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

Jason Siemion, Hydrologist, U.S. Geological Survey, Troy, New York, jsiemion@usgs.gov
Wae D. Davis, Geologist, New York City Department of Environmental Protection, Kingston, New York, DavisD@dep.nyc.gov
Donald B. Bonville, Hydrologist, U.S. Geological Survey, Troy, New York, dbonville@usgs.gov

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).

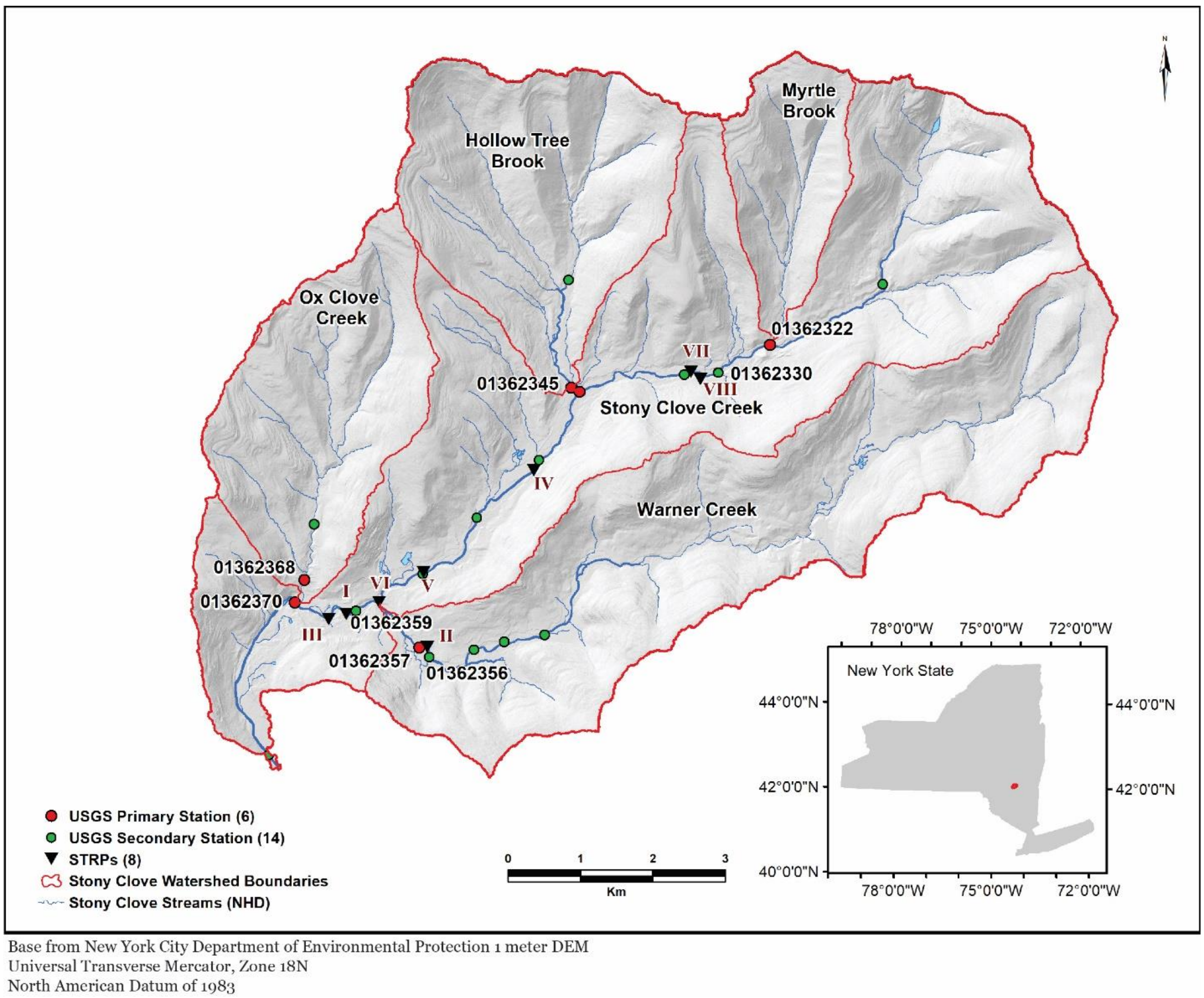

Figure 1. Map of the study area showing locations of Stony Clove Creek, Stony Clove Creek subbasins, U.S. Geological Survey (USGS) water-quality monitoring stations, and sediment and turbidity reduction projects (STRPs), New York, USA. Roman numerals refer to specific STRPs.

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).

