced in 2018 that is simply the subtraction of one DEM from another. Fluvial geomorphologic investigations are increasingly using this method when at least two DEMs representing different periods of the same terrain and resolution are available to quantitatively measure changes in elevation at each DEM cell. Subtracting the more recent DEM from a prior DEM can yield data on erosion (negative values) and deposition (positive values). Preliminary testing finds this method will be useful in depicting zones of erosion (sediment entrainment) and deposition at the reach and sub-basin scales. Work will continue on this task as additional DEM data becomes available.

4.5 Mapping Spatial and Temporal Sediment Source Distribution

DEP uses SFI mapping of erosional sediment sources as the current primary method to gain a spatial understanding of suspended-sediment sourcing from stream channel erosion and channel-hillslope mass wasting. Figure 13 presents the SFI mapping of stream bank erosion in the upper Esopus Creek watershed for the period 2000 to 2017. Table 7 presents a summary of some of the SFI bank erosion mapping results for the Esopus Creek and sub-basins.

Mapping the spatial distribution and relative magnitudes of erosional sediment sources, specifically bank erosion, bed erosion and hillslope erosion, can help explain the basin, sub-basin, and reach scale variations in measured turbidity and suspended-sediment. The method requires using high-resolution capable GPS devices with a digital data form (data dictionary) that records details such as the geology of the eroding feature, the bank failure mechanics, feature dimensions, and other potentially useful metrics. DEP will complete at least two SFIs separated by approximately five years for each monitored stream in the Stony Clove sub-basin to obtain information on the temporal variation in source conditions.

During the 10-year Study period, UCSWCD will continue to perform the SFI mapping in the upper Esopus Creek sub-basins with the exception of the Stony Clove. DEP will perform the SFI mapping in the Stony Clove sub-basin using a Study-specific SFI data dictionary designed to increase potential geomorphic metrics for analyzing the reach scale turbidity monitoring.

Esopus Creek Watershed Mapping

UCSWCD completed baseline SFI mapping for three tributary streams to upper Esopus Creek for the period 2017 to 2018: the Little Beaver Kill (LBK) in 2017, and Hatchery Hollow and Lost Clove Creeks, two smaller tributaries in the headwaters portion of the upper Esopus Creek, in 2018. The LBK data is processed and incorporated into the DEP-maintained geodatabase for all final SFIs. UCSWCD is processing the 2018 SFI data for inclusion in the DEP-maintained geodatabase in 2019.

Stony Clove Sub-basin Mapping

In 2018, DEP completed the first Study SFI on Stony Clove Creek. The previous SFIs completed in 2001 and 2013 used two former versions of SFI data dictionaries. Figure 14 is a map of the pre-Study period mapped erosional suspended-sediment sources categorized by geologic source material, and Table 8 quantifies erosional contacts with suspended-sediment sources. The 2018 SFI used the new Study-specific SFI data dictionary and protocol developed to improve quantitative suspended-sediment source metrics in the Stony Clove sub-basin. DEP has nearly completed extensive quality control review of the 2018 data. The four water quality monitored tributaries to Stony Clove Creek will have repeat SFI investigations in 2019. Data analysis and computation of erosional contact metrics and comparison with previous SFI metrics will take place in 2019 and 2020.

Table 7. Upper Esopus Creek watershed SFI-mapped stream bank erosional sediment source analysis. Sediment sources are lumped into two categories for percentage computation – alluvial and non-alluvial (glacial till and lacustrine sediment).

Stream name	SFI year	SFI stream length (ft)	Bank erosion length (ft)	% Bank erosion[1]	% Erosional contact AL[2]	% Erosional contact N-AL[2]	Dominant N-AL geology
Esopus Creek	2005-06	144,974	25,003	9%	78%	22%	Glacial Till
Birch Creek	2011	49,662	8,940	9%	91%	9%	Lacustrine
Bushnellsville	2013	28,858	8,658	15%	75%	25%	Lacustrine/Till
Broadstreet Hollow	2001	17,992	4,678	13%	86%	14%	Lacustrine
Woodland Creek	2015	33,100	9,508	14%	66%	34%	Glacial Till
Stony Clove Creek	2013	54,459	11,982	11%	45%	55%	Lacustrine
Beaver Kill	2009	50,338	26,175	26%	71%	29%	Glacial Till
Little Beaver Kill	2017	50,338	26,650	26%	85%	15%	Glacial Till

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

[2]AL = alluvium; N-AL = non-alluvium

Table 8. Status of Stony Clove Creek sub-basin SFI and suspended-sediment/turbidity source characterization. Data is from SFI efforts (2010–2015). The N-AL category lumps erosional contact with lacustrine sediment, glacial till and mapped mixes of the two.

Stream name	SFI stream length (ft)	Bank erosion length (ft)	% Bank erosion[1]	% Erosional contact AL[2]	% Erosional contact N-AL[2]	% Erosional contact LS[2]	% Erosional contact GT[2]	% Erosional Contact Mix[2]
Stony Clove Creek	54,459	12,129	11%	48%	52%	21%	23%	9%
Ox Clove Creek	6,696	1,161	9%	70%	30%	14%	16%	0%
Warner Creek	50,144	11,056	11%	82%	17%	6%	11%	0%
Hollow Tree Brook	7,684	1,529	10%	89%	11%	0%	11%	0%
Myrtle Brook	4,281	1,070	13%	100%	0%	0%	0%	0%
TOTALS	123,261	26,946	11%	68%	32%	12%	16%	4%

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

[2]AL = alluvium; N-AL = non-alluvium; LS = lacustrine sediment; GT = glacial till sediment; Mix = either a colluvial mixing of AL and N-AL sediments or stratified deposits of multiple sedimentologic units.

