Evolution and Critiques of Terrain Mapping Techniques in the Upper Esopus Watershed Concerning Turbidity Reduction in the NYC Water Supply

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Honors Thesis
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Abstract

The most recent Pleistocene glaciation ended approximately 12,000 years ago, a cooling interval that deposited lacustrine clay and glacial till throughout the Catskill watershed. These fine-grained glacial legacy sediments erode during heavy rainfall events and create turbidity in the streams. The streams of the Catskills feed into various reservoirs that provide clean drinking water to millions of residents in New York City. Turbidity reduction in the Catskills is a NYS-funded effort to ensure the cleanliness of the New York City Water Supply. Since the early 2000s, the New York City Department of Environmental Protection (NYCDEP) has worked collaboratively with the Ashokan Watershed Stream Management Program (AWSMP), contracted firms, and municipalities to uphold its initiative to reduce turbidity in the Ashokan Watershed. This analysis of stream management explores the evolution of terrain mapping techniques used in the Stony Clove watershed and Broadstreet Hollow Creek watershed, both tributaries to the Upper Esopus Creek. The survey, monitoring, and restoration project phases of stream management all play a crucial role in the success in turbidity reduction. Over the past two decades, these approaches to stream management have evolved as new innovations have been made in the industry. Even so, there are still mentionable critiques of stream management that can be applied to future stream assessments, monitoring studies, and restoration projects.
Acknowledgments

I cannot express enough thanks to my advisory committee: Dr. Alexander Bartholomew, my primary thesis advisor; Dr. Shaiful Chowdhury, my secondary thesis advisor; and Dany Davis, NYCDEP Professional Geologist. In addition, I greatly appreciate my coworkers at SLR Consulting as well as my classmates for all of their support. This project could not have been completed without the support of my closest friends and family. My sincerest gratitude goes out to everyone who helped me throughout my thesis experience.
Abbreviations and Acronyms

AWSMP: Ashokan Watershed Stream Management Program
BEMS: Bank Erosion Monitoring Study
CAD: Computer Aided Design
CCEUC: Cornell Cooperative Extension of Ulster County
DEM: Digital Elevation Model
DSM: Digital Surface Model
DTM: Digital Terrain Model
EDM: Electron Distance Measuring
GCP: Ground Control Point
GCSWD: Green County Soil & Water Conservation District
GIS: Geographic Informations Systems
GLS: Glacial Legacy Sediment
GNSS: Global Navigation Satellite System
LAS: Lidar LASer
LiDAR: Light Detection and Radar
MLS: Mobile Laser Scanning
NYCDEP: New York City Department of Environmental Protection
NYSDEC: New York State Department of Environmental Conservation
RTK: Real-Time Kinematic
SFI: Stream Feature Inventory
STRP: Stream Turbidity Reduction Project
TIN: Triangulated Irregular Network
TLS: Terrestrial Lidar Scanning
UAS: Unmanned Aircraft System
USGS: United States Geological Survey
UCSWCD: Ulster County Soil & Water Conservation District
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1. Introduction to Physiographic Province

1.1 Geologic Setting of Catskills

The bedrock deposits of the Catskills consist of Middle to Upper Devonian mudstones, shales, sandstones and conglomerates, the youngest of which are generally terrestrial deposits of the Upper Devonian, known as the “Catskill Delta” (Isachsen & New York State Geological Survey, 2000). The physiographic region of the Catskill Mountains is a dissected plateau that was formed from an uplift of the Acadian Mountains with later erosion to the region (Figure 1). Associated with active margin tectonics of the Acadian Orogeny, the collision produced a peripheral basin with an eastward-dipping paleoslope to then be filled in with Middle Devonian sediments (Woodrow & Sevon, 1985). During the Pleistocene epoch, glacial ice and meltwater occupied most of the Catskills (Isachsen & New York State Geological Survey, 2000). The retreat of the glaciers left behind glacial legacy sediment (GLS) deposits such lacustrine clay, glacial till, and glacial meltwater deposits (Cadwell and Skiba, 1986). The subsequent erosion to the Catskill Mountains incised the plateau in the highlands and carved steep fluvial valleys throughout the lowlands, covering or replacing these glacial deposits with alluvium or colluvium (Cadwell and Skiba, 1986).
Figure 1: Bedrock geology of the Catskill Mountains. Source: Ver Straeten, 2013.
1.2 The History of the Ashokan Reservoir

During the late 19th century, there was an increase in immigration to New York City. This massive influx in population to the urban hub created the need to find a source of potable water. At the time, the current supplier of water to New York City was the Croton Aqueduct, draining water from the Croton River and transporting it from Westchester County to New York City. However, the Croton River did not have a large enough watershed to supply water to the growing population in New York City. In 1905, the New York City Board of Water Supply was created to tackle this water supply problem. Engineers of this board chose the Catskill Mountains as the new site for a new water supply system. There are five main watersheds in the Catskill Mountains. The watershed farthest to the southeast is the Ashokan Watershed. Also known as the Esopus Watershed, this basin drains into the Esopus Creek, a tributary to the Hudson River. The construction of the Ashokan Reservoir was completed in 1915 by the New York City Board of Water Supply, impounding the Esopus Creek, splitting it into the Upper Esopus Creek and the Lower Esopus Creek. Water from the Ashokan Reservoir travels 92 miles through the Catskill Aqueduct to the Kensico Reservoir in Yonkers New York (Ashokan Streams, 2012). Aside from the Ashokan Reservoir, the Schoharie Reservoir was annexed to the NYC water supply system in 1926. Located to the north of the Ashokan Reservoir, this reservoir was constructed by the damming of the Schohaire Creek, a tributary to the Mohawk River. Water from the Schoharie Reservoir reaches the Ashokan Reservoir by passing through the Shandaken Tunnel. Today, both the Ashokan Reservoir and the Schoharie Reservoir supply millions of NYC residents with clean and unfiltered water (Figure 2).
1.3 Stream Management in the Catskills

In recent decades, further examination of water quality in the Catskill Watershed found the presence of suspended sediment in the Ashokan Reservoir. The sources of the suspended sediment are GLS deposits from the most recent Pleistocene glaciation. These lacustrine clay or glacial till deposits contain clay-sized sediment that is easily erodible during higher flow events. The most concentrated sources of suspended sediment exist along large hill slope failures along
banks in which the channel margin intersects a GLS deposit (U.S. Geological Survey, 2015).
This influx of suspended sediment in the Ashokan Reservoir is a water quality concern. Stream assessments by the New York City Department of Environmental Protection have identified tributaries of the Esopus Creek that generate the largest proportions of turbidity in the Ashokan Watershed (National Academies of Sciences et al., 2020). The Ashokan Watershed Stream Management Program works collaboratively with the Cornell Cooperative Extension of Ulster County (CCEUC), NYCDEP, Ulster County Soil & Water Conservation District (UCSWCD), and municipalities to mitigate this water quality hazard in the Ashokan Reservoir Watershed. The first major step in mitigating turbidity in the Ashokan Reservoir involves taking a Stream Feature Inventory (SFI) of the bank and bed features that contribute to the turbidity of the watershed. Once areas of high turbidity are identified, engineers design Stream Turbidity Reduction Projects (STRPs) to effectively remodel the site and mitigate active erosion of GLS while also preserving the environmental integrity of the sites. Any site of potential future STRPs and completed STRPs are actively monitored to study the constantly changing stream surface.

1.4 Research Questions and Key Objectives

• What are the main projects and goals surrounding stream management in the Ashokan Watershed?

• How have they evolved over the past two decades since the inception of the NYCDEP stream management initiative?
• What are the common inconsistencies with the survey and remote sensing methods that are being implemented in stream management in the Ashokan Watershed?

