

**The Use of Terrestrial Laser Scanning
to Assess the Mobilization of
Contaminated Creekbank Soils in Oak
Ridge, Tennessee**

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ABSTRACT

Streambank erosion contributes significantly to contaminant fluxes in contaminated freshwater streams, yet quantifying its extent and impacts remain challenging. This study employs Terrestrial Laser Scanning (TLS) to measure streambank erosion rates at multiple sites along East Fork Poplar Creek (EFPC) in Oak Ridge, Tennessee, a stream heavily contaminated with mercury. The research aims to address three objectives: The first objective is to quantify erosion rates using TLS and estimate mercury flux from streambank erosion. The second objective is to develop a consistent procedure for the application of TLS in streambank erosion studies and evaluate its feasibility and limitations, and the third objective is to correlate erosion patterns with site-specific factors. Terrestrial Laser Scanning is routinely applied in construction in forestry to track tree canopy changes, and in hydrology for overhead mapping of river networks. However, more studies are needed to evaluate its ability in detecting and quantifying topographic changes in natural environments. The findings in this thesis demonstrate that TLS technology is highly accurate and precise in measuring topographical change of creekbanks, enabling reliable estimation of erosion rates and associated mercury fluxes at several field sites in EFPC. The standardized TLS protocol established here enhances the reproducibility of erosion assessments. Furthermore, integrating erosion data obtained by TLS with site-specific characteristics can help elucidate key drivers of erosional trends. These results provide a robust framework for monitoring streambank erosion and inform targeted remediation strategies for contaminated streams.

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CHAPTER ONE

INTRODUCTION AND GENERAL INFORMATION

1.1 Problem Statement

The U.S. city of Oak Ridge, Tennessee was a primary site for the production of nuclear materials and thereby the first atomic bombs during the Manhattan Project, near the end of the second world war. After World War II, the production of lithium isotopes began at the Y-12 National Security Complex and ran from 1950-1963. The lithium isotope separation process required large amounts of metallic mercury (Fang et. al, 2024). By the time production ended, approximately 11 million kg of mercury had been used, 350,000 kg of mercury had unintentionally been lost to the local environment and a fraction ($128,000 \pm 35,000$ kg) of this total had been discharged into East Fork Poplar Creek (EFPC) (Brooks and Southworth, 2011). This creek flows through the city of Oak Ridge for close to 23 km until it reaches a confluence with Poplar Creek (Brooks and Southworth, 2011). Although the Y-12 plant has discontinued their usage of mercury, it was estimated that 85% of the mercury discharged into the creek was incorporated into the floodplain soils of EFPC downstream of Y-12. The continued and increasing erosion of these soils is gradually mobilizing mercury into the EFPC stream network (DOE, 2014). Recent surveys showed extensive contamination throughout the entirety of EFPC; with a vast majority of streambank samples containing elevated concentrations of mercury compared to natural conditions (Dickson et al, 2019). Even if current and future efforts to stop inputs of mercury into the headwaters of EFPC are successful, the existing large inventory of mercury in the streambanks and floodplains of EFPC could continue to release mercury into the watershed for decades (Southworth et al. 2013). Mercury concentrations in fish have not

declined in response to decreased mercury concentrations in EFPC's headwaters (Southworth et. al, 2010), and concentrations of total mercury continue to exceed the water quality standard set by the Tennessee Department of Environment and Conservation at 51 ng/L (TDEC, 2019). The first step to remediation is establishing a workflow for quantifying flux throughout the watershed in order to determine where resources for remediation of the creek can be best allocated. This study will use Terrestrial Light Detection and Ranging (LiDAR) laser scanning (TLS) to achieve this goal.

1.2 Erosion Measurement

LiDAR is a relatively new technology, with the development of practical applications starting in the early 2000's. Since then, it has quickly gained popularity and has become a commonly used tool in various geospatial applications, particularly in mapping and surveying, forestry and engineering. A relatively underexplored application of TLS involves measuring streambank retreat, defined as the progressive erosion of creek banks.

The goal of this project is to use this TLS technology to measure mercury flux rates at several locations along EFPC by measuring the erosion of its banks. TLS scanners use LiDAR technology to measure distances between a fixed point and surfaces such as topography by emitting infrared laser beams and detecting the reflectivity of the scanned surface, as shown in **Figure 1** (Heritage and Large, 2009). Some TLS scanners also have an integrated camera that works in conjunction with the laser scanner to generate a photo-realistic, high resolution "point cloud," a digital representation of topographic features in the scanned environment (Lemmens, 2011).

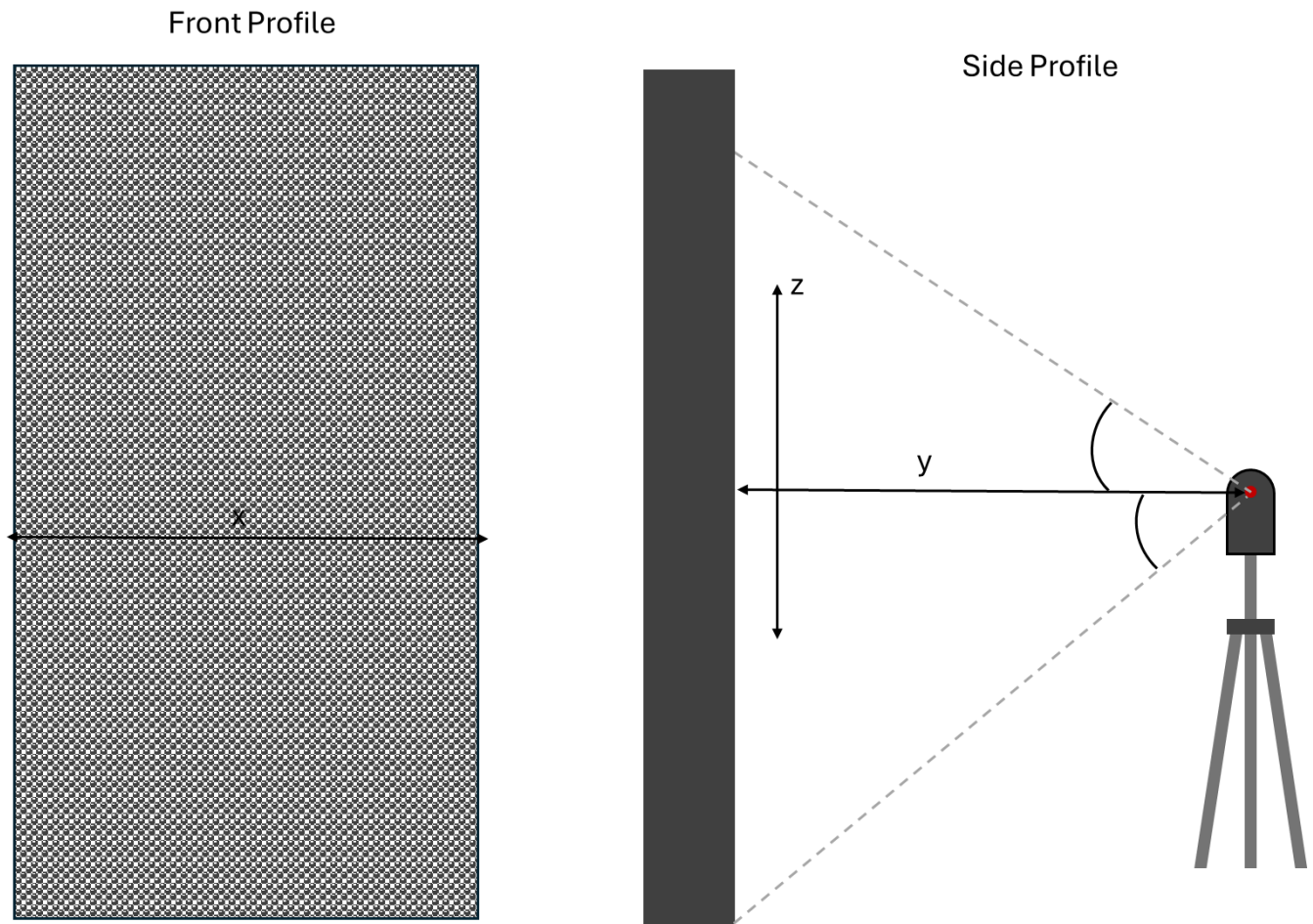


Figure 1: Conceptual diagram of Terrestrial Laser Scanning the front and side profiles

For scanning large areas, the TLS scanner needs to be moved to several locations and the individual point clouds at each location need to be merged into a single, larger point cloud. A standard procedure for scanner setup and registration of multiple scans uses permanent reflective targets to introduce known reference points to improve accuracy (Heritage and Large, 2009). If the coordinates of the reflective targets are known, georeferencing can be applied to each point cloud which helps further improve the spatial positioning and accuracy of the scan (Charlton et al, 2009). The number of scans required to achieve an accurate point cloud depends on the size and complexity of the scanned surface (Heritage and Large, 2009). Surfaces characterized by a higher density of protruding objects will have more shadows cast on the surface. Therefore, it is necessary to include additional scan angles to ensure complete coverage of the surface (Heritage and Large, 2009).

Terrestrial Laser Scanning is best used for precise comparisons of topographical or vegetative change of a small area over the span of a couple of months to a year (McNelis, 2016). The analysis software is used to superimpose point clouds over at a minimum of two time points, to detect changes in topography between measurements, and calculate net changes in volume, i.e., erosion and deposition. This project aims to utilize this technology to monitor changes in the topography over time of mercury-impacted streambanks in order to determine both erosion and deposition of creekbanks in EFPC. With this information, the measured net erosion volumes, combined with previously determined soil mercury concentrations, are used to estimate mercury flux.

Terrestrial Laser Scanning, however, does often encounter difficulties in differentiating between changes in channel topography due to erosion and seasonal variations in vegetation

growth (Collado, 2021). Bank vegetation and other features such as overhanging structures can obstruct the view of the bank. The shadows cast by these features reduce the reflectivity of the streambank and may significantly limit the resolution of the point cloud in these regions (Charlton et. al, 2009). Additionally, the removal of vegetation during the registration process can leave gaps in the point cloud. Although the software used for volume calculation will fill these gaps by interpolation, this process may introduce additional uncertainty in the final erosion calculation results (Day et. al, 2013). The infrared lasers used by the LiDAR scanner are unable to penetrate water, which makes it impossible to obtain a complete representation of a streambank in a perennial stream (Charlton et. al, 2009). Moreover, there is currently no standardized procedure or established criteria for settings such as scan distance, resolution, georeferencing or other factors that are essential to the scanning process, which makes replication of past experiments difficult (Heritage and Large, 2009). Adverse weather conditions can decrease the range between scanner and bank surface and thus result in resolution degradation. Direct sunlight can oversaturate the reflectance of the bank, which may result in lower point cloud resolution (Charlton et. al, 2009).