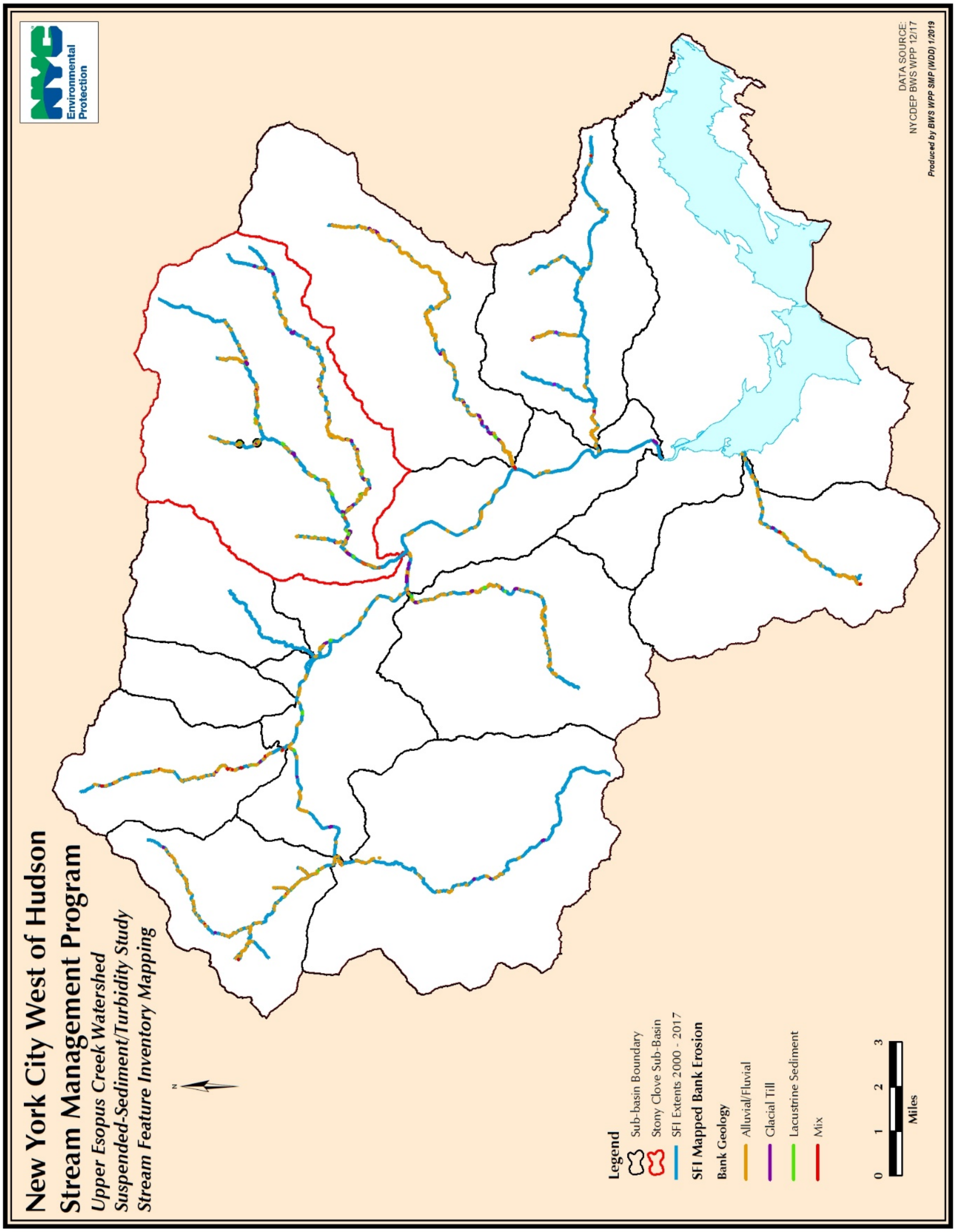

Figure 13. Stream feature inventory mapping of stream bank erosion in the upper Esopus Creek watershed from 2000 to 2017.