• What are some ways to improve the survey methodology of the Ashokan Watershed?

• What are some ways to improve the remote sensing methodology of the Ashokan Watershed?

2. Focus Study Area: Ashokan Reservoir Watershed

2.1 Esopus Creek Overview

The Esopus Creek has an upper and lower watershed, separated by the Ashokan Reservoir. The Upper Esopus watershed is also known as the Ashokan Basin, draining 255 square miles of drainage (U.S. Geological Survey, 2015). The drainage area of the Ashokan Basin encompasses the towns of Hurley, Olive, Shandaken, and Woodstock in Ulster County as well as Hunter and Lexington in Greene County (Figure 3). Stony Clove Creek and Broadstreet Hollow Creek, two tributaries of the Esopus Creek, both contribute turbidity to the Upper Esopus watershed during high flow events.

2.2 Stony Clove Creek Overview

Stony Clove Creek, a primary tributary to the Esopus Creek, is a headwater stream in the Catskill Mountains physiographic province (Figure 4). Originating at Notch Lake, the stream runs primarily southward, passing through the hamlets of Lanesville and Edgewood in Greene County. Stony Clove Creek continues through the hamlets of Chichester and Phoenicia in Ulster County before emptying into Esopus Creek at its confluence. For most of the watercourse, New
York State Route 214 runs nearly parallel to the Stony Clove Creek. Stony Clove Creek contains multiple notable tributaries, including Warner Creek, Hollow Tree Brook, Ox Clove, and Myrtle Creek. With a watershed of approximately 32.4 square miles, the Stony Clove watershed is the largest tributary to the Esopus Creek (Green County Soil & Water Conservation District, 2005). The watershed consists of steeply cut drainage in the West Kill, Hunter, and Plateau wilderness. In 2003, the Stony Clove Creek was first surveyed by the New York City Department of Environmental Protection and the Green County Soil & Water Conservation District. They gathered data across the entire main stem of the stream. This data was compiled into the first stream management plan of Stony Clove Creek. Since this initial survey, the DEP and the United...
State Geological Survey have consistently monitored the quality of the water in the Stony Clove watershed. Over past two decades, multiple surveys of the Stony Clove watershed have been conducted to assess the condition of the watercourses. The water quality monitoring found that the Stony Clove Creek contributes the most to turbidity in the Ashokan Watershed (McHale and Siemion, 2014). The main stem of Stony Clove Creek contains multiple monitoring sites of large GLS bank exposures.
2.3 Broadstreet Hollow Creek Overview

Broadstreet Hollow Creek is a small headwater stream in the Catskill Mountains physiographic province. Originating in the Town of Lexington in Green County, the stream flows in a southerly direction and enters the Town of Shandaken in Ulster County before emptying into the Upper Esopus Creek. The Broadstreet Hollow Watershed is wider at the headwaters, narrowing at its outlet at Esopus Creek. With a drainage area of approximately 9.18 square miles, Broadstreet Hollow Creek is the second largest tributary to the Esopus Creek behind Stony Clove Creek.
(Ulster County Soil & Water Conservation District, 2003). Approximately four miles of the main stem of Broadstreet Hollow Creek run adjacent to Broadstreet Hollow Road, and contains one notable tributary known as Jay Hand Hollow. Broadstreet Hollow exists in the Central Escarpment of the Catskill Mountains with the stream draining the south slope of West Kill Mountain and part of North Dome Mountain. When compared to the Stony Clove Watershed, Broadstreet Hollow contributes much less turbidity to the Upper Esopus Creek. However, Broadstreet Hollow Creek still contains many exposures of lacustrine clay and glacial till (Cadwell and Skiba, 1986). Some exposures are lengthy and contribute turbidity during high flow events. The first stream management plan of Broadstreet Hollow Creek was completed in 2003, dividing the watershed into nineteen management units (Figure 5). The most recent stream assessment of Broadstreet Hollow Creek took place during the summer of 2023. This assessment found some notable GLS hill slope failures that could develop into a STRP in the coming years.
Figure 5: Broadstreet Hollow Creek Watershed organized by management units.
2.4 Geomorphology and Hydrology Background

The sections below summarize the necessary fluvial geomorphology and hydrology topic for the field of stream management. Sub-sections include: basic mechanics of streams, stream processes, stream dimensions, stream patterns, geomorphic responses, GLS and its impact on failure profiles, and the hydrologic cycle.

2.4.1 Basic Mechanics of Streams

The stream mechanics that drive erosion, transport, and deposition of sediment is a balance between driving and resisting forces. The ratio between the driving and resisting forces of a stream channel is a fluid property known as kinematic viscosity, represented by $Re$ (Uruba, 2018). The term $Re$ is the Reynolds number, a dimensionless parameter that expresses the change from laminar flow to turbulent flow with increasing depth and velocity (Ritter et al. 2011). In a state of laminar flow in a channel, the particles of water move in a straight path, uninterrupted by surrounding particles (Ritter et al. 2011). In laminar flow, internal friction is the dominant resisting force, fostering parallel flow layers in which the fluid slide smoothly past one another (Leopold et al. 1964). In a state of turbulent flow, more resisting forces are applied to the water to cause it to not move in straight parallel layers, producing a higher $Re$ value (Uruba, 2018). The resistance associated with turbulent flow is often caused by characteristics such as channel configuration and the size of material in the channel bed.

The definition of the Reynolds number is given by the following well-known formula:

$$Re = \frac{UL}{\nu}$$

$U$ holds for a typical velocity, $L$ is a typical length and $\nu$ is kinematic viscosity.

Figure 7: Reynolds number and its variables. Source: Uruba, 2018.
2.4.2 Stream Processes

Sediment begins in upland areas and moves downstream when the channel possesses enough stream power (Andualem et al., 2023). The rate of sediment transport is directly correlated to the flow rate or stream power (Simon et al., 2006). The main three processes that govern geomorphic change to a stream are erosion, transport, and deposition. Erosion of a stream bed or stream bank can have different causal processes depending on the geomorphic nature of a channel. Fluvial entrainment can occur due to the force generated from a river flow, which is more likely to occur when the stream flow overpowers the cohesion of the bank material (Ritter et al. 2011). In another case, a cantilever can occur when a undercut stream section fails and drops into the stream below, which is more likely to occur with a very cohesive bank material that is heavily vegetated and rooted (Ritter et al. 2011). Sediment transport is heavily governed by the stream discharge and the nature of debris. Generally, fine-grained sediment are part of the suspended load which travels directly downstream with relative ease (Ritter et al. 2011). Larger sediments that roll, slide, or bounce along the channel bottom are known as the bedload (Ritter et al. 2011). Without enough activation energy from driving forces, very-coarse sediment will remain immobile. Higher flow rates produce greater sediment transport capacity, meaning that small flood events can only transport only fine sediment while larger flood events can transport coarser sediment (Andualem et al., 2023). Deposition marks the end of sediment transportation and is heavily governed by the nature of debris, density of water, and fluid viscosity (Ritter et al., 2011). Generally, coarser particles will be deposited first as stream velocity decreases. In an natural alluvial setting, this phenomenon often produces natural sediment grading that can be seen along areas of accumulated deposition such as a sediment bar (Andualem et al., 2023). The nature of
sediment bars are influenced by many channel factors such as stream velocity, channel shape, and the possibility of commercial development and construction.