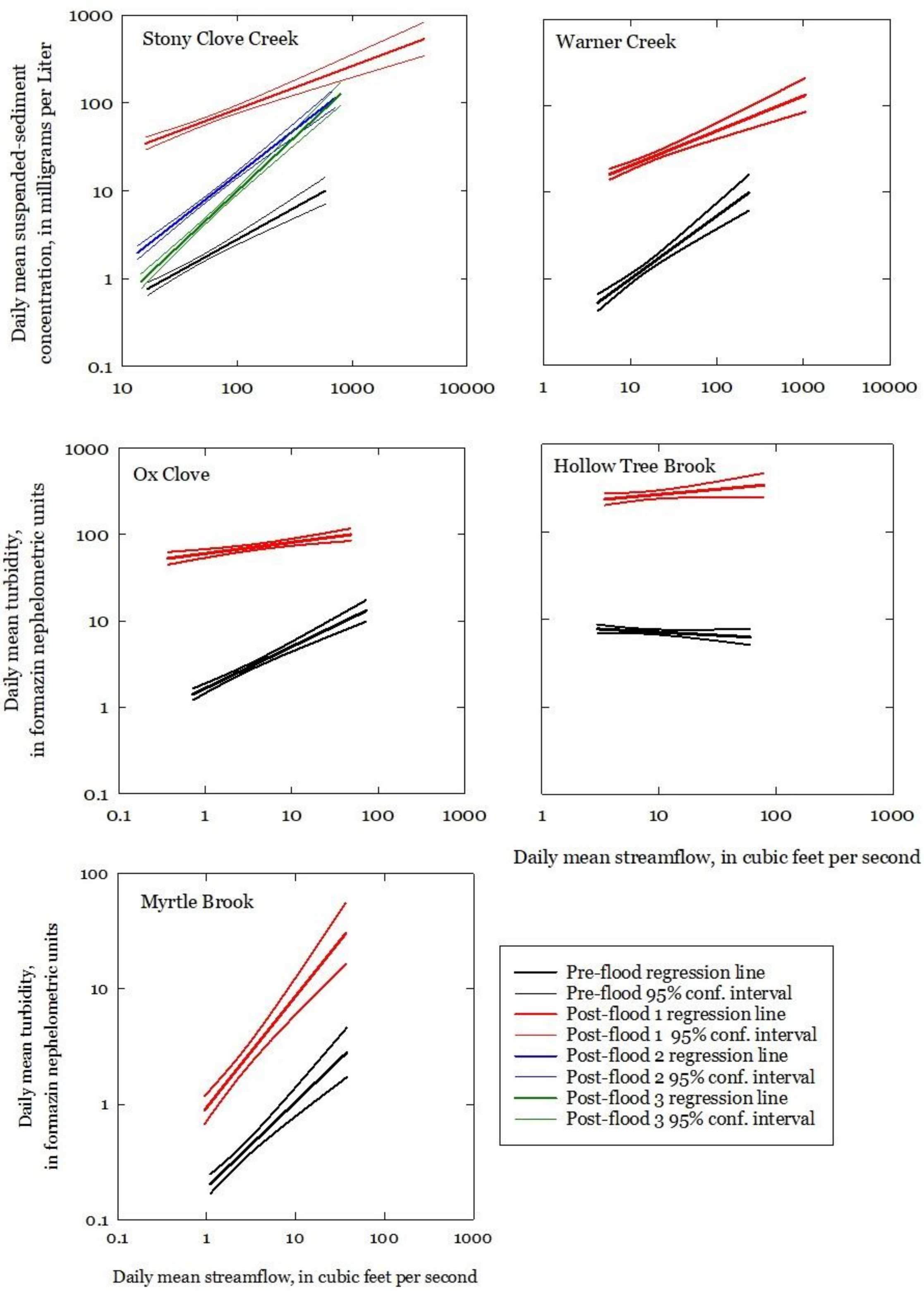

Figure 3. Daily mean suspended-sediment concentration or turbidity as a function of daily mean discharge at Stony Clove Creek (USGS station number 01362370) for 3 months prior to the December 2020 flood and 3 time periods post-flood; and 3 months pre- and post-flood at tributary streams Ox Clove (01362368),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