Conventional erosion measurement techniques have been shown to yield datasets with a limited number of sampling points, resulting in measurements not representative of the full bank, or some measurement techniques may disturb the bank and lead to an overestimation of erosion (Myers et. al, 2019). Terrestrial Laser Scanning, on the other hand, produces high resolution datasets with thousands of individual sampling points, and it is not intrusive to the sampling site, enabling a more precise and accurate estimation of erosion and mercury flux.

1.3 Streambank erosion and processes

Although the data collected will be valuable for measuring mercury flux at the selection of field sites along the creek, a comprehensive understanding of erosional processes is needed to provide an explanation of the erosional trends identified in this study. These processes can be explained conceptually through the lens of the dominant erosional process model, which recognizes three major components: subaerial processes, fluvial entrainment, and mass wasting, which may occur at different parts of the river system (Purvis and Fox, 2016). Subaerial processes include wetting and drying of soil, and freeze-thaw processes (Simon et. al, 2000). These processes do not directly cause erosion, rather they allow for soils to be mobilized easier by fluvial entrainment. Fluvial entrainment is the steady mobilization of sediments by the flow of a river and this process can be particularly impactful for clayey soils (Simon et. al, 2000). Following sufficient fluvial entrainment that leads to the formation of an undercut in a bank, combined with an increase in bank height associated with deeper channels, and an increase in the weight of soils associated with rising soil water content, a mass wasting event may occur, resulting in the collapse of the stream bank. Stream velocity is usually low near the headwaters of a watershed, which allows for subaerial processes to dominate. Moving downstream, stream power accumulates until it hits its peak in the middle reaches of a basin, and fluvial entrainment will accordingly dominate here. In the lower reaches, the channel depth tends to increase and if it increases to a point at which maximum bank height for stability with respect to mass failure is exceeded, resulting in the dominance of mass failure. This trend of changing erosional mechanisms moving from upstream to downstream is visualized in **Figure 2**.

This research employs several tests to evaluate the accuracy and feasibility of using TLS to measure streambank erosion. The primary objective is to quantify erosion of streambanks and determine the implications for mercury flux from contaminated creekbanks from a variety of locations in EFPC. A third objective is to understand the extent and mechanisms of erosional processes in EFPC, potentially allowing for a qualitative understanding of erosional trends observed with TLS. Therefore, this project will compare stream characteristics including bank height, flow velocity, and bank vulnerability to erosion to streambank erosion data to provide insights into the measured erosional trends captured by TLS.

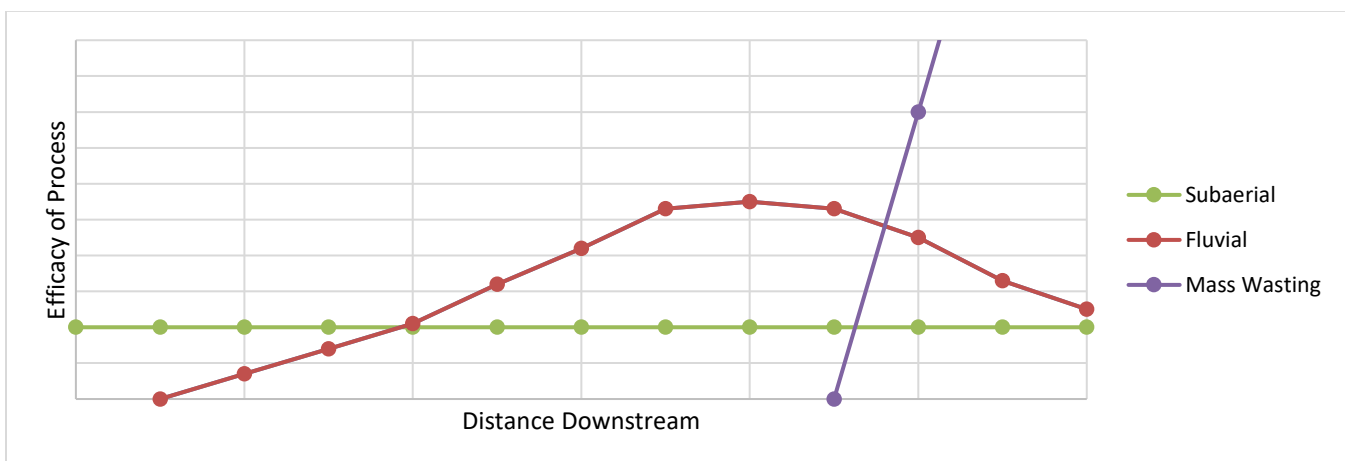


Figure 2: A diagram of the interaction between stream length and dominant erosion mechanisms (reproduced from Simon et. al, 2000).

CHAPTER TWO

SITE DESCRIPTION

2.1 Site Characteristics and Nomenclature

East Fork Poplar Creek is a low-gradient stream with variable soil characteristics. Its headwaters originate within the National Nuclear Security Administration Y-12 plant, and the stream experiences occasional flash flooding due to storm events which contributes to the erosion of streambanks (Peterson et. al, 2011). The concentrations at EFPC streambank sites are as high as 4500 mg/kg for total mercury and 60 micrograms/kg for methyl mercury in some locations (Dickson et. al, 2019). **Figure 3** indicates mercury concentrations through a color gradient along a longitudinal transect and identifies locations of all field sites used in this work. In the areas with the highest mercury concentrations, there is a visible layer of blackened soil at shallow depths (0.3-0.6 m) contaminated with both coal fines (accounting for the black color) and high concentrations of mercury. This soil layer is referred to as the Historical Release Deposit (HRD) (Dickson et. al, 2019). Throughout the entire creek, the creekbanks in EFPC reach an average of 126 mg/kg total mercury and 5 micrograms/kg of methylmercury (Dickson et. al, 2019).



Figure 3: Map of the EFPC watershed. Total mercury concentrations in bank soils are indicated by a color gradient. East Fork Kilometer (EFK) markers show scanned field sites.

While total mercury inventories in stream sediments are down 67% compared to 1984 in part due to prior remediation efforts, most of the mercury that remains is strongly bound to bank soils and sediments regardless of grain size or soil type (Watson et al., 2016). The combined rate of mercury flux from bank soils and bed sediments into the creek is expected to slow and eventually stagnate depending on the rate of contaminated bank erosion flux into creek, the rate of dilution with cleaner sediment, and the rate of mercury desorption from soils and sediments into the water column (Watson et al., 2016). Each creekbank location along the river has been labeled with kilometer markers measuring the distance upstream from the confluence, labeled as EFK followed by the respective kilometer marker. This naming convention allows for easy identification of field sites. Scanning began at nine field sites in August of 2020, and continued through February of 2025, resulting in 81 total point clouds (Collado, 2021). Flow gauge stations have been installed at two of the field sites for other projects in EFPC but were used to establish flow patterns in the watershed.

2.2 Flow data

The flow data of two EFPC streamflow monitoring stations are displayed below (**Figure 4**). Consistently higher flow velocities were observed at EFK 5.4 (**Figure 4a**) compared to EFK 16.41, (**Figure 4b**), only having significantly higher flow velocity at EFK 5.4's lowest point around day 320 and on average having about 0.5 FPS lower flow velocity. It is important to note that these flow velocity values end around September 2023 for **Figure 4a** and September 2022 for **Figure 4b**, so a full comparison cannot be made between high flows and erosion sampling dates. While the flow velocity for EFK 5.4 was measured at the scanning site, the flow velocity at EFK 16 was not measured at EFK 16.41, but around 0.2 kilometers downstream, at EFK 16.2.

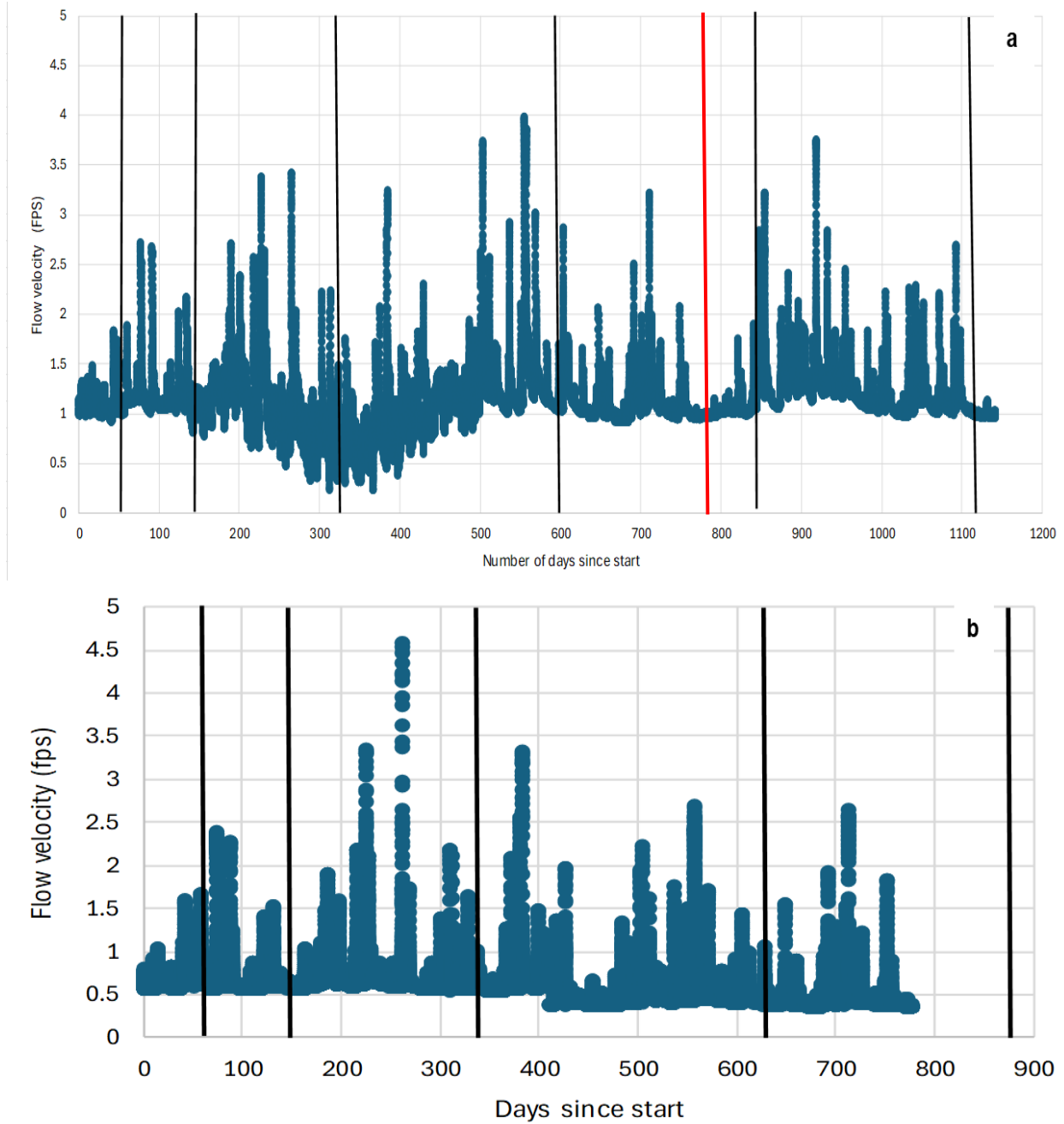


Figure 4: The recorded stream velocities at EFK 5.4 (a) and EFK 16.2 (b) marked with scan sampling dates. EFK 5.4 flow data is also marked with where the data at EFK 16.2 ends.