2.4.3 Stream Dimensions

A stream can be characterized by understanding the geometry of a channel. To understand the geometry of a stream, a stream surveyor would derive the dimensions of a stream segment. The channel profile at any given stream length has a width measurement and a depth measurement which can be used to calculate the cross-sectional area of a segment of stream (Ritter et al., 2011). In addition, the ratio of the stream bankfull width and stream depth can determine the available energy of a channel to help predict the outcomes of a high flow event (Jennings & Harman, 1999). Another important stream dimension is the slope of a stream segment. To take a longitudinal profile and find the slope, a “rise” dimension and a “run” dimension need to be taken. The “run” dimension or length measurement is the channel thalweg, a line that represents the greatest depth in a channel along a stream segment (Ritter et al., 2011). The change in elevation along the thalweg line is the “rise” dimension of stream slope.
2.4.4 Stream Patterns

The shape of a stream channel is measured by the dimension known as sinuosity, defined as the channel thalweg divided by the valley length (Jennings & Harman, 1999). Streams commonly have a sinuous pattern in which they meander back and forth. It is a rarity for streams to have straight channels for a long length. Along a particular meander bend, the outer bank receives more hydrologic resistance than the inner bank which produces erosion along the outer bank or cutbank and deposition along the inner bank or point bar (Ritter et al., 2011). As streams are dynamic systems, the channel geometry of a meandering streams always adjust its pattern so that it sustains hydrologic inputs. The geometry of a meandering stream can be measured using various parameters described below (Figure 8).

Figure 8: Common features of natural streams. Source: Hey et al., 1993.
A common occurrence in meandering streams, the thalweg tends to migrate back and forth over long periods of time (Ritter et al., 2011). This natural movement of the thalweg line is the stream’s attempt to maintain equilibrium. The increase in overall stream flow can open up additional channels and cause streams to become braided. Furthermore, streams can develop side channels that can be active or inactive depending on the stream flow intensity. Besides hydrology, the size and shape of bed material in a channel can also influence the channel shape and the spacing of pools and riffles. Bedload, mixed load, and suspended load all produce different geomorphic stream patterns over time (Jennings & Harman, 1999). The different modes of sediment transport are depicted below (Figure 9).
2.4.5 Geomorphic Responses

During a high flow event, energy is added to the stream system, creating conditions for the greatest geomorphic change. In natural conditions, a stream can maintain its morphology over a long period of time without any major aggradation or degradation. Natural conditions allow for stream stability, a balance between stream flow, bed load, and channel morphometry. Unstable conditions occur when this natural balance is breached by a change to the system, often increased stream flow. Excessive erosion to a channel bank can cause scour, a process in which the channel margin can incise or degrade over time (Jennings & Harman, 1999). A drastic increase in erosion also comes with a drastic increase in deposition. This sudden increase in erosion can cause stream channels to become entrenched, developing distinguishable terraces along bankfull stage. Aggradation can also occur, producing an elevated channel bed to compensate for the increase in transported bed load sediment (Jennings & Harman, 1999). An increase in stream flow or stream
slope will always increase sediment load and the size of sediment in transport (Jennings & Harman, 1999). Additional factors such as basin morphometry, climate, lithology, sediment load and channel character all influence the nature of a geomorphic response to high stream flows (Ritter et al. 2011). During a high flow event, bankfull discharge is a very important hydrologic measurement, marking the beginning of the floodplain in a channel, representing the elevated stream flow that transports most of the sediment load and ultimately shapes a channel over time (Jennings & Harman, 1999). A stream flow event that reaches bankfull stage occurs approximately every 1.5 years. Although, the Rosgen stream classification system utilizes bankfull stage to find the width/depth ratio, entrenchment ratio, and sinuosity, bankfull stage can sometimes be difficult to precisely identify (Figure 10).

Figure 10: Rosgen stream classification system.  
Source: Rosgen, 1996.
2.4.6 Glacial Legacy Sediment and its Impact on Bank Failure Profile

A incising bank comprised of GLS will create a different type of bank failure than a bank comprised of alluvium due to the difference in geology. As GLS contains mostly very fine-grained sediment, the forces binding the bank together act differently than a typical alluvium bank, creating a different failure profile. Given the abundance of GLS deposits in the Ashokan Watershed, there can be different failure profiles (Figure 11).

Figure 11: Different stream bank failure profiles. Source: Cluer et al., 2011.
2.4.7 The Hydrologic Cycle

Streams can be described as open systems because of the properties of the hydrologic cycle, the continuous transportation of water on, above and below earth’s surface. Focusing on the hydrology of a stream system on land, such an environment naturally receives input forces from precipitation and groundwater in the form of surface runoff. The water supply can replenish itself because of the output forces of evaporation and transpiration, completing the open system of the hydrologic cycle (Figure 12).

Figure 12: Components of the hydrologic cycle. Source: Callahan, 2014.
3. Stream Management Methods

3.1 Stream Feature Inventory (SFI)

A stream feature inventory is a type of geomorphic assessment that the Ashokan Watershed Stream Management Program has utilized over the past few decades to collect important geomorphic data on watercourses in the Ashokan Watershed. Commonly conducted in the summer months by foot, a stream assessment can involve taking field notes, geospatial data, and photos of a segment of stream. The survey is often conducted in a team of 2-3 people so the workload of data collecting is most effective. SFIs can have varying project scopes depending on the project location and project goals by the client. Some stream assessments may only be a particular stream reach while others require assessing the entire main stem of the stream. Below is a table of equipment that is commonly used in a SFI (Figure 13).
In this analysis, the focus will be on the stream assessment methods of Broadstreet Hollow Creek. The first stream assessment of Broadstreet Hollow Creek was published during June of 2003, and was divided into two volumes. The first volume overviews the watershed characteristics and background information. The second volume consists of a segmented analysis by dividing the main stem of Broadstreet Hollow into nineteen management units. Each of the management units contains sections covering flood erosion threats, water quality, and stream ecology. A reassessment of Broadstreet Hollow Creek was completed over the summer of 2023. This reassessment used the nineteen management units from the 2003 stream assessment to keep data collection principles consistent. The report for this reassessment will be published during 2024. For this analysis, the focus will be on the current approach to collect geospatial data.

<table>
<thead>
<tr>
<th>Equipment Commonly Used in a SFI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chest Wader</td>
</tr>
<tr>
<td>Wader Boots</td>
</tr>
<tr>
<td>Traction Spikes</td>
</tr>
<tr>
<td>Field Notebook</td>
</tr>
<tr>
<td>Shovel</td>
</tr>
<tr>
<td>Field Phone</td>
</tr>
<tr>
<td>Measuring Stick</td>
</tr>
<tr>
<td>Measuring Wheel</td>
</tr>
<tr>
<td>Range Finder</td>
</tr>
<tr>
<td>Trimble Geo 7x</td>
</tr>
<tr>
<td>Telescopic Rod</td>
</tr>
<tr>
<td>GNSS Antenna</td>
</tr>
</tbody>
</table>

Figure 13: Common equipment necessary for a Stream Feature Inventory.
In addition to field notes and photos, surveyors logged geospatial data with a Trimble Geo 7x, a handheld computer that is a highly accurate data collecting device (Figure 14). Although the Trimble Geo 7x can be handheld, the device can also be mounted to a telescopic rod. The telescopic rod can help stabilize the Trimble Geo 7x when collecting an new point file. Stabilizing the device can also improve satellite connectivity. The device can also be connected to a Global Navigation Satellite System (GNSS) antenna to improve satellite connectivity and collect more accurate data. The type of antenna used for the reassessment of Broadstreet Hollow
Creek was the Zephyr 3 Rover GNSS. This antenna is a high performance system that uses Real-Time Kinematic (RTK) positioning to provide low elevation tracking, which is essential considering the steeply cut landscape of the Catskills (Trimble, 2017). Through a set of guidelines implemented by the NYCDEP, surveyors can characterize the stream feature by selecting particular attributes when creating a new data point. The software TerraSync was used to collect all of the geospatial data for the most recent assessment of Broadstreet Hollow Creek. In TerraSync, each classification of stream feature has a different set of attributes to choose from. The attributes for a Bank Erosion Sediment Source are shown below (Figure 15).