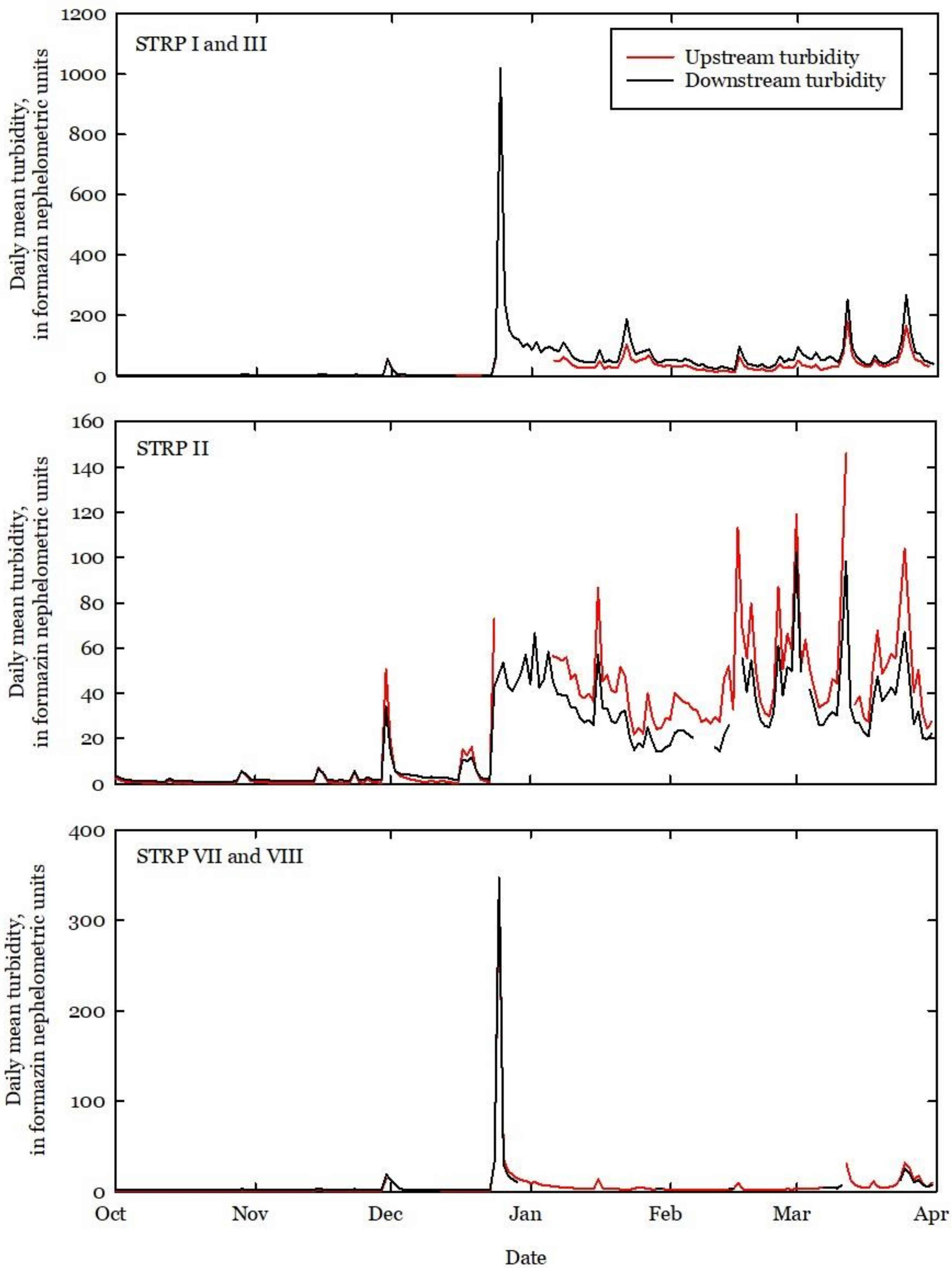

Figure 4. Daily mean turbidity upstream and downstream of sediment and turbidity reduction projects (STRPs) for 3 months prior to the December 2020 flood and 3 months post-flood.

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.