Since these are so close that this study assumes that the flow conditions at EFK 16.41 are likely very similar to those at EFK 16.2. The presented flow data demonstrates the flashiness of this watershed, with relatively moderate baseflow around 0.5-1 feet per second, but peaks as high as 4.5 FPS with occasional storm events. Its trends are also consistent with the dominant erosional process model, which describes that stream velocity should increase moving from upstream to downstream. However, there are several factors that go into flow velocity including factors such as channel geometry. The impacts of some of these other site-specific factors on erosion rates will be discussed later.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Terrestrial Laser Scanner and Registration Software

This study used a Leica BLK 360 G1 Imaging Laser Scanner (Leica Geosystems AG, Heerbrugg, Switzerland), which is a portable 360° laser distance scanner with high-definition panoramic imaging, to create three-dimensional, high-resolution point clouds. The instrument can capture 360,000 data points per second with a point error of less than 6 mm at a range of 10m providing a full 360° scan of the entire area within a 60m radius (Leica Geosystems, 2020). Scanner control in the field and registration are performed in the corresponding Field 360 and Cyclone 360 software.

3.2 Software for Calculation of Erosion Volumes

Trimble RealWorks (Trimble Geospatial, Sunnyvale, CA, USA) was used to compare point clouds collected for each stream bank and perform erosion volume calculations by comparing scans taken at different times.

3.3 Field Scanning Procedure

Scans were taken in the field every three to six months with a total of three scans taken at each field site, except for EFK22, which was sufficiently large that it required four individual scans to adequately cover the entire bank. Multiple scans for each site was necessary to mitigate issues related to shadowing resulting in obscured bank sections by taking scans from multiple angles. The scanner was set up on a stable and leveled tripod in stream locations upstream, centered on, and downstream of the field site. Additionally, any scans, besides those taken for the estimation of error, were taken during the late fall or early spring to avoid issues introduced

by scanning banks covered in dense vegetation. However, other tests were done to evaluate the uncertainty of the technique under controlled conditions during the summer which included estimating uncertainty in the field.

3.4 Georeferencing Setup Procedure

Each streambank section was delineated to ensure consistency in repeated scans over time, beginning in August 2020 and ending in February 2025. Using a post driver, 2-meter T-posts were installed at the upstream and downstream ends of the streambank section of interest, and a third post was installed behind the two T-posts. The final T-post was installed on the opposite bank across the creek from the bank of interest. Zip ties were then used to fasten high contrast, black and white metal panel targets near the tops of the posts. A metal tag labeled with the corresponding post number of the LiDAR target (LT) was also fastened to the T-post. This was done at all 9 field sites, totaling in 36 T-posts with metal tags labeled LT 1 through LT 36. These posts were then surveyed at the location of the target panels so that their survey coordinates can be input into registration software and applied as control points to point clouds for application of georeferencing. This work was performed in February of 2024, which means that any previous scans were georeferenced through retroactive georeferencing (covered in section 3.4). A field setup with some georeferencing targets is shown in **Figure 5**.

3.5 LiDAR Registration Procedure

Once the field sites have been scanned, the 3 (or 4) scans are then uploaded directly from the scanner into the Cyclone 360 application on the computer. The imported scans were linked together by selecting common points of interest (POI), such as the georeferencing targets. Once scans are effectively matched, they will automatically merge into a complete point cloud.



Figure 5: Photo of a regular field setup with georeferenced targets circled in red.

Then, the point cloud is trimmed to include only the streambank section needed for the volume calculation, labels were applied to the georeferencing targets with their respective LT numbers in the software. Each bank had a set height and width based on boundaries described in the next section. The final step of registration involved importing the target coordinates into the software and matching target numbers and their respective coordinates to the labeled targets. The result of this process was a georeferenced point cloud, as shown in **Figure 6**.

3.6 Retroactive georeferencing

Although control points can be applied to all new scans, most scans were collected prior to the installation of the LT targets and associated georeferencing. This presents a challenge when comparing new scans to old scans, as the two point clouds are in different coordinate systems. Furthermore, georeferenced scans allow for more accurate registration and volume calculations. To overcome this issue, while maintaining consistency in area of point clouds at every sampling interval, the coordinates of four common landmarks, such as tree roots, rocks, other sampling equipment, etc., were logged from the recent georeferenced scans.

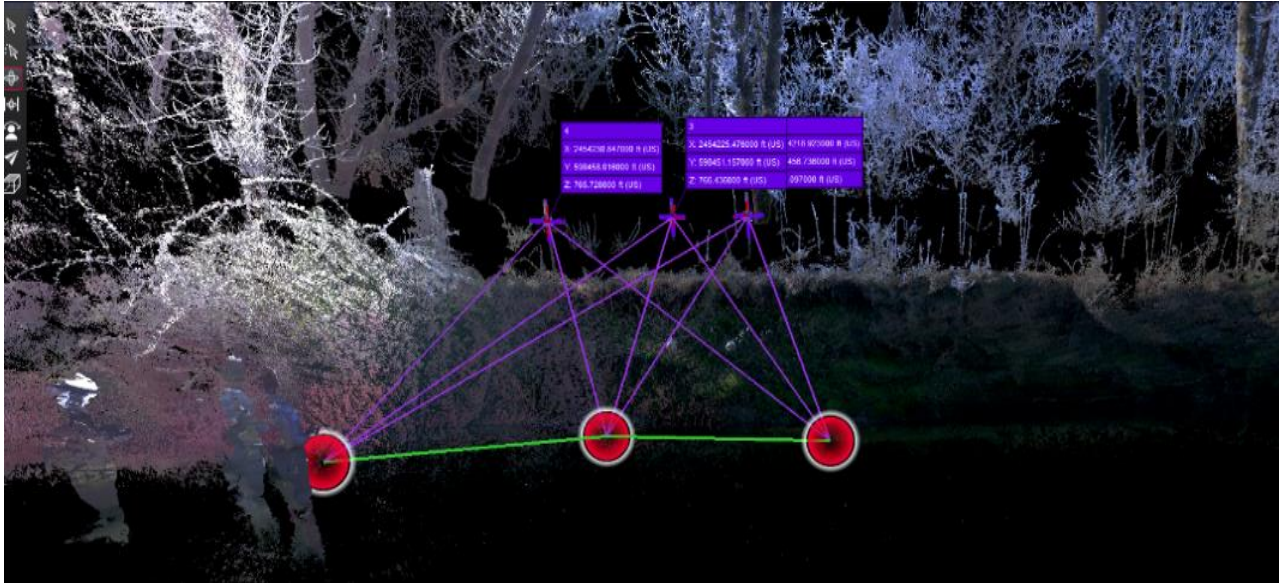


Figure 6: A registered field site with georeferencing applied in Cyclone 360

These landmarks were found and labeled in the older scans and their coordinates were imported into the software to apply georeferencing to scans that could not undergo georeferencing otherwise. Characteristic landmarks served as the left and right bounds of the scan, with the high boundary being the top of the bank, and the low boundary being determined by the highest water level out of all the sampling times. An example of one of these scans with retroactive georeferencing is shown in **Figure 7**.

3.7a Calculation of Erosion Volume

Once registration in Cyclone 360 is complete, two point clouds subject to comparison were imported into Trimble RealWorks at the same time and then superimposed on one another. The registration tool automatically aligns the two point clouds and identifies common points between the older point clouds (reference cloud) and the newer point cloud (moving cloud). The alignment improves substantially if the imported scans are georeferenced and in the same coordinate system, as shown in **Figure 8**. Once the scans are superimposed, a sample layer is created in preparation for volume calculations.

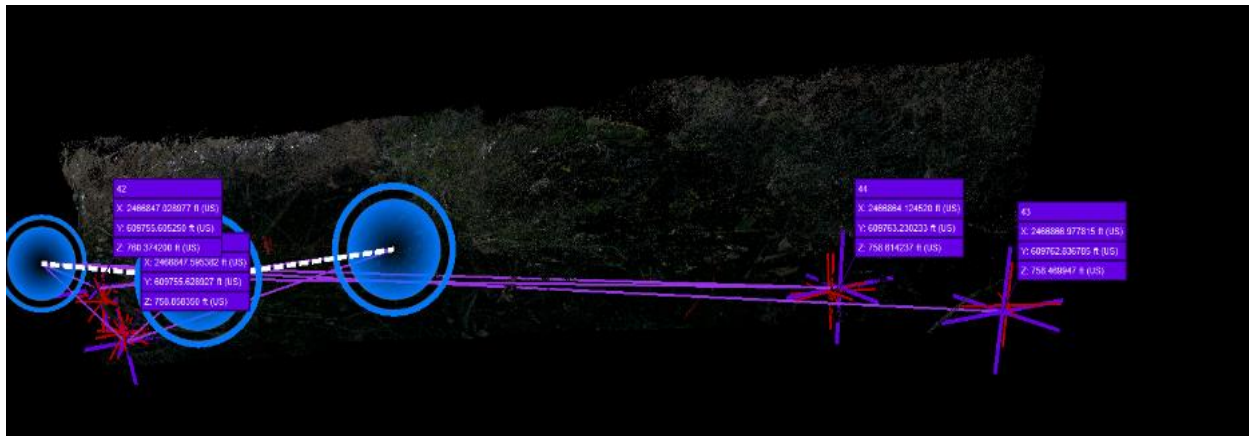


Figure 7: Trimmed point cloud of a field site retroactive georeferencing applied.