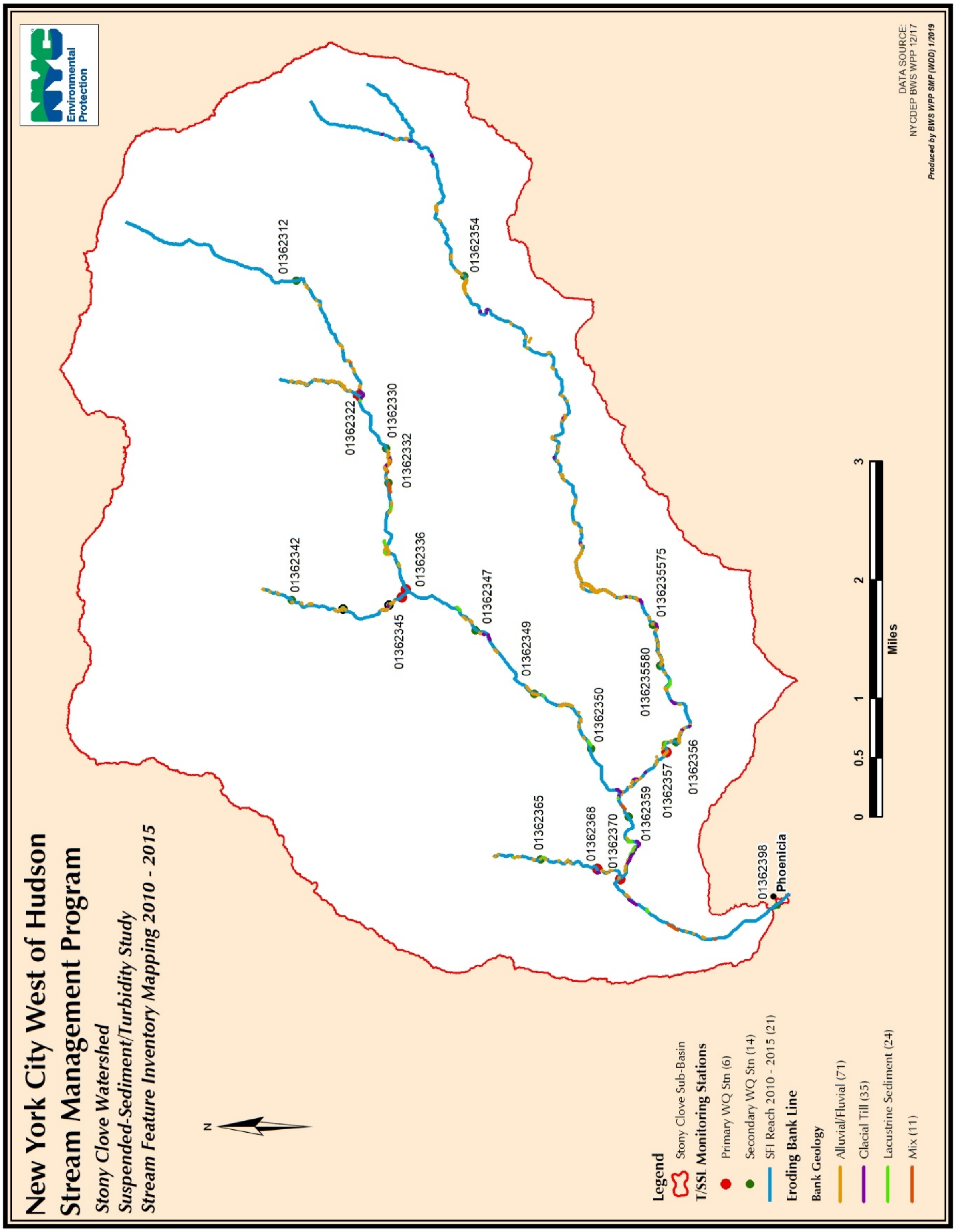

Figure 14. Stream feature inventory mapping of stream bank erosional suspended-sediment sources in the Stony Clove sub-basin. SFI mapping completed during the period 2010 to 2015.

4.6 Stream Channel Erosion Monitoring

The Study design includes site to reach scale stream channel erosion monitoring with a set of bank erosion monitoring sites (BEMS) in the Stony Clove sub-basin selected from previously SFI-mapped erosional suspended-sediment sources. DEP established eight BEMS during the period 2016 to 2018 (Table 9 and Figure 15). Monitoring methods include topographic surveys, hydraulic modeling, bank erosion hazard index (BEHI) characterization, and stream bank sediment sampling for grain size analysis (see Section 4.7). Selected sites represent a range of erosional source conditions expected to contribute measurable levels of suspended-sediment and turbidity.

Under contract to DEP, Milone & MacBroom, Inc. (MMI) performs and documents the BEMS scope of work. Because DEP is currently reviewing a draft summary BEMS analysis report submitted by MMI in March 2019, discussion of BEMS analysis findings is limited at this time.

Topographic Survey

The Study design report detailed use of standard fluvial geomorphic survey methods comprising longitudinal profile and cross-section surveys using self-leveling laser levels. DEP modified the methods to include use of total station equipment to survey the stream channel, banks and adjacent terrain to produce topographic maps rather than just cross-sections and longitudinal stream profiles. This allowed for a more comprehensive accounting of geomorphic process-response conditions between surveys. Subsequent to that modification, in 2017 MMI pilot-tested use of Unmanned Aerial System (UAS) technology to develop higher resolution topographic surfaces using Structure-from-Motion (SfM) techniques at two of the BEMS locations (OC-BEMS-01 and WC-BEMS-02). MMI compared the SfM-derived topographic surfaces with the land-based survey surfaces and concluded the SfM method was much more representative of actual surfaces and could yield better estimates of geomorphic change. There are some limitations with this method from vegetation cover obscuring terrain, which is primarily controlled for by having all surveys occur during leaf-off conditions with no (or minimal) snow cover. DEP authorized MMI to complete similar SfM surveys for SC-BEMS-03 and WC-BEMS-01. Upon completion of the review of the final MMI BEMS report, DEP will revise the Study design report methods accordingly. Table 8 summarizes the status of topographic surveys for all current BEMS.

Provisional results of a recent round of SfM surveys completed for BEMS sites WC-BEMS-01, WC-BEMS-02, and SC-BEMS-03 demonstrate the value of terrain topographic surveys versus discrete profile surveys. Discrete profile surveys (cross-sections) can only provide estimates of bank retreat/sediment loss at one discrete location; whereas topographic surveys covering the entire eroding bank can provide more accurate estimates of aerial retreat and volumetric sediment loss. For example, the following provisional estimates for the three BEMS sites nominated as priority future STRP sites (see Section 5.2):

- Warner Creek BEMS Site 1 (WC-BEMS-01) had an estimated loss of 110 yd^3 of stream bank alluvium and lacustrine sediment between April 2018 and December 2018. Localized bank retreat was up to 3 to 4 feet

- Warner Creek BEMS Site 2 (WC-BEMS-02) had an estimated loss of 99 yd^3 of stream bank alluvium and lacustrine sediment between November 2017 and December 2018. Localized bank retreat was up to 8 feet.