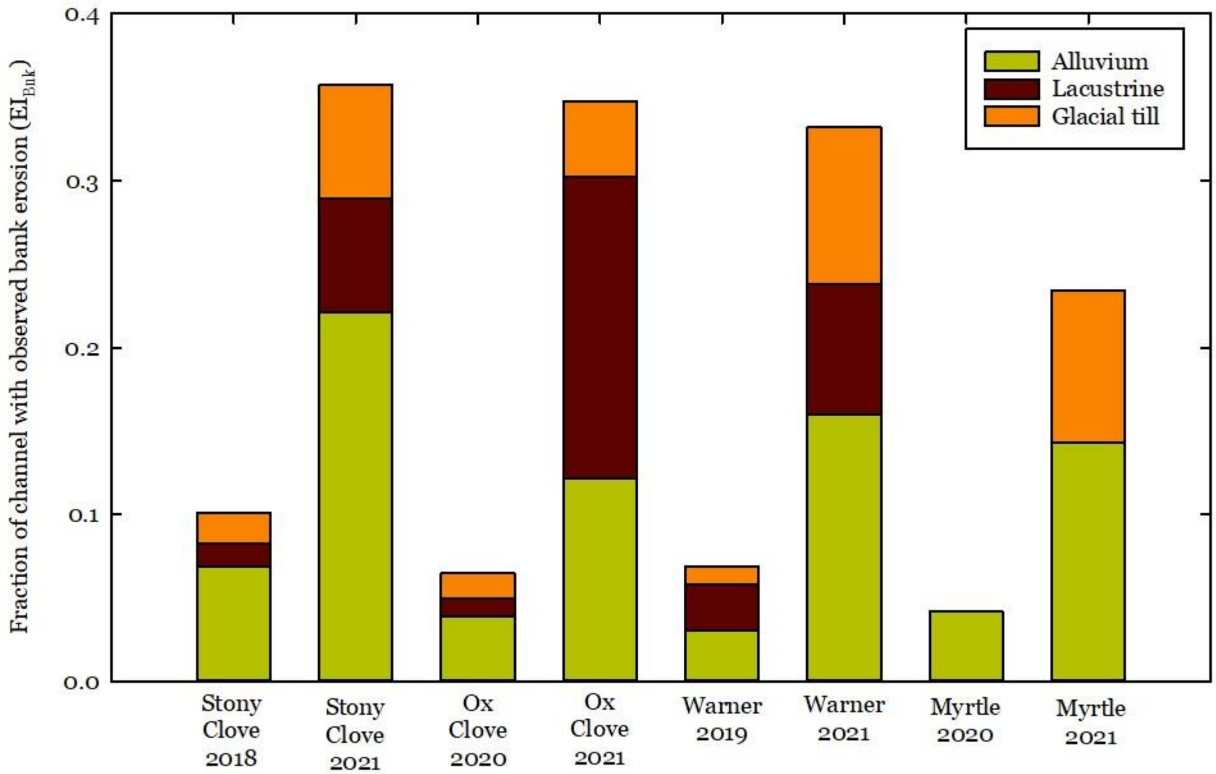

Figure 5. Pre- and post-flood observed bank erosion and associated sediments for non-sediment and turbidity reduction project (STRP) reaches on Stony Clove Creek and three tributaries. EI_{Bnk} = streambank erosion index.

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.

References

Cadwell, D.H., Skiba, J., 1986. Surficial geologic map of New York: , Albany, N.Y., New York State Museum.

Davis, D., Kneupfer, P., Miller, N., and Vian, M. 2009. Fluvial geomorphology of the upper Esopus Creek waterhed and implecations for stream management. In New York State Geological Association 81st annual meeting field trip guidebook. New York State Geological Society; 8.1-8.20.

Dethier, E., Magilligan, F.J., Renshaw, C.E. and Nislow, K.H., 2016. "The role of chronic and episodic disturbances on channel–hillslope coupling: the persistence and legacy of extreme floods." Earth Surface Processes and Landforms, 41 (10), 1437-1447. https://doi.org/10.1002/esp.3958

Edwards, T.K., Glysson, G.D., Guy, H.P., Norman, V.W., 1999. Field methods for measurement of fluvial sediment, US Geological Survey Denver, CO.