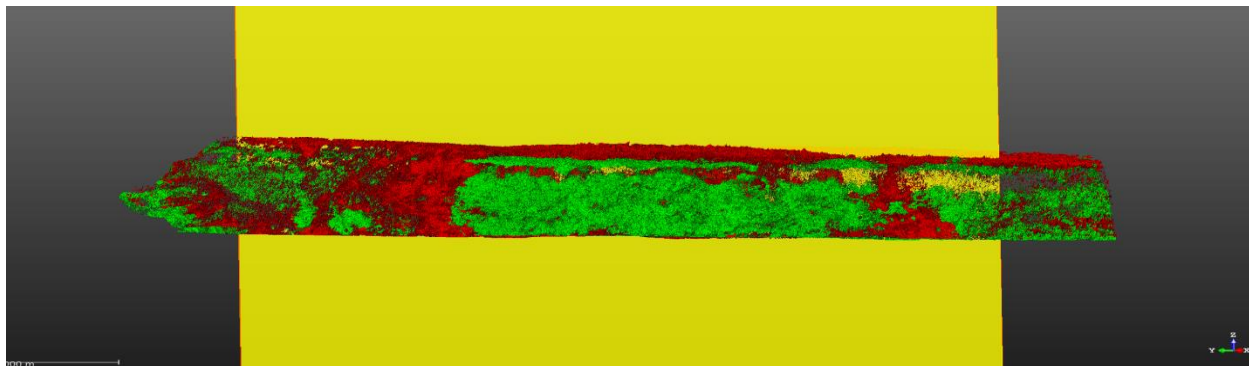


Figure 8: Trimble superimposition of the reference (red) point cloud and the moving (green) point cloud

Then the point clouds are processed using the mesh creation tool, manually trimming away any extra roots or vegetation, and defining a plane parallel to the superimposed point clouds (i.e., a vertical orientation parallel to the orientation of the streambank). For each point cloud, the software generates two distinct triangulated mesh surfaces to conform to the organic shape of the stream bank. The software then calculates the volume of the space between the two mesh surfaces along a defined plane, distinguishing between cut (material removed) and fill (material added), representing erosion and deposition volumes, respectively. In addition, net volume changes (fill – cut) volume, and total (cut + fill) volume were calculated. A visualization of the volume calculations using complete meshes is shown in **Figure 9**.

3.7b Normalization of Erosion Volume Using Bank Surface Area

Once a volume has been calculated, it can be normalized to the surface area of the bank, which allows for comparison of erosion trends between different field sites. Instead of calculating the full surface area of the mesh, which would be subjective and very difficult, the left and right bank heights in the field of view were averaged, and the top and bottom widths of the bank were averaged in order to approximate the mesh as a rectangular surface for a simpler surface area calculation (**Figure 10**). An example of these surface areas for each field site can be observed in **Table 1**. Once the surface area based on this rectangular approximation was calculated, the erosion volume of the mesh was divided by this surface area. The result represents normalized erosion or deposition volume allowing for comparison of volume changes across field sites. The same area was used for each subsequent scan so there is consistency in the area interrogated over time.

3.8 Comparison of Methods for Measuring Total Volume

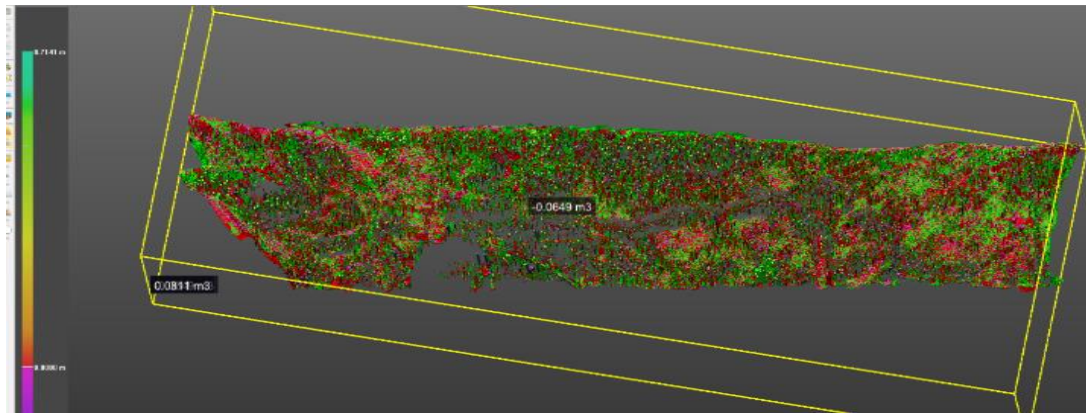


Figure 9: Results of a volume calculation run on a mesh in Trimble (color scale on left).

Table 1: Surface areas used for normalization in section 3.9

5.4	14.56	16.41	19.02	19.07	19.32	19.34	20.27	22
9.70	8.04	6.25	12.82	14.56	7.59	6.35	5.78	22.22

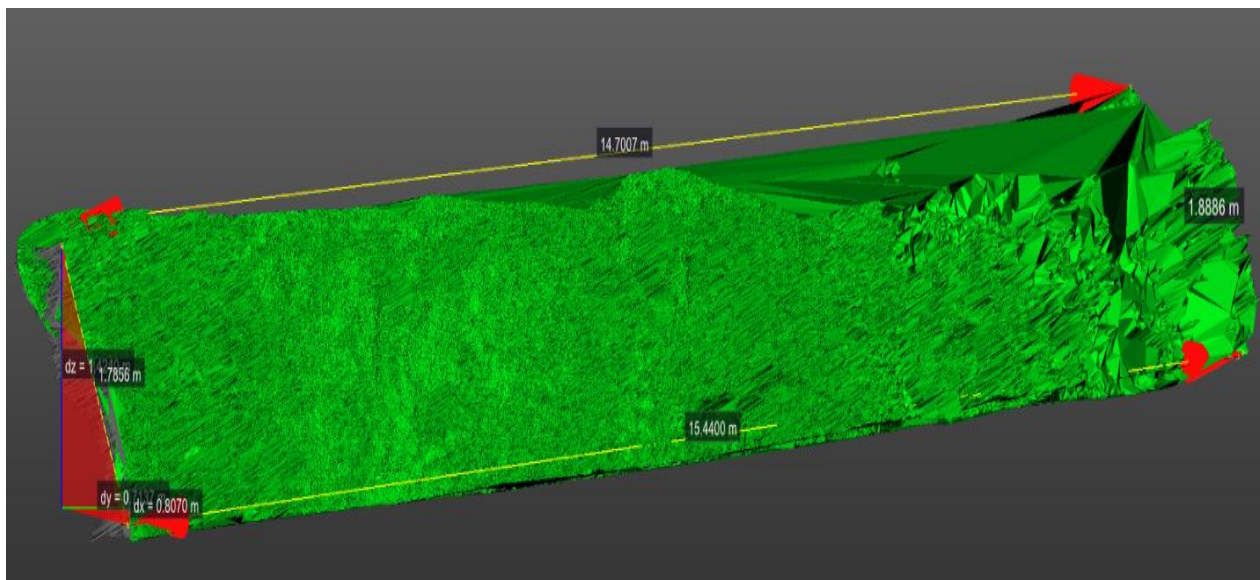


Figure 10: The measurements taken in Trimble to measure the surface area of a mesh

Two different methods for calculating the total volume change in each field site were compared. The “cumulative method” is used to calculate the total erosion volume over the entire sampling period by summing the erosion volumes from each 6-month sampling interval. A diagram comparing the procedures of these two methods is shown in **Figure 11**. Although the cumulative method might be one of the best available methods for the visualization of erosion trends over time, the summing of individual erosion calculations to find the cumulative method volume could be compounding the error in each individual calculation, resulting in error in the final erosion calculation. This source of error can be mitigated by calculating erosion using the single method and calculating erosion between the oldest scan taken in August of 2020 and the most recent scan taken in February of 2025. A comparison was made using the erosion calculated by the cumulative method and the single method (**Figure 12**). Since these two methods for calculating total erosion use the same timeframe to measure volume, the resulting volumes calculated using each method should be similar to each other.

3.9 Estimation of uncertainty in the field

In June 2024, replicate scans were taken at all field sites to assess the error associated with each scan. It is important to note that, due to the sunny conditions, and the dense vegetation present on the banks during the scans, this error estimate represents a conservative upper bound of the potential error for any individual scan of a field site. The same field procedure was used that would normally be used for a given scan sampling, but rather than 3 scan setups per bank, a total of nine scans (three replicates for each scan setup) were taken in the same session, and three replicate point clouds were created. These point clouds were registered, georeferenced, and the volume difference calculated between the replicate point clouds in Trimble RealWorks.

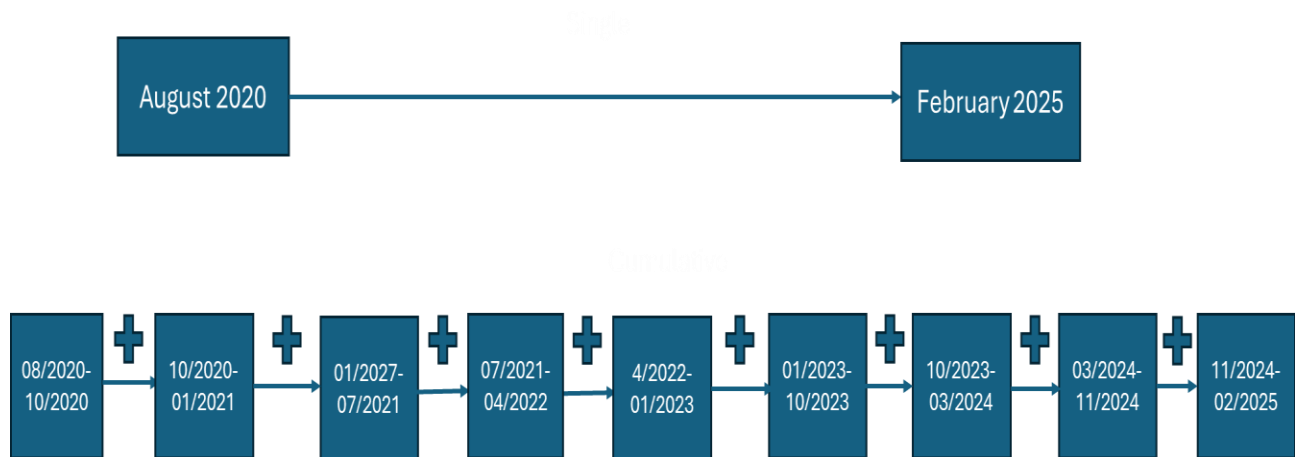


Figure 11: A comparison of the “single method” and the “cumulative method” procedure