- Stony Clove Creek BEMS Site 3 (SCC-BEMS-03) had an estimated loss of 1000 yd^3 of stream bank alluvium and lacustrine sediment and measurable terrace mass wasting.

DEP will continue to have MMI conduct topographic surveying using both SfM and land-based methods annually to biennially for the eight existing BEMS and for up to two future BEMS locations. Future reporting will include a more comprehensive characterization of the BEMS topographic survey findings.

Hydraulic Modeling

The BEMS study methods include developing hydraulic models with HEC_RAS using the topographic survey data and the existing FEMA flood study models available for the Stony Clove watershed. The hydraulic modeling simulates the process-response impacts of flood hydrology on sediment transport and bank failure at the BEMS locations. MMI recently completed calibrating existing conditions hydraulic models for the Stony Clove Creek and Warner Creek BEMS locations. DEP will task MMI for hydraulic modeling the two Ox Clove Creek BEMS locations in 2019. DEP will include more detail on hydraulic modeling in a future Study status report.

4.6 Source-Sediment Analysis

Distinct geologic sediment sources (sedimentologic units) exposed in the streambed, stream banks and channel-connected hillslopes can supply suspended-sediment through the process of stream, erosion and mass wasting. DEP defines a sedimentologic unit as a mappable geologic source of sediment that is identifiable in the field and has distinct sediment size distribution and erodibility characteristics. DEP currently maps four distinct sedimentologic units exposed in eroding stream channels and mass wasting hillslopes:

Holocene and Pleistocene alluvium – stream sorted unconsolidated alluvium composed principally of sand to small boulder size material with interstitial finer grained sediment. Pleistocene pro-glacial meltwater streams occupying higher elevations in the valley deposited alluvium now stored in valley bottom high terraces. Holocene (post-glacial to present) streams occupying the valley during a previous lateral and vertical position deposited alluvium now stored in stream banks and low to moderately high fluvial terraces. This is the typical and most abundant material exposed in the active eroding valley bottom. Examples of Holocene and Pleistocene alluvium are included in Figure 16.

Glacial Till – unsorted and typically over-consolidated aggregation of sediment ranging in size from clay to boulders. Coarser sediment is embedded in a dense silty-clay matrix. It was deposited sub-glacially as lodgement till or supra-glacial as moraines. Glacial till is typically exposed in erosive stream contacts with valley wall slopes or glacial terrace hillslopes. It can also be exposed in streambed headcuts and channels that have incised below the stream alluvium. An example of glacial till exposed in an eroding stream bank is included in Figure 16.

Lacustrine sediment (pro-glacial lake deposits) – stratified and cohesive layers of clay, silt and some sand deposited subaqueously in impounded glacial meltwater. This unit is commonly exposed along the toe of eroding stream banks and as distinct layers in mass wasting hillslopes. It can also be exposed in streambed headcuts and channels that have incised below the stream alluvium. An example of lacustrine sediment exposed in an eroding stream bank is included in Figure 16.

Colluvium – unsorted and variably consolidated aggregation of sediment ranging in size from clay to bouders. Terrestrial erosional processes such as mass wasting deposit colluvium. It is often a mix of two or more of the other sedimentologic units and can be very variable in sediment composition. An example of colluvium exposed in a mass wasting hillslope is included in Figure 16.

DEP, USGS and MMI advanced geologic source-sediment characterization through grain size analysis of bulk samples representing the different sedimentologic units exposed in eroding stream banks and hillslopes at BEMS locations and at sampling sites for the suspended-sediment source fingerprinting pilot study. Results are still currently under review and will be compiled and presented in future reporting. DEP plans additional bulk sample grain size analysis for 2019 and 2020 to include alluvium stored in streambed depositional features to help estimate the percentage of fine-grained sediment in streambed storage. Upon completion of the analysis, DEP will rank sedimentologic units by percent composition of potential suspended-sediment, and further categorize SFI-mapped erosional sources.

In 2017, DEP and USGS introduced suspended-sediment source fingerprinting as a source-sediment characterization Study method. The AWSMP funded this pilot study, led by the USGS Maryland Water Science Center to test the hypothesis that sedimentologic units are detectable as source material in sampled suspended-sediment.

Work to date includes establishing sediment source fingerprints and analyzing samples from one storm runoff event. USGS successfully developed an erosional source-sediment library based on chemical analysis of 100 source-sediment samples collected in the Stony Clove sub-basin and 20 samples in the Woodland Valley sub-basin. Sampling also included forest soils and road sanding source material as additional source-sediments in the library. USGS analyzed the samples for more than 40 parameters to develop a unique chemical signature for each geologic source.