Effler, S. et al., 1998. "Turbidity and particle signatures imparted by runoff events in Ashokan Reservoir, NY," Lake and Reservoir Management, 14(2-3): 254-265. https://doi.org/10.1080/07438149809354335

Gartner, J.D., Dade, W.B., Renshaw, C.E., Magilligan, F.J., Buraas, E.M., 2015. "Gradients in stream power influence lateral and downstream sediment flux in floods," Geology, 43(11): 983-986. https://doi.org/10.1130/G36969.1

Gelda, R.K., Effler, S.W., Peng, F., Owens, E.M., Pierson, D.C., 2009. "Turbidity Model for Ashokan Reservoir, New York: Case Study," Journal of Environmental Engineering, 135: 885. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000048

Graziano, A. P., and Siemion, J., 2022, Flood-frequency data for select sites in the Esopus Creek Subbasin, New York: U.S. Geological Survey data release, https://doi.org/10.5066/P9O6GJCP.

Guy, H., 1969. Laboratory theory and methods for sediment analysis: US Geological Survey Techniques of Water-Resources Investigations Reports, book 5, chap. C1.

Hicks, D.M., Gomez, B., Trustrum, N.A., 2000. "Erosion thresholds and suspended sediment yields, Waipaoa River basin, New Zealand," Water Resources Research, 36(4): 1129-1142. https://doi.org/10.1029/1999WR900340