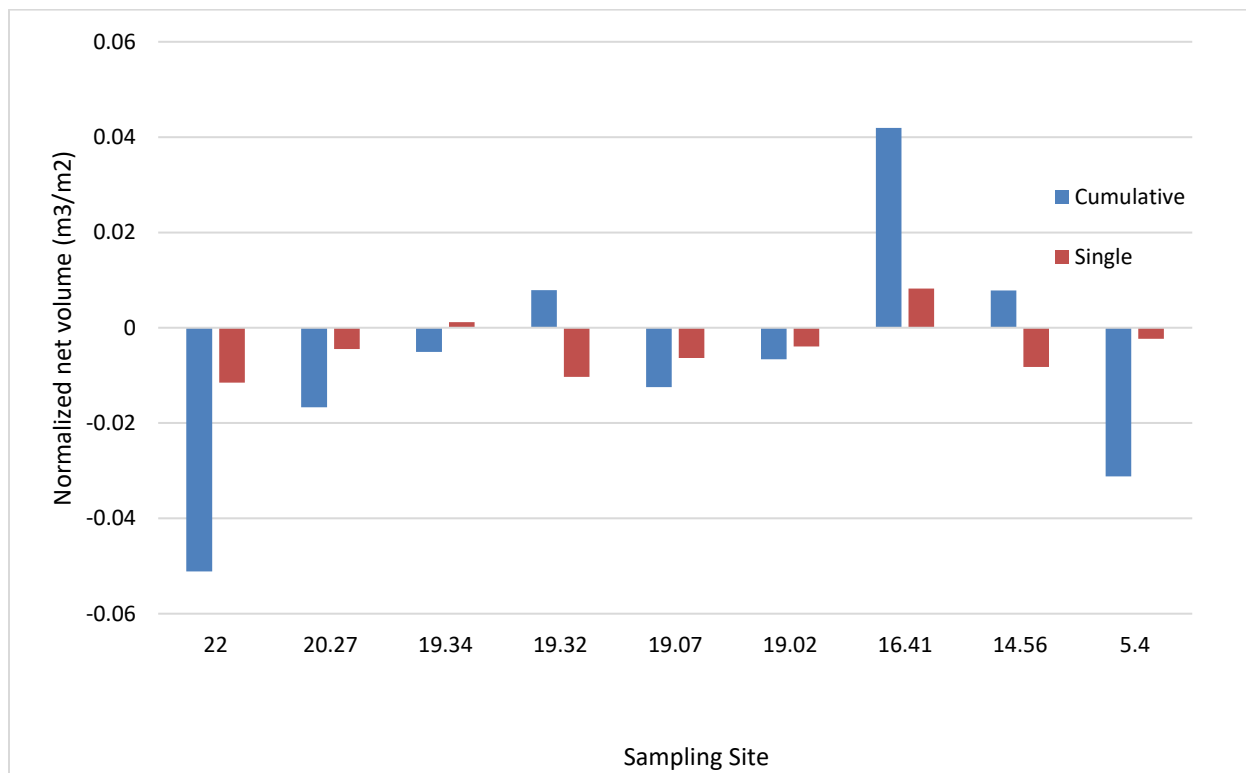


Figure 12: The normalized erosion volumes measured by the cumulative method and the single method

The total volume (positive and negative) was used to obtain error estimates in cubic meters, and the surface areas of the banks were used to normalize volumes so the errors obtained for all the sites could be compared to one another (in units of m). Since the scans were taken at the same time, the difference should be zero, and any differences that were found in these comparisons were considered measurement uncertainties. **Figure 13** demonstrates that the highest normalized error was around 0.037 m at EFK 5.4, and an average of every site resulted in an error of 0.012 m.

3.10 Controlled study of factors that impact accuracy

The overlapping scans enabled the assessment of the estimated error at each field site. To identify sources of error introduced by other factors, a simulated erosion site was constructed allowing for the evaluation of various factors under controlled conditions. A wall consisting of 36 (6x6) concrete blocks, each with a volume of 0.149 m^3 , was built under overhanging trees to better simulate creek bank conditions and the effect that the presence or absence of sunlight may have on the accuracy of the scans. In addition, a control scan, which consists of a scan and a volume calculation with no “treatments” applied, was taken on every sampling day. To find the best distance between scanner and the simulated bank, scans were taken 3 and 6 m from the wall. In addition, three widely spaced scans, and two narrowly spaced scans were taken at both distances.

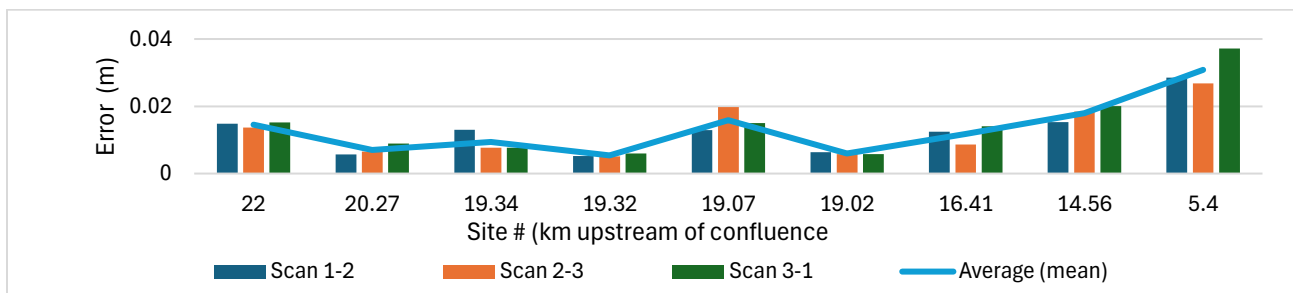


Figure 13: The normalized % error found from taking overlapping scans of the field site

There were no specific angles or placements for the scanner in these tests, but rather the narrow scans occurred within the width of the wall. The wide scans involved placement of the scanner outside both ends of the wall with a third scan occurring near the center of the wall. To test the accuracy of erosion measurements for each of the treatments, a concrete block was removed from the wall, the volume of which is known, and a piece of plywood was placed behind the wall to ensure the scanner was not picking up more than just the area of the hole. After comparing the measured volume removed with the actual removed volume, it was found that taking three wide-angle scans three m from the wall resulted in the most accurate measurement of the differential volume. Subsequent tests were performed at the same distance and angle. The remaining scans were used to evaluate the effect of vegetation and roots, overhanging banks, and location of volume removal. A total of three configurations were evaluated by scanning the simulated bank with and without the volume removed at the optimal distance and angle. The first test involved using shrubbery and grass picked up from the area to cover the wall and specifically the area where the volume was removed to simulate the impact of vegetation (**Figure 14a**). This volume was subsequently calculated with and without trimming the vegetation from the point cloud using tools in Trimble RealWorks. The second test involved using a large piece of plywood placed on top of the bank, pushed far out and a lot closer to the bank to simulate a creekbank with slight and bigger overhanging features (**Figure 14b**). The third test involved cutting down thick branches from nearby trees and placing them in front of the wall and over the hole, as shown in **Figure 14c**, to simulate the presence of roots on a creekbank. A final test involved removing a concrete block from the lower left part of the wall rather than the center of the wall. Since the scans were taken on a wall with and without volume

removed for every test, a differential volume was calculated for each test allowing for easy comparison between the expected “erosion” volume and the measured volume in each test. Three replicate point clouds were collected for each of the treatments at the concrete wall, using the same scanning procedure as the one that was used for estimating uncertainty in the field. The resulting point clouds were processed using three different methods available in Trimble RealWorks: 1. the Twin Surface Inspection (TSI) tool which, as displayed in **Figure 14d**, highlights potential erosional hotspots in the point cloud through the application of an automatic topographic change gradient; 2. the regular surface volume calculation tool (SV); and 3. the mesh creation tool, and then the surface volume calculation tool (MSV). The surface volume tool compares the differences between matched points in the two point clouds without editing while the mesh creation tool triangulates individual points, in theory conforming better to the organic surface of a stream bank, and then a surface volume calculation is made on the mesh. Both the surface volume and mesh creation calculations were able to be split into “full” (SVR) and “reduced” (SVF) views with the full view including the entire concrete wall in the volume calculation and the reduced view only using the area where the hole in the wall appears. This result in five separate measurements, as described in **Table 2**. All these methods for processing point clouds were used to measure the volume of the void after removing the concrete block from the wall. Moreover, isolated treatments such as roots, vegetation, or an overhanging bank were used to test how much the volume measurements deviate from the known void volume to evaluate accuracy (**Figure 15**). Overall, the overhang on the bank caused the most error, and the addition of roots caused the least error among all possible confounding factors commonly found at the field sites.

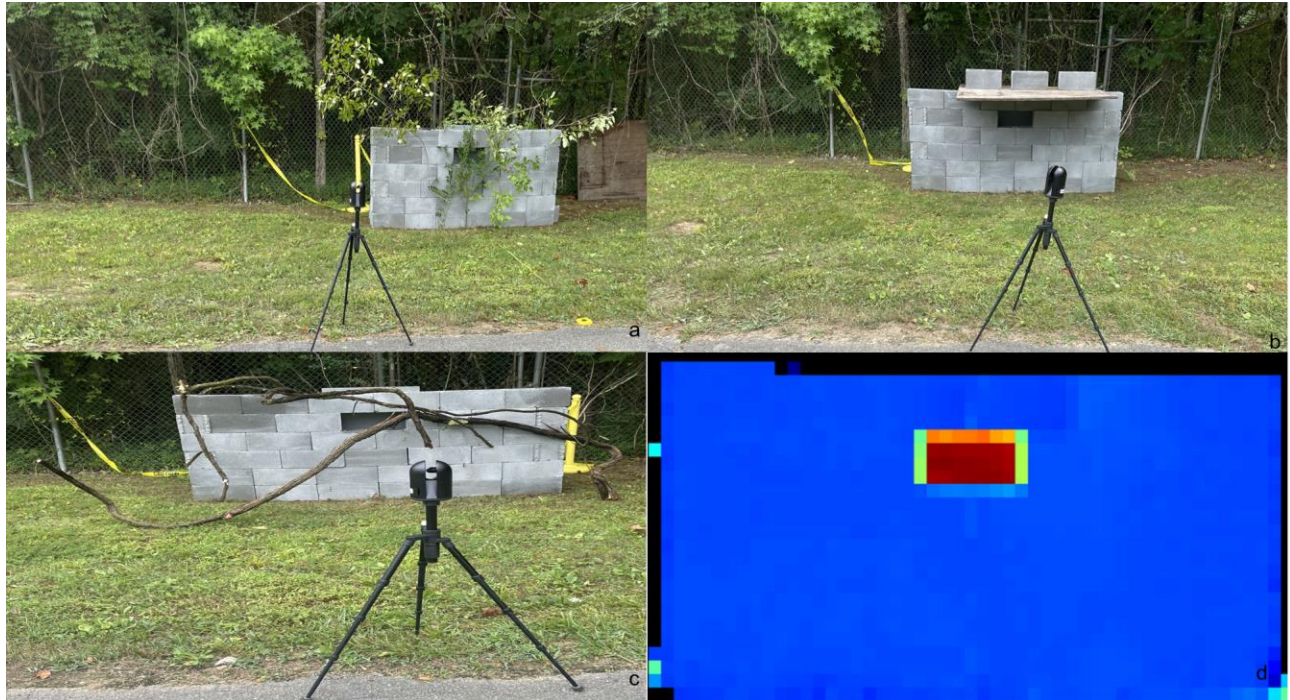


Figure 14: A concrete wall setup up with fake vegetation (a) overhanging bank (b) roots (c) and having its erosion measured in TSI (d)

Table 2: Legend for the different scan techniques shown in **Figure 15**.