<table>
<thead>
<tr>
<th>FEATURE</th>
<th>DESCRIPTION</th>
<th>ATTRIBUTES DEFINING LINES</th>
</tr>
</thead>
</table>
| Bank_ESS     | Bank erosion sediment source – points collected to record location of bank erosion that can contribute suspended sediment. Number of points depends on changes in various attribute values. | Conf_S = site confinement  
               |                                                                             | Cnf_Margin = confining margin type  
               |                                                                             | Status = erosional status of bank  
               |                                                                             | Bank_Type = bank material properties  
               |                                                                             | Bank_Geo = geologic composition of bank  
               |                                                                             | Bank_Matri = sediment characteristics of bank  
               |                                                                             | SS_Primary = primary suspended-sediment source  
               |                                                                             | SS_Second = secondary suspended-sediment source  
               |                                                                             | Fail_Gen = general causes of bank erosion  
               |                                                                             | Fail_Spec1 = primary mode of bank failure  
               |                                                                             | Fail_Spec2 = secondary mode of bank failure, if present  
               |                                                                             | VegCovPer = percentage range of vegetation cover  
               |                                                                             | Toe_Debris = natural bank toe protection  
               |                                                                             | Wood_Buff = range of width of woody riparian buffer  
               |                                                                             | Severity = estimate of bank erosion severity  
               |                                                                             | Causal_P = estimated cause of bank erosion  
               |                                                                             | Hyd Align = hydraulic alignment influencing bank erosion  
               |                                                                             | Geotech_P = geotechnical process influencing bank erosion |

Figure 15: Description and attributes for a bank erosion sediment source. Source: (Davis, 2018).

To collect a point, the “Skyplot” feature is used to collect and average together many positions (Beyerhelm, 2008). To take a point, the device must be held in place so that the accuracy of the satellites available can be as high as possible (Figure 16). Once geospatial data is collected and
stored in a geodatabase file, it can be uploaded to an ArcGIS map to be observed. The data can be seen in a table format with all of the attributes chosen during characterization. As surveyors walked down Broadstreet Hollow, they identified and took inventory of various primary features including bank/bed erosion, natural features such as large wood accumulations and bedrock, and man-made features such as revetment, bridges, culverts, grade controls, and head cuts. In addition, photos were taken along the entire length of the stream and assigned to points even if there was no presence of primary stream features. These photos are useful in identifying the general dimensions and shape of each stream segment.

Figure 16: TerraSync software with explanations of the Skyplot section. Source: Beyerhelm, 2008.
3.1.2 Inconsistencies

There are no noticeable critiques to be made about the methodology of taking field notes and photos. However, there are some critiques to be made about the approach to collecting geospatial data with the Trimble Geo 7x. Below are three notable inconsistencies found in the current SFI geospatial data collection methodology.

**Critique #1: Inaccuracies**

There is a consensus to reduce the Predicted Post-processing Accuracy (PPA) to an acceptable value. A common dilemma with the 2023 Broadstreet Hollow Creek SFI was that the PPA was often greater than an acceptable value, creating the need for manual changes to the geospatial point data after field work. The increased PPA during point collection is due to many factors such as the lack of satellites, the steeply cut environment of the Catskills, and the old age of the Trimble Geo 7x. To make data collection more efficient and productive, the vertical and horizontal accuracies after post-processing need to always remain below one meter.

**Critique #2: Accessibility**

The accessibility of the Trimble Geo 7x creates limitations on the note-taking process. An attached stylus is used to type on words or phrases on the TerraSync software. Although suggested phrases appear during typing, the touch screen on the device is very small. In addition, working during wet weather can make note-taking on the Trimble Geo 7x more difficult due to the small touch screen.

**Critique #3: Battery Life**
The Trimble Geo 7x was released in 2014, nearly a decade ago. According to its specifications, the Trimble Geo 7x has a rechargeable lithium-ion battery pack with a capacity of 2.5 ampere-hours (AH) or 2500 milliampere hours (mAh). A fully charged lithium ion battery should be able to run for at least 8 hours. However, with extended use, the run time of the GNSS can decrease. This creates a risk of the GNSS running out of battery during field work, limiting the data collection capabilities to the battery capacity of an outdated GNSS.

3.1.3 Proposed Solution

The solution that addresses the SFI inconsistencies mentioned above is gathering funding for a newer GNSS device. The Spectra Precision SP20 Decimeter GNSS Handheld is the perfect upgrade for SFI survey (Figure 17). Released in 2018, the SP20 features a touch screen size of 5.3” and a lithium-ion capacity of 6.4 AH or 6400 mAh (Spectra Geospatial, 2018). Upgrading to a SP20 would improve geospatial accuracy, accessibility, and battery life. This, in turn, would reduce the manual labor required to fix inaccurate point data and increase field work efficiency.

Figure 17: Spectra Precision SP20 Decimeter GNSS Handheld. Source: SEP Geospatial, 2018.
3.2 Stream Surface Comparison Methods

Understanding the past and present states of a stream surface can help predict the future geomorphic change that will occur to a stream reach. A joint effort between NYCDEP and USGS, the Bank Erosion Monitoring Study (BEMS) was created in 2016 to monitor hill slope failures in the Stony Clove Creek watershed that contribute turbidity to the NYC Water Supply (2023-2025 AWSMP Action Plan, 2023). Monitoring the amount of erosion and deposition that occurs at these sites can have a significant application to understanding the principles that drive such stream processes. In the coming years, the BEMS will have accumulated ten years of stream surface comparison data (Davis et al., 2016). Over the course of ten years, there have been different methods of stream surface comparison. In this analysis, the evolution of methods will be discussed and the process of each methodology will be critiqued.

3.2.1 Cross Sections and Longitudinal Profiles

The first round of stream surface surveys took place during 2016 and 2017. The seven BEMS sites utilized ground-based topographic survey methods to take cross sections and longitudinal streambed profiles. In the case of smaller stream channels, cross sections can be measured by hand with a survey wheel and a survey rod. Larger stream channels will require a total station system to measure the cross section dimensions. A total station, also known as an auto level, uses electronic distance measuring (EDM) to acquire highly accurate distance and angle measurements (TheConstructor, 2017). Laser scanning devices, such as a total station, are mounted in place with a tripod to ensure a consistent measurement. It is a common practice to take multiple cross sections upstream, downstream, and within the monitoring site. Each cross
section requires a width dimension and a depth dimension. The width measurement of a cross section should be taken at the bankfull stage to acquire the bankfull width. To acquire the depth dimension of a cross section, measurements should be taken at regular interval along the bankfull width. To attain a complete profile of the depth of the channel, landmark measurements should be taken at the channel thalweg, the edge of water on both banks, and at bankfull on both banks. Look downstream to differentiate left bank from right bank in measurements. With the width measurement and the depth measurements, parameters such as the cross sectional area, the width to depth ratio, mean bankfull depth, entrenchment ratio, and channel discharge can be calculated.