Levene, H., 1961. Robust tests for equality of variances. Contributions to probability and statistics. Essays in honor of Harold Hotelling, 279-292.
Magilligan, F.J., Buraas, E., Renshaw, C., 2015. "The efficacy of stream power and flow duration on geomorphic responses to catastrophic flooding," Geomorphology, 228: 175-188. https://doi.org:10.1016/j.geomorph.2014.08.016
Mano, V., Nemery, J., Belleudy, P., Poirel, A., 2009. "Assessment of suspended sediment transport in four alpine subbasins (France): influence of the climatic regime," Hydrological Processes, 23(5): 777-792.
McHale, M.R., Siemion, J., 2014. Turbidity and suspended sediment in the upper Esopus Creek subbasin, Ulster County, New York. US Geological Survey. http://dx.doi.org/10.3133/sir20145200
Mukundan, R. et al., 2013. "Factors affecting storm event turbidity in a New York City water supply stream," Catena, 107: 80-88. https://doi.org/10.1016/j.catena.2013.02.002
New York City Department of Environmental Protection (NYCDEP). 2022 Stream Management Program Upper Esopus Creek Subbasin Turbidity/Suspended Sediment Monitoring Study: Mid-Term Report, Valhalla, New York, 111p. https://catskillstreams.org/wp-content/uploads/2022/12/UEC-Watershed-Tn_SS-Monitoring-Study-Mid-Term-Report.Final_.pdf
R Core Team (2013). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.
Rich, J.L., 1935. Glacial geology of the Catskill Mountains: Albany, N.Y., New York State Museum Bulletin 299, 180 p.
Sauer, V.B., Turnipseed, D.P., 2010. Stage measurement at gaging stations. US Department of the Interior, US Geological Survey. https://doi.org/10.3133/tm3A8.
Siemion, J., McHale, M.R., Davis, W.D., 2016. Suspended-sediment and turbidity responses to sediment and turbidity reduction projects in the Beaver Kill, Stony Clove Creek, and Warner Creek, Subbasins, New York, 2010–14. 2328-0328, US Geological Survey. https://doi.org/10.3133/sir20165157
Siemion, J., Bonville, D.B., McHale, M.R., Antidormi, M.R., 2021. Turbidity–suspended-sediment concentration regression equations for monitoring stations in the upper Esopus Creek subbasin, Ulster County, New York, 2016–19. 2331-1258, US Geological Survey. https://doi.org/10.3133/ofr20211065
Siemion, J., 2023, Estimated streamflow data and suspended- sediment loads for select sites in the Esopus Creek watershed, New York, water years 2017 through 2021: U.S. Geological Survey data release, https://doi.org/10.5066/P9CSVDB1.
Staub, L.E., Cashman, M.J., and Gellis, A.C., 2022, Sediment Sample Data for Identifying and Monitoring Source Sediment Fingerprints within Stony Clove Creek, Catskills, NY from 2017 to 2020: U.S. Geological Survey data release, https://doi.org/10.5066/P9YFWCN4.
Turnipseed, D.P. and Sauer, V.B., 2010. Discharge measurements at gaging stations (No. 3-A8). US Geological Survey. https://doi.org/10.3133/tm3A8.
Underwood, K.L., Rizzo, D.M., Dewoolkar, M.M., Kline, M., 2021. "Analysis of reach-scale sediment process domains in glacially-conditioned catchments using self-organizing maps," Geomorphology, 382: 107684. https://doi.org/10.1016/j.geomorph.2021.107684
U.S. Geological Survey [USGS], 2006, Collection of Water Samples (ver. 2.0): U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A4. http://pubs.water.usgs.gov/twri9A
U.S. Geological Survey, 2016, National Water Information System data available on the World Wide Web (USGS Water Data for the Nation), http://dx.doi.org/10.5066/F7P55KJN.
Wagner, R.J., Boulger Jr, R.W., Oblinger, C.J. and Smith, B.A., 2006. Guidelines and standard procedures for continuous water-quality monitors: station operation, record computation,

and data reporting: U.S. Geological Survey Techniques and Methods 1-D3, 51 p. https://doi.org/10.3133/tm1D3.
Wang, K., Davis, D., Steinschneider, S., 2021. "Evaluating suspended sediment and turbidity reduction projects in a glacially conditioned catchment through dynamic regression and fluvial process-based modelling," Hydrological Processes, 35(9): e14351. https://doi.org/10.1002/hyp.14351
Wilcox, R.R., 2005. An approach to ANCOVA that allows multiple covariates, nonlinearity, and heteroscedasticity. Educational and psychological measurement, 65 (3): 442-450. https://doi.org/10.1177/0013164404268670.
Yellen, B. et al., 2014. "Source, conveyance and fate of suspended sediments following Hurricane Irene. New England, USA," Geomorphology, 226: 124-134. https://doi.org/10.1016/j.geomorph.2014.07.028