TSI (Navy)	SVR (orange)	MSVR (Green)	SVF (Light blue)	MSVF (Purple)
Twin-Surface Inspection	Surface volume reduced	Mesh surface volume reduced	Surface volume full	Mesh surface volume full

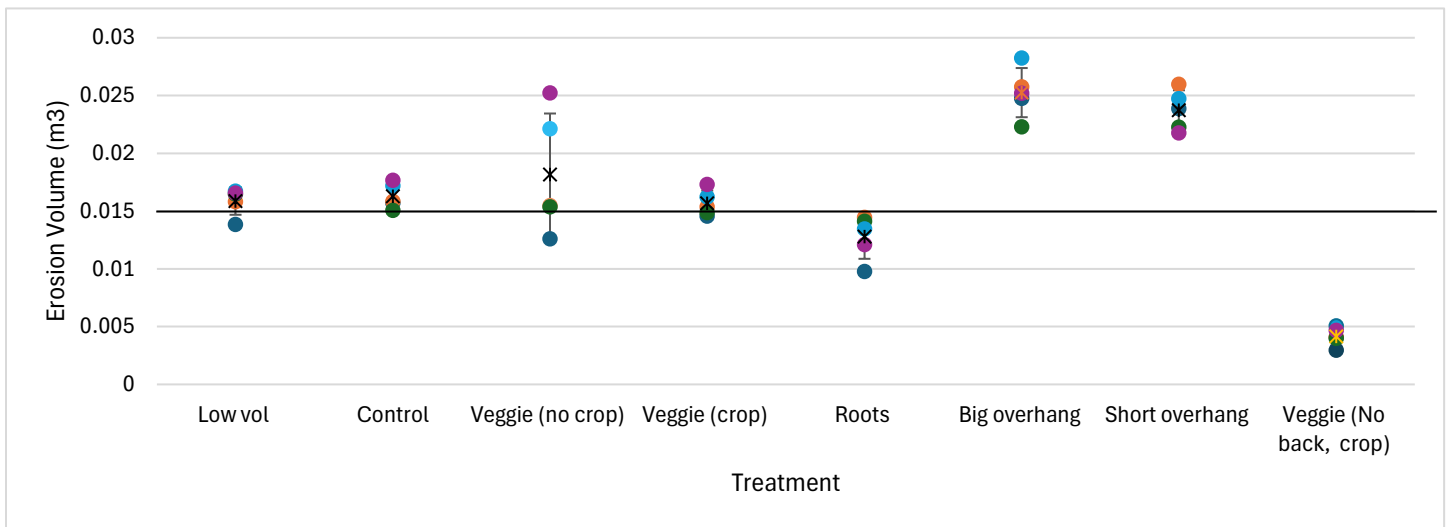


Figure 15: Comparison of volume calculations methods in relation to treatments used in the concrete wall study and the actual volume difference (black horizontal line = 0.0149 m³)

The mesh surface volume resulted in a higher error for the vegetation treatments, and the regular surface volume calculation method resulted in the highest error for the overhanging bank treatment. These findings are important because while there are controls that can be put in place to reduce the impact of vegetation, such as trimming the vegetation manually or during the registration process as is shown in **Figure 15**, there are not many options available for avoiding difficulties caused by overhanging banks besides avoiding scanning them altogether.

3.11 Assessment of Uncertainty: Before vs. after georeferencing

To understand the impact of the application of georeferencing, a comparison was made between erosion volume calculations performed on georeferenced point clouds and those that did not have georeferencing applied. The volume difference between August of 2020 and November 2024 was obtained at field sites EFK 5.4, 16.41, and 19.02 using the “single” method before applying georeferencing to any of the point clouds. The results were then compared to an erosion volume calculation between the same point clouds, but after georeferencing had been applied, followed by normalization of both sets of volume calculations by the area of the bank being scanned. For the final accuracy measurement, the percent error was calculated between the two erosion calculations to determine the impact of georeferencing on the accuracy of the erosion measurements, shown in **Figure 16**.

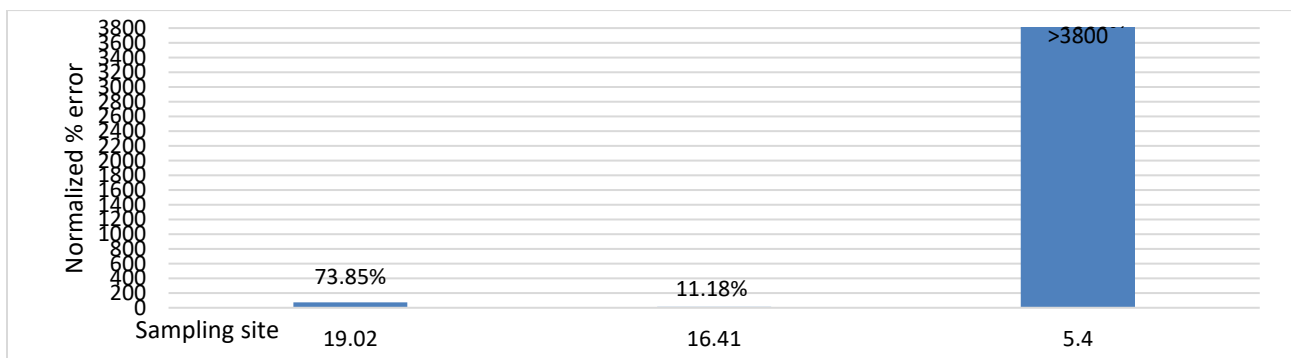


Figure 16: Percent error volume for the non-georeferenced vs. georeferenced comparison

3.12 Mercury Flux Calculation

The final goal for the project was to use known site-specific information to calculate the mercury mass flux per year at each field site. Mercury flux is calculated using four parameters: total erosion volume of the site over the entire sampling period, the total sampling period in years, the average bulk density of the soils, and the average mercury concentration of the soils, with the latter two measurements taken as close as possible to the TLS measurement locations . The mercury concentration values were obtained by averaging soil concentration data from samples obtained within 0.2 km of the LiDAR field site (Dickson et al. 2019). The bulk density values were taken by digging out the soils at each field site (Collado, 2021). The mercury flux from each field site, in grams per year, was calculated as demonstrated in **Equation 1**. The mercury flux, as well as the standard deviation of the mercury concentrations and the standard deviation of uncertainty in erosion measurements taken at each field site were used to calculate the margin of error for the mercury flux concentrations, as shown in **Equation 2**.

$$J_{Hg} = \frac{(\rho_b) * (V_E) * (c_{Hg})}{t * A}$$

Equation 1: Equation for calculating normalized mercury flux (J_{Hg}) in $\text{g} \cdot \text{m}^{-2} \cdot \text{yr}^{-1}$. Soil bulk density (ρ_b) in kg/m^3 ; erosion volume (V_E) in m^3 ; mercury concentration (c_{Hg}) in g/kg ; sampling time (t) in yr; bank surface area (A) in m^2 .

$$\Delta J_{Hg} = \sqrt{\left(\frac{\rho_b \cdot c_{Hg}}{t \cdot A} \Delta V_E\right)^2 + \left(\frac{\rho_b \cdot V_E}{t \cdot A} \Delta c_{Hg}\right)^2}$$

Equation 2: Equation for propagating independent measurement errors to obtain the uncertainty of the normalized mercury flux (ΔJ_{Hg}), where ΔV_E represents the uncertainty of erosion volume in the field and Δc_{Hg} represents the standard deviation of the mercury concentration.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Cumulative erosion calculations

Terrestrial laser scanning was evaluated at nine field sites as a field-deployable technique to detect and quantify erosion of streambanks contaminated with mercury. Data was collected every 3-6 months, processed, and normalized to identify differences in erosion trends across field sites. Cumulative erosion was obtained by adding changes in net erosion or deposition measured over each data collection interval between August 2020 to February 2025. By graphing the results as cumulative changes in erosion, high amounts of deposition per unit area were identified at EFK16.41, along with minor deposition at EFK14.56 and EFK19.32 (**Figure 17a**). In contrast, major erosion was observed at sites EFK22 and EFK5.4 (**Figure 17c**), whereas the remaining sites showed mild to moderate erosion (**Figure 17b**). Based on these site-specific trends, an overall pattern can be identified, which indicates that mass erosion is occurring around EFK22, transitioning to mild erosion downstream, and even some net deposition at several sites where the HRD layer is present (EFK19.02 - EFK20.27). Net deposition is apparent at EFK16.41 and EFK14.56. Further downstream, bank height and stream velocity increase to a point where major erosion is observed again at EFK 5.4.

4.2 Mercury flux from contaminated bank soils to EFPC

The mercury flux from creek banks to EFPC at each field site can be estimated using the measured soil erosion volume, soil mercury concentrations (Dickson et. al, 2019), and soil bulk density data (Collado, 2021). Furthermore, the flux data was normalized to site surface area to enable comparisons between stream banks of differing widths and heights.