USGS collected suspended-sediment samples at a Stony Clove Creek monitoring station (01362336) and the Woodland Creek monitoring station (0136230002) during the October 30, 2017 discharge event for source-fingerprinting analysis. Insufficient sediment mass was available from the Stony Clove station for conclusive findings. There was enough sediment mass in samples from Woodland Creek to analyze different parts of the storm hydrograph. The provisional results suggest this application of sediment fingerprinting can work for the intended purpose. During the early part of the rising flood stage, the sediment was mostly from alluvium and glacial till with some forest soils and little lacustrine material. During the two discrete flood peaks, alluvium and glacial till still dominated as sources with less forest soil and little lacustrine material detected. The falling flood stage sample marked a big change: lacustrine sediment almost entirely replaces alluvium as the dominant source for the remainder of the prolonged waning flood stage. Turbidity values in Woodland Creek remained elevated for many days following this event and originated at stream channel contact with lacustrine material. The pilot test provisional results for this sampled event provide empirical data to support the prior assumption that lacustrine material is the primary source for chronic suspended-sediment load following storm events. USGS and DEP will summarize the results in 2019 and plan to integrate this methodology into the Study.

Table 9. Stony Clove sub-basin BEMS status table.

Site	Started	Surveys	Survey method[1]	Sediment analysis[2]	Description
SC-BEMS-01	2017	1	TS	Yes	Mass wasting of glacial till with alluvium in mountainside. Stream contact is with a colluvial mixture of glacial till and alluvium.
SC-BEMS-02	2017	1	TS	No	Hydraulic erosion and mass wasting of glacial till and alluvium in a high terrace.
SC-BEMS-03	2018	2	SfM	No	Hydraulic erosion and mass wasting of glacial lacustrine sediment and alluvium in a high terrace with some lacustrine sediment exposed in streambed.
WC-BEMS-01	2016	4	TS SfM	Yes	Hydraulic erosion and mass wasting of glacial lacustrine sediment and alluvium in high terrace with some glacial lacustrine sediment exposed in streambed.
WC-BEMS-02	2016	4	TS SfM	Yes	Hydraulic erosion and mass wasting of glacial lacustrine sediment and alluvium in low to high terrace at stream avulsion with some glacial lacustrine sediment exposed in streambed.
WC-BEMS-03	2016	2	TS SfM	Yes	Mass wasting of glacial till and glacial lacustrine sediment in mountainside.
OC-BEMS-01	2016	2	TS SfM	Yes	Mass wasting of glacial till in high terrace.
OC-BEMS-02	2017	1	TS	Yes	Hydraulic erosion and mass wasting of glacial till and glacial lacustrine sediment in high terrace.

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

[2] Sediment grain-size distribution analyses were completed for several sites to get representative ranges of fine sediment content (clay-silt) in the sedimentologic units of alluvium, glacial till, lacustrine sediment and colluvium.