To monument the completed cross section for future reference, the ends of each cross section are marked with capped rebar. Longitudinal profiles are taken to acquire multiple depth measurements across a stream length, getting the channel slope. The thalweg line is used as the “run” or length dimension of the downward slope. Multiple depths are taken at a regular interval to get the “rise” or change in elevation. The longitudinal profiles spanned approximately twenty times the baneful width upstream and downstream of the center of each monitoring site (SLR Consulting, 2023). The final product of the first round of BEMS survey was a topographic map at each monitoring site with a 2-ft contour interval (SLR Consulting, 2023).

3.2.2 First Usage of Structure From Motion Techniques

After the initial topographic survey at the BEMS sites, a new survey technology emerged known as aerial photogrammetry. Photogrammetry is the technique of obtaining three-dimensional models from photos. An Unmanned Aircraft System (UAS) can collect hundreds of orthophotos of a site in one drone flight. UAS-based photogrammetry has been used to monitor stream
corridors in Vermont watersheds using similar processing techniques (Hamshaw et al., 2019). In the case of the aerial photogrammetry used in the BEMS sites, a DJI Phantom 4 Pro was used to take the aerial photos. UAS-based orthophotogrammetry uses a survey method known as Structure-from-Motion (SfM), which allows for two-dimensional (2D) aerial images to be converted into three-dimensional (3D) digital surfaces using post-processing techniques on the softwarePix4Dmapper. Compared to topographic survey, the previous methodology, UAS-based orthophotogrammetry provides superior surface coverage.

3.2.2.1 Post-processing UAS Data

To start processing on thePix4Dmappersoftware, a project folder must first be created for the chosen site. Project setup for processing involves adding the UAS aerial images, setting the coordinate system, and choosing the output units. For processing UAS drone data, there are three main processing steps: Initial Processing (1), Point Cloud and Mesh (2), and DSM, Orthomosaic and Index (3). Each step requires extensive computer processing taken multiple hours to complete. Once all of the project data is imported, the project can be created and the processing of Step 1 can begin. After Initial Processing is complete, the final project outputs can be chosen (Figure 18). For the BEMS sites, final outputs include a Digital Terrain Model (DTM) raster, an orthomosaic aerial image, and 1-foot topographic contours that were created from the Digital Surface Model (DSM).
Figure 18: Processing tab on Pix4Dmapper showing each processing step and outputs.
The result of the *Initial Processing* step is a 2D surface of all of the drone images in which they are overlain and meshed together. During the UAS drone flight of the site, ground control points (GCPs) were strategically placed to create tie points to reference during the *Point Cloud and Mesh* step. These GCPs must be manually identified on the 2D surface and matched with their XYZ location to create these tie points. Once a tie point is created, the center of each survey target must be selected at every drone image containing the target to pinpoint the XYZ location. During survey, the XYZ coordinates were already derived so marking the images will calculate an *Error to GCP Initial Position* (Figure 19). These errors of each dimension should be below 0.1 US survey feet for optimal point cloud processing. Once all of the GCPs are inputed and tied to their proper targets using the *Reoptimize* selection in the process menu, the *Point Cloud and Mesh* processing step can be run.
After Step 2 of processing is complete, there will be a “point cloud” of generated points representing high vegetation, buildings, cars, and ground surface. This next processing step involves manually editing the point cloud to disable any points from the model that are not the ground surface. This includes high vegetation, buildings, or any other manmade structures. This processing step requires tracing a box around the points to select and disable them from the model. Removing unwanted points from the model can take multiple hours of manual labor.
Once all desired points are removed from the model, all remaining points must be classified as *Ground* and an updated *3D Textured Mesh* must be generated. Finally, the *DSM, Orthomosaic and Index* step can be run to acquire the DTM, DSM, orthomosaic, and 1-foot contours. These models can be uploaded to *ArcGIS* to perform surface comparisons.

On *ArcGIS*, a LASer format file (LAS) can be imported from *Pix4Dmapper* to be converted into a Triangulated Irregular Network (TIN) surface through a series of 3D Analyst tools in the geoprocessing section (Esri). LASer format files of sites tend to use a large amount of computer processing power due to the large file size. Once the LAS file is added to the GIS map, the *Thin LAS* tool is used to reduce the file size of the LASer file (Esri). This tool uses a 2D thinning dimension and a *Closest to Average Height* point selection method to simplify the original LAS file into a “thinner” version. Next, the LAS file needs to be clipped to only the desired study area. To do this, a polygon shapefile is created to distinguish the outer boundary. In addition, internal regions of the LAS file can be clipped out in areas lacking sufficient LAS points or areas with obvious outlying points (Figure 20). It is crucial to ensure that there aren’t any significant errors in the LAS file because they will greatly impact the accuracy of the completed TIN surface.
Once the desired LAS points remain within the newly-created polygon shapefile, the Create LAS Dataset tool is used to combine both the thinned LAS file and the boundary polygon into an LAS dataset (Esri). The LAS dataset can then be converted to a TIN surface with the LAS Dataset to TIN tool (Esri).

Figure 20: Creating polygon shape file to clip out unwanted LAS points. Source: ArcGIS.

3.2.2.2 Critique of UAS-based Orthophotogrammetry

Although it is a very extensive process, the UAS-based surface comparisons were a significant improvement from the previous methodology of only using ground-based topographic techniques. After being tested in a pilot program in 2017, UAS-based orthophotogrammetry was fully implemented in 2018 for the next round of BEMS survey (SLR Consulting, 2023). The
addition of UAS technology greatly improves topographic accuracy and overall survey coverage. However, over the next few rounds of BEMS survey, it became clear that there was a key component missing from the stream surfaces. Although the UAS-based survey can accurately cover land surfaces, a review found that the DSM products provided limited coverage of channel bathymetry (SLR Consulting, 2023). The review led to the development of surface combination techniques by adding bathymetric channel data to the UAS-based TIN surface.

3.2.3 Implementation of Bathymetric Data to UAS-based Orthophotogrammetry

To obtain the bathymetric data, ground survey products and a DSM are needed to construct the channel bottom surface. Compared to the predeceasing method, the surface combination between the existing DSM and bathymetric data requires additional processing steps. The bathymetric data points the UAS-based survey points in areas in which the stream bed cannot be accurately measured. Surface combination also included supplemental ground-based survey points of monumented cross sections, longitudinal profiles, and deep channel pools to increase precision of the DSM.

UAS-based coverage of the channel is replaced with the bathymetric data using tools in ArcGIS (Esri). This modified approach still uses the same Pix4Dmapper post-processing techniques as the predeceasing method. For BEMS, surface combination methods were used from 2021 through 2023, performing two rounds of surface comparisons. The first round performed in 2022, utilizes the DSM raster and the orthomosaic, both products of Pix4D post-processing, to replace the UAS points with bathymetric data around ground survey. The second round performed in 2023 was a modification of the first round. Instead, the ground survey points and
thalweg line area added to the LAS dataset before converting it to a TIN surface. Both techniques utilize the same total station survey methods to acquire ground survey products. Also, both techniques use AutoCAD Civil 3D to create a thalweg line from the ground survey points. The key differences in method exist within the choice of ArcGIS 3D analyst tools.