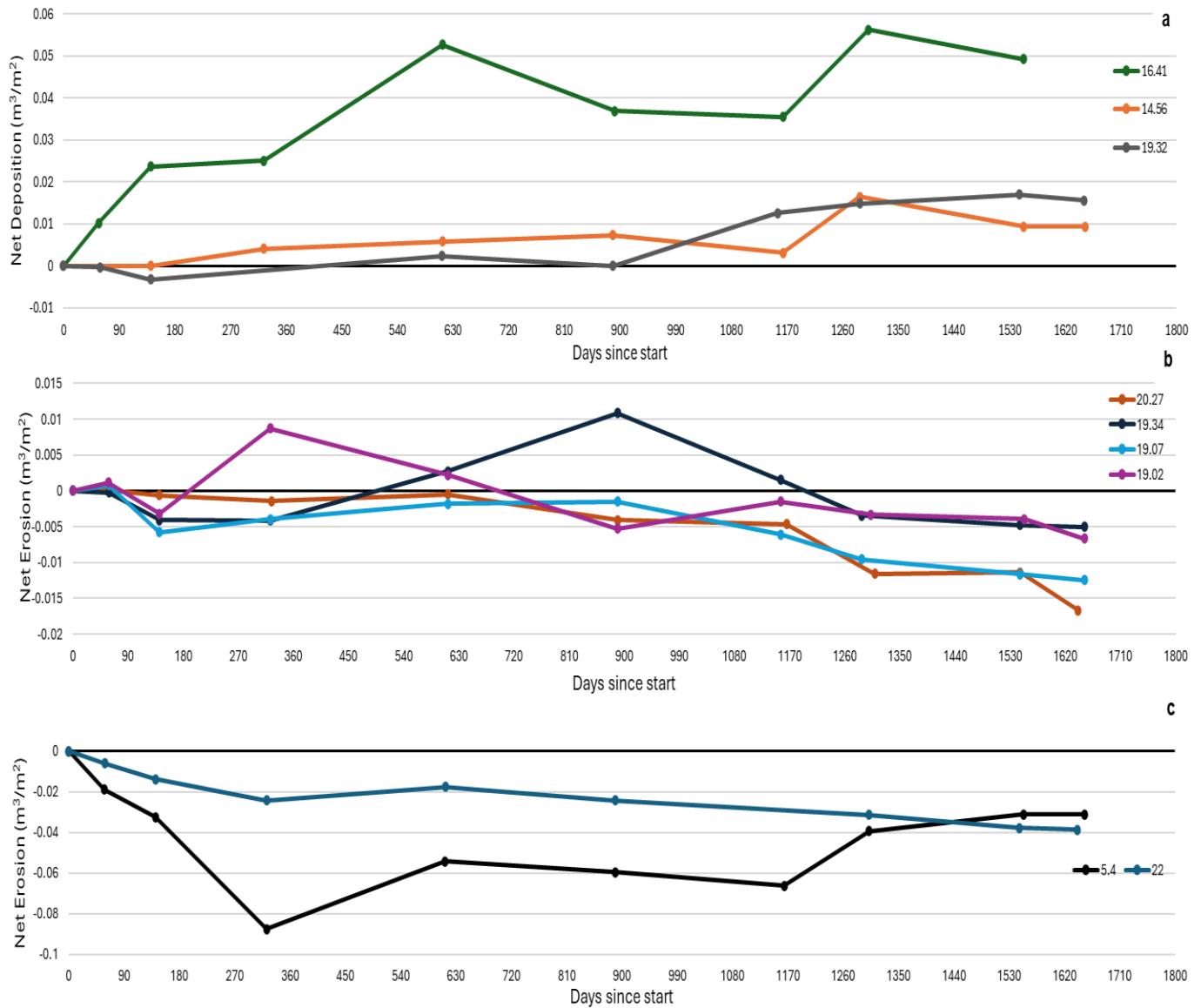


Figure 17: Cumulative erosion and deposition volume trends normalized to bank surface area (m^3/m^2) (a) predominant deposition at sites EFK 14.56, 16.41 and 19.32, (b) deposition and erosion at sites EFK 19.02, 19.07, 19.34, and 20.27, and (c) predominant erosion at sites EFK 5.4 and 22, in m^3/m^2

The erosion volumes and mercury content at EFK 22 are both so much higher compared to the remaining field sites, that it needed to be separated from the remaining sites in order to better visualize the trends and error bars of the remaining sites (**Figure 18a** vs. **Figure 18b**). **Figure 18** displays the mercury flux (in $\text{g/m}^2\cdot\text{year}$) normalized by dividing site-specific fluxes by the bank surface area. Error bars represent the uncertainty of mercury flux, which was calculated using **Equation 2**. Mercury fluxes were highest at EFK 22, which is associated with an exposure of the HRD, followed by a dip then an increase at EFK 19.07, which corresponds to another site where the HRD soil layer is present as seen in **Figure 3**. Interestingly, EFK 20.27 and other sites adjacent to the HRD soil layer (EFK 19.34, EFK19.32) showed lower mercury fluxes with no significant variations downstream of EFK19.07 besides a minor increase from EFK 16.41 to EFK 14.56. It is difficult to quantify any one reason that this may occur, but it could be due to the significant floodplains found in the HRD area, leading to higher concentrations of mercury, combined with simple variation in erosion rates of creek banks, with EFK 19.07 and EFK 22 being at the highest erosion rates.

4.3 EFPC qualitative site-specific characteristics

A qualitative research data set obtained from a kayak study of East Fork Poplar Creek measuring stream characteristics such as bank height, protection, riparian vegetation, etc., was also used to help understand erosional trends (Ayers and Wade, 2013). This kayak is mounted with an Above Video Mapping System equipped with GPS-based cameras, underwater cameras, laser distance sensors, sonar depth sensors, and a Garmin GPS receiver. This combination of technology was used examine creek qualitative and quantitative characteristics throughout East Fork Poplar Creek, resulting in the final dataset that links these characteristics to site coordinates.

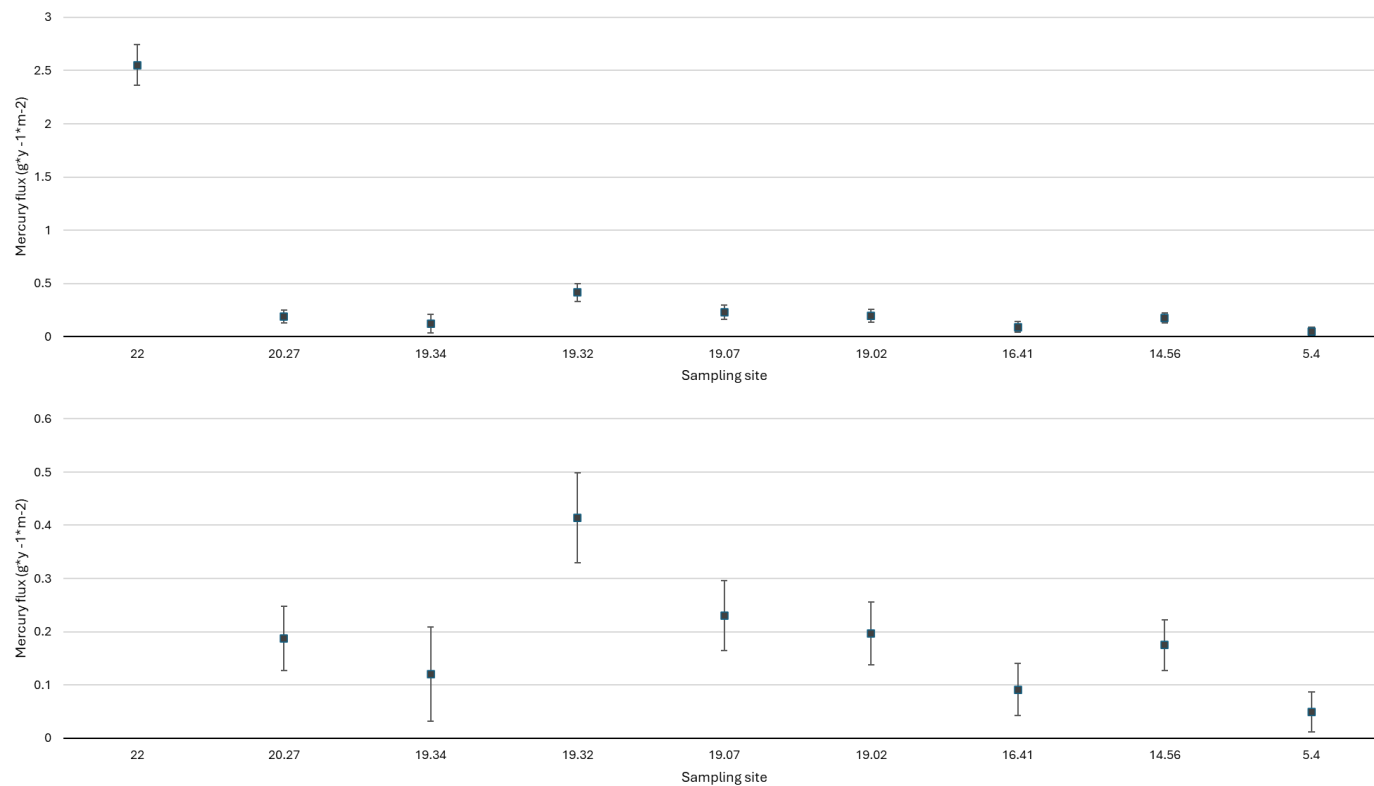


Figure 18: The normalized yearly mercury flux at (a) all sites with their respective margins of error applied and (b) a focused view without EFK 22 to facilitate comparisons.

From the figures produced by this data, the creek width increases downstream and is the widest around EFK16, but some significant widening also occurs near EFK 19.02-EFK 20.27 where HRD layer soils are present. However, the trends in individual reaches of the river are variable, with a more variable width in the stream channel in the upstream areas, and slower contraction and widening in the downstream areas. Bank heights were variable throughout EFPC with banks being the tallest on average at EFK 19.07, and the shortest at EFK 19.34, all banks at EFK 5.4 as well but most of the remaining banks being moderately tall. For bank angle, banks were the steepest around high EFK 16 to low EFK 17. The creek has high riparian diversity, primarily near sections where the HRD layer is present, with moderate diversity throughout most of the rest of the creek. The sinuosity of East Fork Poplar Creek is higher in the upper 50% of EFPC, with a trend of decrease in lower sections. After a closer look at the site characteristics specifically measured around the field sites, it was found that there is a high Bank Erosion Hazard Index (BEHI) rating throughout EFK 19 as well as moderate ratings through EFK 16 and close to EFK 5, with a high rating also occurring at EFK22. This index, originally developed using Wildland Hydrology concepts by David Rosgen, considers factors such as bank material, stratification, root depth and density, bank angle, the bankfull height to bank height ratio, and the amount of surface protection present on a bank in order to assign a value of susceptibility to erosion for the streambank (Rosgen, 2001). The highest Near Bank Stress (NBS), which is defined by direction of flow, channel geometry, and flow mechanic, is also in the HRD as well as in upper EFK 16 to lower EFK 17, EFK 14 to 15, and EFK 6 to 7. However, in a comparison between site characteristics and erosion volumes, a correlation could not be established with the BEHI ratings (**Figure 19b**), NBS scores (**Figure 19c**), or bank heights (**Figure 19a**).