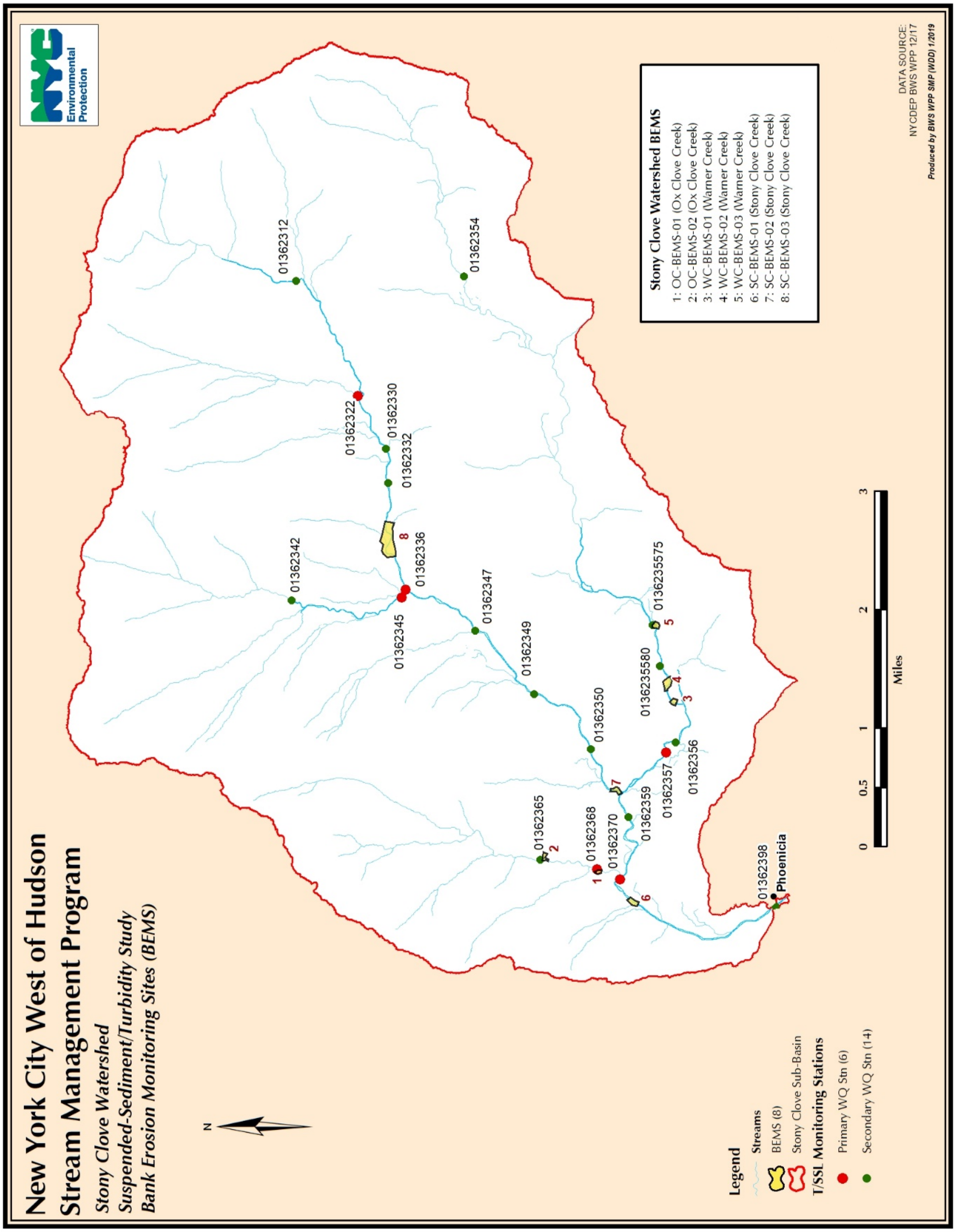

Figure 15. Stony Clove sub-basin BEMS locations and USGS monitoring stations.

Figure 16. Examples of the four primary sedimentologic units mapped using SFI methodology. (A) unconsolidated Holocene alluvium; (B) consolidated glacial till; C) cohesive lacustrine sediment overlain by alluvium; (D) unconsolidated colluvium from mass wasting of Pleistocene alluvium and glacial till.

5. Sediment and Turbidity Reduction Projects

One of the primary goals of the Study is to evaluate the efficacy of STRPs in the Stony Clove sub-basin on measurably reducing turbidity at a range of spatial, temporal and hydrologic scales. It is too early in the scope of the current Study to present any conclusive findings on this goal given that USGS continues to process turbidity and SSC data collected during the first two years of the Study. For purposes of this report, USGS provided updated turbidity-discharge relations in the Warner Creek sub-basin. DEP expects to present more findings on evaluating potential reductions in turbidity and SSC for Stony Clove sub-basin and Esopus Creek basin as measured at the Esopus Creek at Coldbrook station (01362500) in future status reports.

5.1 Existing STRPs

Esopus Creek Watershed STRPs

DEP funded the design, construction and monitoring of three STRPs in the upper Esopus Creek watershed during the Study period. The two Beaver Kill at Van Hoagland STRPs were constructed in 2016, and the Woodland Creek STRP in 2018. These projects are not explicitly part of the Study; however, analysis of turbidity and SSC trends in each monitored Esopus Creek tributary sub-basin will consider potential impacts from these and other future upper Esopus Creek watershed projects. The AWSMP funded upstream and downstream turbidity monitoring by USGS for the Woodland Creek project as a separate evaluation effort. Once post-construction monitoring is complete and results are available, DEP will incorporate that information into a future status report.

Stony Clove Sub-basin STRPs

DEP funded the design, construction and morphometric monitoring of eight STRPs in the Stony Clove sub-basin from 2012 to 2016 (Figure 17). The Stony Clove Creek at Lanesville STRP was originally completed as a stream restoration demonstration project in 2006 as part of the Stony Clove Stream Management Plan. Post-Irene flood damage to this project required revised engineering design and implementation completed in 2015; this project was subsequently incorporated into the set of Stony Clove STRPs.

The Study design includes “bracketing” most existing STRPs with upstream and downstream monitoring stations in an attempt to detect differences in turbidity above and below monitoring reaches that have STRPs. Unfortunately, the timing of the Study started after the construction of the existing STRPs; therefore, the existing STRPs will largely be combined and evaluated for the cumulative sub-basin scale effect.

UCSWCD conducts recurrent post-construction morphometric monitoring for all STRPs as part of the stream disturbance permit requirements for each project. Such work includes longitudinal profile surveys, cross-sectional surveys and pebble counts. Future work may include accounting for geomorphic metrics associated with the STRPs in addition to the more direct measurement of turbidity.

Past research concludes that individual and cumulative STRPs in the Stony Clove watershed appear to reduce turbidity and suspended-sediment load for a limited range of discharge for the short monitoring period following implementation (Siemion, et al. 2016). Using provisional turbidity monitoring data from 2016-2018, USGS updated the turbidity-discharge plot for the Warner Creek sub-basin primary station 01362357 (Figure 18). The Warner Creek Site 5 STRP constructed in 2013 is the only STRP in the sub-basin. The pre-treatment site condition was a chronic source of turbidity from a channel-hillslope coupled mass failure in lacustrine sediment that contributed suspended-sediment in non-flood conditions. The initial analysis (upper panel in Figure 18) showed an immediate post-project reduction in the turbidity-discharge process-response relationship for the tributary. In the five years since STRP construction, the turbidity-discharge relationship is trending back toward pre-construction conditions (lower panels in Figure 18).

Monitoring above/below the STRP for the current Study period shows an increase in turbidity through the monitored reach (Stations 01362356/01362357 in Figure 11). Since construction, the STRP has adjusted in response to storm hydrology, yet there are no observable erosional exposures of lacustrine sediment. DEP will investigate potential turbidity sources at Warner Creek Site 5 in 2019. Figure 11 shows, however that there are significant turbidity sources upstream of the STRP reach. Three mapped locations upstream erode lacustrine sediment currently monitored as BEMS and by upstream water quality monitoring stations.