3.2.3.1 Obtaining Ground Survey Products Necessary For A Bathymetric Surface

As stated in previous sections of this report, total station survey is a method of ground-based topographic survey that can collect geospatial data necessary for various stream elevation profiles. The geospatial data consists of ground survey points that identify the channel thalweg, monumented cross sections, and longitudinal profiles. These geospatial products from the total station survey of the site are added to the GIS map and converted to a shapefile. Using the AutoCAD Civil 3D software, a 3D polyline can be created by connecting the thalweg survey points to form a thalweg boundary marking the deepest point in the channel across a longitudinal length (Figure 21). Before proceeding, the thalweg data needs to be checked to insure that the points will accurately represent the stream channel. In split channels, additional thalweg lines will need to be drawn. In other cases, it may make sense to remove ground survey data in areas deemed suitable for UAS-based survey coverage.
3.2.3.2 2021-2022 Surface Combination Method

This round of BEMS surface comparisons combined a UAS-based DSM raster and bathymetric survey. After the thalweg line is created, the DSM raster must be resampled to a cell size of 1-2
feet using a cubic resampling method found in the Resample tool (Esri). The resampled raster needs to be modified to remove areas in which there are errors from post-processing. To remove unwanted areas, a polygon shapefile can be created to identify the clipping boundary. The DSM raster can be converted to a hillshade to better visualize the clipping boundary (Figure 22). Once the clipping geometry is finalized, the Clip tool can be used to resize the resampled raster (Esri).

Figure 22: Hillshade and its clipping boundary. Source: SLR Consulting, 2023.

After performing the Clip on the resampled raster, it can be converted to a point shapefile. Along with this new point file, a polygon shapefile can be created to identify the outer boundary of the entire TIN surface. Areas within these internal and external boundaries of this polygon shapefile
include both UAS-based points and points to be replaced with ground survey points and become the bathymetric area. The bathymetric area consists of only the stream bed. The outer boundary of the bathymetric area should mark the edge of water as well as any large boulders along the bank and side channel sediment bars. Furthermore, any areas in which the UAS could accurately cover the stream bed can be excluded from the bathymetric area. Inner areas within the bathymetry can be removed such as any significant boulders and middle-channel sediment bars. Creating internal boundaries to the bathymetric area polygon shapefile will create additional polygons. Once the bathymetric areas are identified, the polygons should be merged to a single polygon before proceeding. It is helpful to look at the UAS orthoimagery and the bathymetric survey points to determine the bathymetric area. The entire process of deriving the bathymetric area can require additional manual labor to ensure precision. Upon finalization of the bathymetric area polygon shapefile, any UAS points within the bathymetric area must be deleted by using the *Spatial Join* tool to merge the attribute tables of the bathymetric polygon shapefile and the UAS point shapefile (Esri). An attribute can be created in the newly joined attribute table that marks all UAS points that overlap within the bathymetric areas. Once highlighted, these unwanted points can be deleted from the file, leaving only the relevant bathymetric areas (Figure 23).
At this point in the processing steps, all of the inputs to create the TIN surface have been created. A TIN can now be created with the following inputs: the clipped UAS point shapefile, the bathymetric survey point shapefile, the clipped polygon shapefile of the outer boundary of the TIN surface, and the 3D polyline of the channel thalweg. This action is done using the *Create TIN* tool (Esri). The produced TIN surface needs to be assessed to ensure that it accurately represents the terrain of the site. A useful approach to checking a TIN surface involves

*Figure 23: Bathymetric areas. Source: SLR Consulting, 2023.*
comparing it to the UAS-orthoimage to see if the interpolation of the points makes sense with the site. In some cases, modifications to the TIN inputs will be needed to fix any inaccuracies.

3.2.3.3 2022-2023 Surface Combination Method

The surface combination approach used in the 2022-2023 BEMS surface comparison begins with importing the LASer file from *Pix4Dmapper* to a GIS map and performing the *Thin LAS* tool to reduce the LASer file size and density (Esri). Along with the thinned LASer file, a 3D thalweg line and ground survey points can be added to the GIS map. A polygon shapefile is created to define the internal and external boundaries of the LASer file. This shapefile should only include areas with sufficient and accurate LAS point data. Any unwanted LAS points can be clipped out of the polygon shapefile by creating an internal polygon, clipping the outer polygon, and deleting the inner polygon. Similar to the previous approach, a polygon shape file is created to show the bathymetric areas in which the UAS-based points will be replaced with ground survey data. Checking the UAS orthoimagery, DSM surface, and the ground survey points assist in defining the bathymetric areas. Very shallow areas that were captured well by the UAS survey can be excluded from the bathymetric area. In addition, large boulders along the stream bed can be removed from the bathymetry through the same clipping procedure used to remove internal polygons from the LAS border shapefile. The final bathymetric area polygon shapefile may contain multiple polygons, requiring that it must be merged into one polygon before proceeding (Figure 24).
Once the bathymetric areas are finalized, the *Merge* tool is used to join the LAS boundary polygon shapefile and the bathymetric area polygon shapefile (Esri). Next, the bathymetric area polygon is highlighted and removed so that only the over-bank area remains (Figure 25).
Using the *Extract LAS* tool, the LAS data from the thinned LASer file can be extracted to only the desired over-bank areas, excluding the bathymetric areas (Esri) (Figure 26).

Figure 25: Over-bank areas highlighted in pink. Source: SLR Consulting, 2023.
Using the Create LAS Dataset tool, the extracted LASeR file containing just the overbank areas, the channel thalweg line, ground survey points, and the LAS boundary polygon shapefile can be inputted as surface constraints to the dataset (Esri). The produced LAS dataset can be converted to a TIN surface using the LAS Dataset to TIN tool (Esri). Similar to the previous technique, the TIN surface must be analyzed to ensure there are no significant inaccuracies in the TIN surface. Mitigating any inaccuracies in the TIN surface is a crucial step to take before proceeding to the DSM surface comparison to measure geomorphic change.

3.2.3.4 DSM Surface Comparisons
Geomorphological change can be determined by expressing the difference between two DEM models of the same survey location, a dataset that is commonly referred to as the DEM of Difference (DoD) (Hamshaw et al., 2019). To perform a surface comparison of two stream surfaces, two surface files from the same site must be added to the GIS map. These two surface files could be an LAS dataset or a TIN surface. In addition, a shapefile representing the comparison boundary should be added to only include areas in which the two surfaces overlay. Continuing with 3D Analyst tools, the *Surface Difference* tool is used to create a polygon shapefile and raster file of the changes between the recent survey and the previous survey (Esri). With the *Surface Difference* tool, it is important to input all of the spatial data correctly. This includes the two surface files, the companion boundary to mark the processing extent, and the raster cell size to optimize spatial resolution.

Depending on the project objectives, it may be necessary to include a minimum tolerance when performing the surface difference, which will essentially remove any negligible changes from the surface difference shapefile and raster. Only the significant erosional and depositional changes remain on the surface difference files. After performing the initial *Surface Difference*, the *Raster Calculator* tool can be used to create a raster differencing negligible change from significant change by a chosen tolerance factor (Esri). For this Spatial Analyst tool, a Python syntax runs a map algebra expression to execute the calculation. Next, the *Raster to Polygon* tool is used to convert the limited raster into a polygon shapefile (Esri). This polygon shapefile must be clipped so that only the areas of significant change remain. In the attributes table of the shapefile, there is a value that distinguishes the areas of negligible change from the areas of significant change. This makes it easy to clip out the areas of negligible change and merge the remaining polygons
into a singular polygon. The final step involves using the Surface Difference tool again. The same TIN surfaces from the first Surface Difference are used. However, the processing extent will be the new limited boundary shapefile that only highlights areas of significant erosional and depositional change. The final products of the second Surface Difference will be a polygon shapefile and a raster. The elevation data presented in these final products can be quantified to make inferences on the geomorphic nature of a site.

3.2.3.5 Critiques of 2023 UAS-based Orthophotogrammetry and Surface Combination Methods

UAS-based orthophotogrammetry is undoubtably a major innovation in the watershed surveying sector. To add to this, the implementation of surface combination techniques to depict the stream bed profile pushed the capabilities of UAS-based survey even farther than originally expected. In comparison to the 2022 surface combination methods, the 2023 surface combination methods provide a more simplistic approach. Yet, there are a few disadvantages of UAS-photogrammetry and surface combination methods. The major critiques of these techniques are organized into three core groups: UAS Survey, Post-Processing Drone Data, and Surface Combination and Surface Comparison.

**Critique #1: UAS Survey**

There are many variables that can limit UAS-based data such as the GCP placement, the number of GCPs, the flight elevation, and the need for multiple flights at larger sites. Natural factors such as light, wind, vegetation cover, water quality, and bank angle can also make identifying the stream bed difficult. Photogrammetric survey must be done during calm and clear weather so that the stream flow is not turbulent. Even so, accuracy of the UAS-based survey is greatly weakened
by the lack bathymetric coverage due to vegetation cover. Vegetation cover can block the drone’s ability to accurately capture the stream bed.

**Critique #2: Post-Processing Drone Data**

Identifying GCPs on *Pix4Dmapper* can create issues if there is a high *Error to GCP Initial Position*. To mitigate this inaccuracy, GCPs with abnormally high errors can be removed from consideration. However, fewer GCPs can cause the rest of the surface to become less accurate.

Another major concern with post-processing on *Pix4Dmapper* is inaccuracies that arise during the point cloud identification process. Manual point cloud identification on large sites can take multiple work days. In addition, inaccuracies arise when too much vegetation is removed and when not enough vegetation is removed. Areas that are “overdone” will have many gaps in the surface to be filled in by the *3D Textured Mesh*. Areas that still have vegetation will produce a bumpy and variable ground surface. There is a very difficult balance to reach during point cloud identification that requires a high attention to detail. Nonetheless, a highly accurate surface takes a long amount of manual attention.

**Critique #3: Surface Combination and Surface Comparison**

Although supplemental ground survey products can be added to the DSM, there are many complications during post-processing with differentiating UAS-based survey from bathymetry during surface combination. During surface combination, there are many instances in which the DSM needs to be checked for errors. In addition, boundary shape files need to be accurately
delineated or the surface comparison won’t be accurate. As such, the surface combination methodology opens up the surface to additional inaccuracies due to human error.

3.2.4 Aerial LiDAR

Implementation of Light Detection and Radar (LiDAR) scanning at BEMS sites started in late 2023. After a review of UAS-based orthophotogrammetry in 2023, the NYCDEP decided to continue the bank erosion monitoring study with aerial LiDAR techniques. LiDAR is a type of laser scanner that is an extremely strong remote sensing tool that can obtain accurate 3D information by measuring the distance between the sensor and a target. Using the principles of radar scanning, pulses of light emitted from the laser scanner travel to and from the target in which the time and intensity of the reflections are measured to derive a distance measurement (Meade, 2021). Along with the LiDAR sensor, a GNSS and additional high-accuracy sensors are necessary to measure the LiDAR sensors position in space (Meade, 2021). A LiDAR sensor can be mounted to an aerial drone to acquire many scanning positions of the terrain to geo-reference and develop a highly detailed elevation model. This technology of Mobile Laser Scanning (MLS) has been proven very effective in collecting elevation data and producing DEMs (Meade, 2021; Di Stefano et al., 2021). The aerial LiDAR BEMS survey in the fall of 2023 used 3-return aerial LiDAR, meaning each XY coordinate can have up to 3 Z coordinates. The LAS data collected from survey can be uploaded to Trimble Business Center for post-processing. The vegetation removal processing is now automated on Trimble Business Center, eliminating the need for Pix4Dmapper manual post-processing and the preceding surface combination techniques. Even so, there is still some manual processing involved with adding in bathymetric
data to the surface model on AutoCAD software. Bathymetric data includes the thalweg line and other ground-based features such as cross sections and longitudinal profiles. The final surface model can be checked for any inconsistencies by looking at the aerial imagery of the site and comparing it to the TIN surface. The final elevation model can then be utilized in a surface comparison to measure geomorphic change with a prior surface of the same site. The completed TIN surface is added to ArcGIS and can be compared immediately with no additional steps.

3.2.4.1 Critique of Unmanned Aerial LiDAR

The main disadvantage of aerial LiDAR is the inaccuracies that arise due to natural factors of the site. Along very steep or undercut stream banks, it is difficult for the LiDAR to obtain an accurate vertical measurement (Meade, 2021). This vertical measurement can be further limited by heavy vegetation along the stream bank. In this instance, these are geomorphological and ecological factors that cannot be altered for the sake of improving accuracy. Heavy vegetation also hinders vertical accuracy in the floodplain due to the infrared lasers inability to penetrate through the vegetation or its inability to return the signal from the ground surface (Meade, 2021). Furthermore, LiDAR often cannot penetrate through the water to measure the stream bed but rather reflect off of the water surface. This occurrence is likely due to the presence of turbid flow or deep pooling regions along the stream bed. The implementation of ground survey to the final TIN surface helps to mitigate this concern. However, deciding where to use the LiDAR data along the stream bed becomes a huge challenge for the survey crew.

3.2.5 Future of Stream Surface Models
After assessing each technique for developing DEMs of stream surfaces, aerial LiDAR is the most up-to-date and innovative approach. It is expected that the NYCDEP will continue with aerial LiDAR technology for the next round of BEMS surface comparisons during 2024, upgrading to 5-return LiDAR, greatly improving accuracy in densely vegetated regions. In the past few years terrestrial LiDAR scanning (TLS) has been used to supplement in areas in which the aerial LiDAR can’t accurately reach the ground (Figure 27).

Figure 27: Terrestrial Lidar Scanner capturing XYZ coordinates on the ground surface. Source: Meade, 2021.
Often used in forestry departments, TLS has a very high resolution and can capture areas along stream banks that are difficult for aerial LiDAR to reach (Myers et al., 2019). A Trimble SX10 has been used on selective BEMS sites that have very steep or incised banks that are not easily measurable with aerial LiDAR. TLS provides superior measurement precision and accuracy when compared to Airborne LIDAR and some UAS-based applications (Meade, 2021). However, other cases studies haven proven that the technology produces the highest quality data from bare stream banks rather than those with dense vegetation (Meade, 2021). To add to this limitation, there can also be optical issues with water reflection that could skew results along the stream channel (Meade, 2021). With that being said, aerial LiDAR along with supplemental total station ground survey and terrestrial LiDAR scanning can produce a highly accurate stream surface models for geomorphic comparison. The survey work that goes into collecting and processing all of the elevation data requires excellent communication between all parties involved. To make processing more seamless, a goal of future stream monitoring studies would be to further minimize any manual processing steps. Another focus for future studies would be to further improve accuracy of survey data in areas with dense vegetation while also preserving the riparian buffer.

3.3 Stream Turbidity Reduction Projects (STRP)

The final step of stream management in the Ashokan Watershed involves designing and developing Stream Turbidity Reduction Projects (STRP). Over the past two decades, the NYCDEP and the AWSMP have been implementing STRPs to mitigate the turbidity impact of this watershed on the NYC Water Supply (2023-2025 AWSMP Action Plan, 2023). The
monitoring sites of the Bank Erosion Monitoring Study consist of prospective sites for STRPs as well as completed sites of STRPs. The most recent completed BEMS-driven STRP in the Stony Clove Watershed is the Lanesville STRP which was completed in 2022. Before the inception of the Bank Erosion Monitoring Study, an STRP was completed at Broadstreet Hollow Creek in 2000. In this section, the 2000 Broadstreet Hollow Creek STRP and the 2022 Lanesville STRP at Stony Clove Creek will be overviewed and critiqued.