5.2 Future Stony Clove Watershed STRPs

In January 2019, DEP submitted a FAD report nominating three priority proposed STRPs (and two alternate sites) in the Stony Clove watershed based on the water quality monitoring station data and the geomorphic assessment and monitoring efforts. The proposed STRPs include two reaches on Warner Creek (WC1 and WC2) and one reach on Stony Clove Creek (SCC1) (Figure 18). Using mean daily turbidity values for water years 2017-2018 and storm event turbidity values recorded at each monitoring station, USGS and DEP confirmed measurable increases in turbidity attributed to the proposed treatment locations. The two Warner Creek sites (WC1 and WC2) were located between two monitoring stations until November 2018, when USGS relocated the uppermost monitoring station (01362354) from a problematic location that was not functioning for the Study objectives to a location between WC1 and WC2. The new station location will serve to monitor the potential turbidity reduction effects associated with each project.

DEP and UCSWCD are currently working on scoping additional site assessment needed to inform project design. If feasible, DEP and UCSWCD will target STRP implementation for the 2020 and 2021 construction seasons to allow for five to six years of post-construction monitoring.

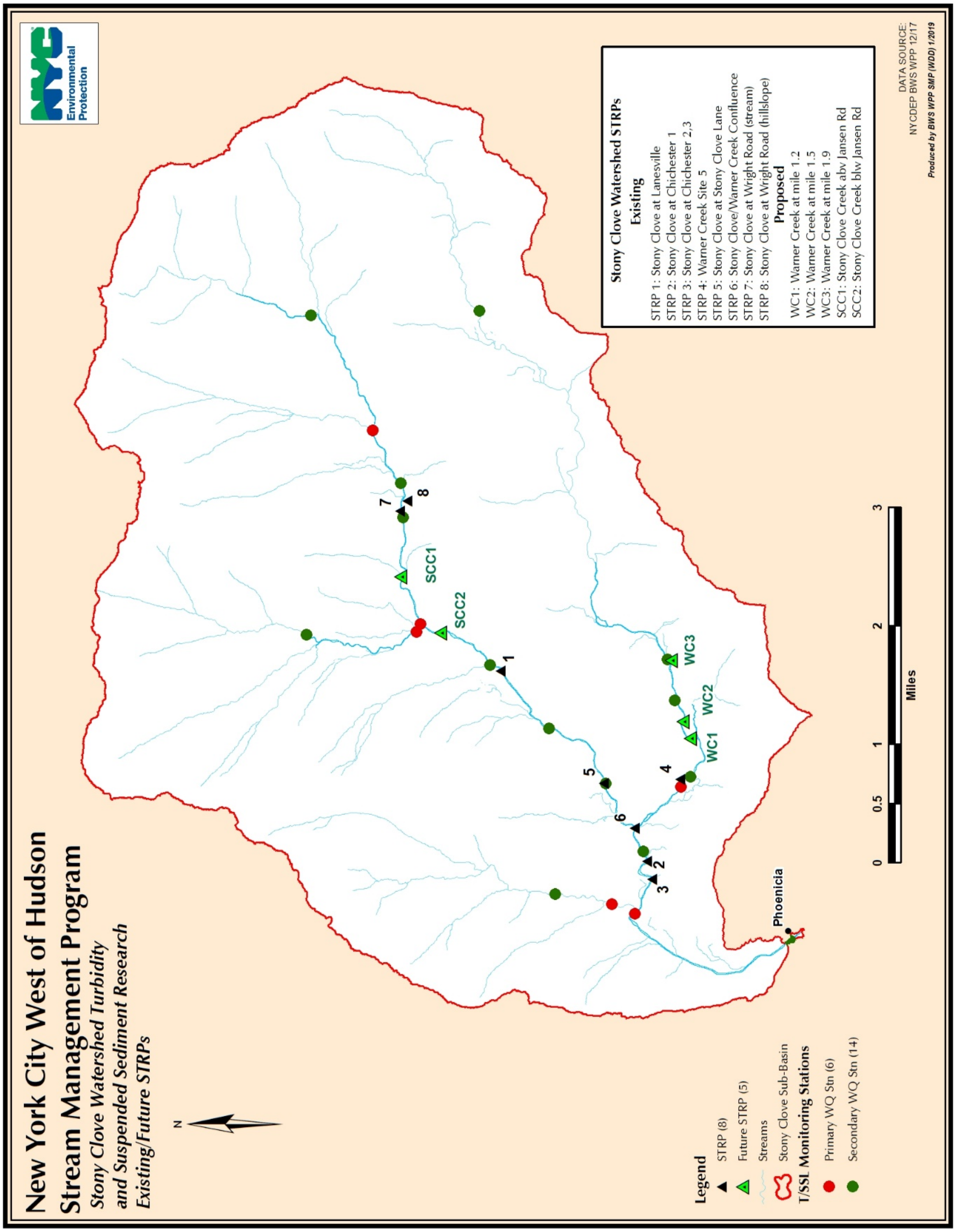

Figure 17. Stony Clove sub-basin existing and nominated future STRPs.