3.3.1 2000 Broadstreet Hollow Creek STRP

One year prior to the first stream assessment of Broadstreet Hollow Creek, a stream turbidity reduction project was constructed with the primary objective of stabilizing the stream channel to mitigate turbidity caused by erosion and rotational failure (Greene County Soil & Water Conservation District, 2008). Cross veins were constructed to provide grade control and stabilize the channel bed. In addition, relief wells were constructed to drain out excess water from high flow events. Sheet pile walls were also added along banks to help withstand the excess stress applied during high flow events. Following construction of the STRP, an as-built survey was conducted to gather cross sections, water surface elevation, a thalweg profile, and further assess the condition of the site. Survey created 1-foot contours and planted willow fascines to foster the growth of a strong riparian buffer (Figure 28).
During the stream assessment of Broadstreet Hollow Creek, this STRP site was sectioned as management unit three of the nineteen total management units along the main stem (Ulster County Soil & Water Conservation District, 2003). There was continuous monitoring of the site from 2001 through 2007 to analysis the condition of structures, channel stability, and riparian vegetation. Each inspection of the project site also offered recommendations for construction repairs. In the short term, the project successfully mitigated clay erosion and protected the private property along the left bank. However, a major flooding event occurred in early April of 2005 caused extensive damage to many of the cross veins and clogged the relief wells (Green County Soil & Water Conservation District, 2008). It was reported by the GCSWD that a clay mud boil reappeared at the site during the summer of 2007. Aside from the damages to the in-

Figure 28: Post construction topographic survey showing location of cross veins and relief wells. Source: GCSWD, 2003.
stream structures, it was recommended that the diversity of riparian vegetation could be improved. Although maintenance projects were suggested in the monitoring report, it is not conclusive whether these projects were implemented in the years following the major flooding event. However, a reassessment of management unit three in 2023 found that the constructed rock structures were still heavily damaged and there was extensive clay erosion throughout the stream reach in the bed and banks. This stream reach is definitely a prospective location of an STRP in the coming years. The engineering design team will be challenged with giving this STRP a longer lifespan than the 2000 construction project. Another challenge comes with the availability of land to construct on as most of the left bank sits on private property.

3.3.2 2022 Lanesville STRP

In early 2023, construction completed on a segment of Stony Clove in the hamlet of Lanesville, a $2 million stream restoration project that was one of the largest STRPs to be completed in the Ashokan watershed (2023-2025 AWSMP Action Plan, 2023). The design and construction process was very complicated due to occasional high stream flows and a limited window of construction. To benefit, the wide valley bottom of the site gave designers and construction more available land. In addition, a home that was being threatened by an eroding hill slope was acquired by the NYCDEP to give the design team even more room to work with (Figure 29).
This project was a full channel reconstruction that halted the erosion of any active hill slope failures, added in natural stream features to stabilize the channel, and planted native plants to foster strong riparian buffer along the banks (SLR Consulting, 2023).
After construction was completed during the summer of 2023, the site was inspected by the design team to point out any improvements that could be made for future STRPs. Although many of the suggestions are minor, the most crucial points are summarized below.

1: Ecology

A common threat to the riparian buffer in the Ashokan Watershed is the invasive plant known as *Fallopia japonica* or Japanese knotweed. To prevent the spread of invasive species at an STRP site, it is important to develop a strong riparian buffer consisting of diverse native shrubs, plants,
and trees. For the Lanseville STRP, only willow fascines were planted along the floodplain. Future projects should consider more native plant diversity to strengthen the overbank regions.

2: Floodplain

Along the floodplain, it is important to develop a strong root system to keep the stream banks stable. A great way to ensure the bank’s stability is to add native material to the floodplain. Burying rootwads or logs in the floodplain can help develop a stronger riparian buffer and promote topographic diversity (SLR Consulting, 2023).

3: In-stream Feature

Adding wood features to the channel riffles can hold the stream feature together, provide ecological benefits, and improve hyporheic change between the stream water and the groundwater. Proper infilling is crucial to preventing any subsurface flow that could damage the project site over time. The Lanseville STRP used rounded native stones which are more difficult to source and cause issues with having enough enough material to complete grades and fill structures (SLR Consulting, 2023). For future projects, it may be more beneficial to consider both angular stones and rounded stones as angular stones can be easier to source and lock in place much better than rounded stones.

4: Bank Slope Treatment

For constructing the banks, the order of construction could use improvements to optimize plant growth as well as the overall strength of the bank. The post-construction investigation of Lanesville suggests that the banks should be filled in as the boulder revetment is being constructed to minimize subsurface flow. In addition, the fill material could include topsoil where plantings are being installed to improve the growth medium and increase survivability.
3.3.3 Future of Stream Turbidity Reduction Projects in the Ashokan Watershed

Since 2001, the AWSMP has completed 19 stream restoration projects in the Ashokan Reservoir Watershed, most of which are associated with mitigating sources of suspended sediment (2023-2025 AWSMP Action Plan, 2023). In Stony Clove Creek, the largest suspended sediment contributing tributary the Ashokan Reservoir Watershed, 10 STRPs have been completed in there since 2012 (2023-2025 AWSMP Action Plan, 2023). Between 2011 and 2016, suspended sediment concentrations (SSC) decreased due to the construction of 7 STRPs (Davis et al., 2016). The AWSMP and cooperating agencies plan to continue identifying sources of suspended sediment and constructing STRPs in the Ashokan Watershed. An STRP along Hollow Tree Brook, a tributary to Stony Clove Creek is expected to be constructed in the next year. Notably, this STRP is planning to use bio-engineered logjams to enhance topographic direct, supporting the goal of improving the longevity of projects while still fostering strong ecological growth.

4. Discussion and Conclusion

4.1 Summary

The goal of this project was to explore the evolution of terrain mapping techniques used in stream management in the Ashokan Reservoir Watershed. This exploration was an expansion on topics learned during an internship with SLR Consulting in their water resources department. The survey, monitoring, and restoration project phases of stream management all play a crucial role in the success in turbidity reduction. Over the past two decades, these approaches to stream management have evolved as new innovations have been made in the industry. Even so, there are
still mentionable critiques of stream management that can be applied to future stream assessments, monitoring studies, and restoration projects. The AWSMP plans to compile a stream management plan for the Ashokan Watershed once the entire watershed has been assessed (Ashokan Streams, 2012).

4.2 Limitations

This research paper could have included interviews with project managers and engineers to gain more insights about the various stream management projects. In addition, there was a personal bias due to having more expertise with stream assessments and UAS post-processing than stream turbidity reduction projects. These two research limitations didn’t impact the initial research questions and objectives.

4.3 Overall Recommendations for Future Stream Management Projects in the Upper Esopus Watershed

For future stream management projects in the Upper Esopus Watershed, final recommendations can be made to inspire future innovative pursuits in stream management. For stream assessments, there are some improvements to be made with accessibility so that data collection can be swift but also accurate. As for surface comparisons, the main goals would be to further minimize any manual processing steps and to further improve accuracy of densely vegetated areas along stream banks. The key for STRPs is maximizing project longevity while also preserving ecological development. There is great innovative potential in the geo-referencing sector stream
management to improve terrain mapping techniques. It is important to be able to reflect on completed works to determine how to raise the bar for what can be accomplished.
References


“Catskill Watershed Corporation – Protecting Water Quality in the NYC Watershed West of the Hudson River.” (n.d.). *Catskill Watershed Corporation,* [cwconline.org/#!/text=The%20Catskill%2DDelaware%20Watershed%20text=Throughout%20the%201%2C597%20square%20mile](https://cwconline.org/#!/text=The%20Catskill%2DDelaware%20Watershed%20text=Throughout%20the%201%2C597%20square%20mile)