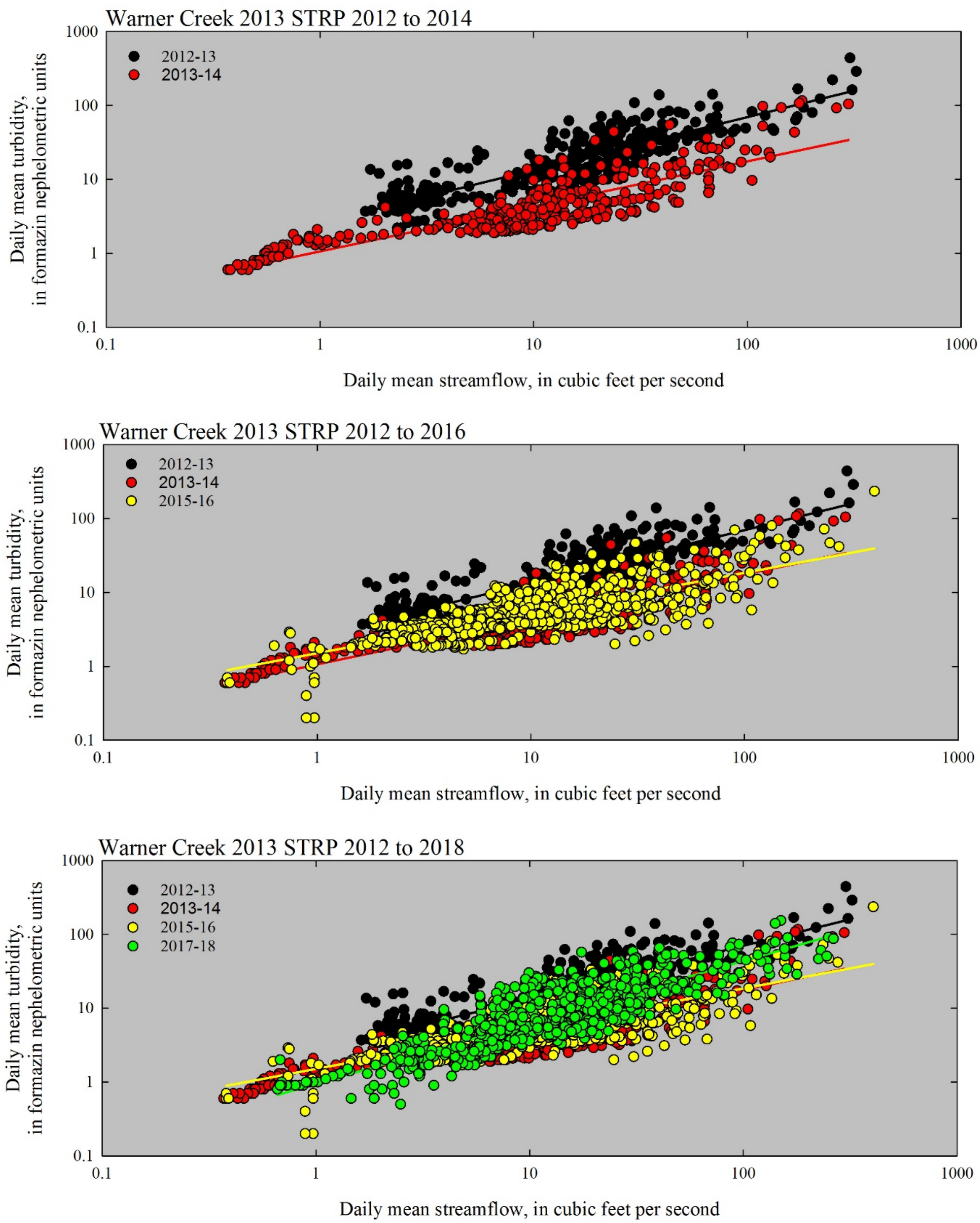

Figure 18. Turbidity-discharge relations through time for Warner Creek primary station 01362357. The upper panel plots the pre-construction and first-year post-construction results show a clear reduction in turbidity for the monitored discharge range. The two lower panels plot turbidity-discharge for WY 2015 to 2016 and WY 2017 to 2018 showing a trend toward less turbidity reduction for the monitored discharge range.

6. Project Reporting

USGS and DEP presented Study design overview and preliminary results at three conferences in 2018:

- NYC Water Supply Watershed Science Technical Conference, September 2018

Evaluating Suspended-Sediment Dynamics and Turbidity in the Upper Esopus Creek Watershed: A Comprehensive Study. Jason Siemion, Dany Davis, Michael R. McHale, and Matthew Cashman

- Catskill Environmental Research Monitoring Conference, October 2018

Evaluating Suspended-Sediment Dynamics and Turbidity in the Upper Esopus Creek Watershed: A Comprehensive Study. Jason Siemion, Dany Davis, Michael R. McHale, and Matthew Cashman

- American Geophysical Union Fall Meeting, December 2018

A comprehensive approach to informing and monitoring results of stream management practices in the Upper Esopus Creek Watershed (poster). Jason Siemion, Dany Davis, Michael R. McHale, and Matthew Cashman

7. Conclusions

DEP and USGS are successfully implementing the upper Esopus Creek watershed suspended-sediment/turbidity study with a fully instrumented water quality monitoring network and ongoing geomorphic investigations. The first two years of the 10-year Study centered on establishing the monitoring network, testing and revising methods as needed, selecting future STRPs, and beginning to examine the available data. The next set of FAD reports are due March 30, 2021 and November 30, 2021; the latter five-year report will summarize the research findings and discuss the scope for the concluding five years of the Study period.

8. References

McHale, M. R., & Siemion, J. 2014. Turbidity and suspended-sediment in the upper Esopus Creek watershed, Ulster County, New York: U.S. Geological Survey Scientific Investigations Report 2014-5200.

Nagle, G. N., Fahey, T. J., Ritchie, J. C., and Woodbury. P. B. 2007. Variations in sediment sources and yields in the Finger Lakes and Catskills regions, of New York. Hydrological Processes 21, 828-838

DEP. 2008. Evaluation of Turbidity Reduction Potential through Watershed Management in the Ashokan Basin. Valhalla, NY