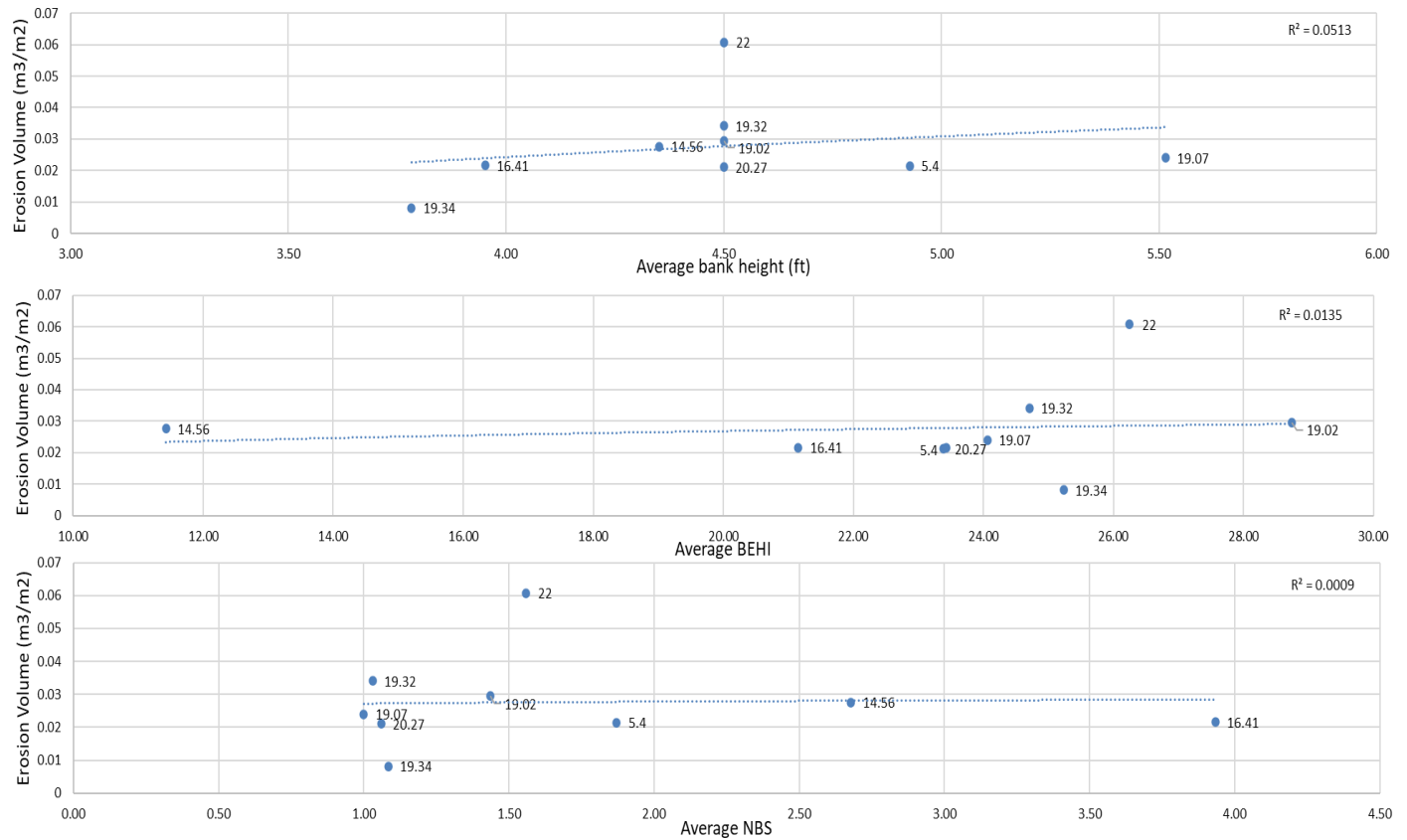


Figure 19: Comparisons between site characteristics and normalized erosion along a linear regression for all field sites. **Figure 19a** compares erosion volume and bank height, **Figure 19b** compares BEHI and erosion volume and **Figure 19c** compares NBS rating and erosion volume.

4.4 Discussion of results

Overall, EFK 22 and EFK19.32 saw the highest amount of net erosion. These two sites have several differences, starting with their difficulty to sample. EFK 22 was very challenging due to a lack of distinct features on its banks, while EFK 19.32 has very distinct root networks and minimal vegetation on its banks. This difference in difficulty is shown in each site's respective error in **Figure 13**. While the high erosion measured at EFK 22 could be an overestimate considering its moderate error, higher erosion amounts were also measured at EFK19.32. Sites EFK 16.41, and 19.34 demonstrate locations where net deposition outweighs erosion. This makes clear that there are many variations in erosive stress throughout the creek, and that creek location is not definitive for the degree of erosion. High deposition is consistent with the presence of sediment bars at sites EFK 16.41, and EFK 19.34, which are both located on bends, and each have visible soil slumping features.

The high BEHI ratings at the many of the EFK 19 sites likely contribute to the net erosion observed at these sites, although to a lesser extent than at EFK 22. However, EFK 20.27 had a greater measured erosion rate than EFK 19.02 while having a BEHI as low as the rating at EFK 5.4, which could be due to its moderate erosion to deposition ratio. Out of the remaining field sites, EFK 20.27 is the only site that does not have overhanging banks, which could indicate that unlike other banks, there is not an overestimation of deposition after mass wasting events; thus, highly erosive events are only measured as erosion.

However, the high erosion observed at EFK 14.56 is slightly more difficult to explain. This site has one of the lowest bank heights, it is an outlier for how low its BEHI is but does have a high NBS rating. This site has a scour toe forming across the stream from the sampling

site which could indicate highly erosive flows, which probably explains its high NBS rating. As a result, a disproportionately high amount of erosion occurs at EFK 14.56. This theory is consistent with the high mercury flux at EFK 14.56, relative to its location in EFPC, as well as EFK 14.56 having a high Near Bank Stress rating.

These results are different from the results demonstrated in **Figure 17**, because they are based off the single method net erosion volumes rather than the cumulative method. While the cumulative method is better suited for demonstrating net erosion trends over time, compounding errors from individual measurements lead to large deviations in the final net erosion volumes, as demonstrated in **Figure 12**. While most of the comparisons indicated that erosion volumes were overestimated, at certain sites such as EFK 19.32 and 14.56, when switching from cumulative method volume to single method volume, net erosion instead of net deposition was measured, whereas at EFK 19.34, net deposition was measured instead of net erosion. It is important to note that when looking at the cumulative trends of these sites in **Figure 17**, these three sites are the ones closest to zero erosion, there being simultaneously high amounts of erosion at deposition at EFK 19.34. However, EFK 19.32 and EFK 14.56 have much higher erosion than deposition amounts, which means they should always have much higher net erosion values than was calculated by the cumulative method. This could indicate that the cumulative method tends to overestimate deposition, especially considering that in **Figure 17**, high deposition events occur during the scanning intervals with the lower quality scans, taken in the middle of the spring or summer, where there is dense vegetation and bright sunlight, causing lower resolution and overestimation of deposition. The single method avoids this entirely by not utilizing these low-resolution point clouds.

All of these correlations between BEHI and erosion trends must be analyzed with the established caveat that a linear correlation was unable to be established between site-specific factors such as bank height, NBS, and BEHI, and erosion volume. Bank height is the tallest at EFK 19.07, a field site with moderate erosion, which indicates that it is unlikely that there is a correlation between erosion and bank height in EFPC. On the other hand, the BEHI should be a good indicator of a site's capacity for erosion. So, it considers many other site-specific factors besides only bank height, also considering bank protection, the material in the soils, and bank angle. However, it is also possible that this index qualitatively considers so many factors in its final assessment of an area's vulnerability to erosion that some of these factors get confounded, creating variability in the BEHI data that makes it difficult to compare to actual erosion measurement. Additionally, the BEHI is based on river characteristics in Colorado, which could be significantly different from the flow conditions found in East Tennessee (Rosgen, 2001). This failure to establish a linear correlation between the BEHI, and NBS of field sites and their respective erosion amounts is consistent with a study that was done in the Bakreshwar River of the Rarh region of Eastern India. Although the river morphology of this area might also be different from the conditions of East Tennessee, the study's usage of cross-sections from a five-year sampling period ensures that it measures a similar tracking of change in flow regimes (Ghosh Pal and Mukhopadhyay 2016). This study used the BEHI–NBS calibration method, a method originally developed by Rosgen in order to combine NBS with the BEHI in order to determine the stress of flow on the bank of concern (Rosgen, 2001). Ultimately, the study found that this calibration method is not a significant predictor for actual erosion rates (Ghosh Pal and Mukhopadhyay 2016), which is consistent with my results, and cites the usage of NBS as the

primary source of error, finding better correlation when using the BEHI model. This is also consistent with my results in which the correlation between BEHI and erosion volume is higher than the correlation between erosion volume and NBS, but the correlation for both is very low.

The erosion trends measured at EFPC's field sites are consistent with the relative trends measured by the erosion pins in sites EFK22, 19.34, ~16.41, 14.56, and 5.4 in 2015 (Watson et. al, 2016). A previous study comparing erosion pin measurements and TLS erosion measurements in EFPC over a two-month period also found similar erosion trends (Collado, 2021). However, they found that due to the significant amount of error associated with the usage of erosion pins, they should only be used for situations in which dense vegetation is present at the field site, or erosion only needs to be measured for relative, qualitative comparisons, not precise, quantitative measurements (Collado, 2021). The presence of vegetation can affect the accuracy of erosion and deposition measurements by TLS, because it may be incorrectly measured as bank deposition, and plant dormancy in winter may be detected as erosion (Collado, 2021). The impact of vegetation on TLS measurements was also confirmed in the present study. Therefore, evaluation of scanning accuracy in the field was evaluated under controlled conditions, which was discussed in previous sections.

4.5 Accuracy of TLS for erosion volume measurements

In experiments designed to evaluate the uncertainty of erosion measurement under field and controlled conditions, several common trends were observed. Generally, field sites with the high levels of vegetation or those with complex topography, such as overhanging banks, resulted in the highest uncertainty in erosion with a maximum of 0.037 m error at EFK 5.4, where these features are most prevalent. In addition, relatively high errors were observed at sites EFK14.56

and EFK19.07 (**Figure 13**). All these field sites have some mix of vegetation, roots, or overhanging banks resulting in errors higher than the average measurement error of 0.0132 m. The main reason for this could be because TLS tends to struggle with obtaining accurate erosion measurements when dealing with medium to heavy vegetation, and overhanging banks (Collado, 2021). This finding is conceptually consistent with literature that cites how TLS scanners struggle with obscuration; how the areas behind vegetation or in the shadow of an overhanging bank will be obscured (Charlton et. al, 2009). This can have consequences such as reduced point resolution or may be missed by the scanner altogether (Charlton et. al, 2009). Additionally, the seasonal change in the presence of vegetation can affect the erosion and deposition values measured by the scanner because the vegetation may be considered as part of the bank (Collado, 2021). It is important to note that overlapping scans to estimate uncertainty in the field measurements were all taken in the middle of June, when the sun shines the brightest on the scanned banks, and the vegetation density is highest. As a result, these error estimates represent the upper limit of the uncertainty range during data acquisition in the field. Since the scanner utilizes infrared lasers, it is unable to scan through water (Charlton et. al, 2009). This means that parts of the bank that are below the stream water level at the time of the scan will not be included in the point cloud. Therefore, collected erosion data represents only the visible portion of creek bank at a particular field site and erosional processes below the water surface, such as fluvial entrainment, may not be captured by TLS. This could explain why at certain sites where there are clear signs of mass wasting, such as EFK 5.4, the net erosion measured is very low. The scanner can measure the slump of soil onto the face of a bank as a result of a mass wasting event but is

unable to measure the entrainment of sediments that occurs at the submerged toe of the bank. Thus, data collection should only occur when the water levels are low.

The impact of vegetation, overhanging banks, and roots on TLS are also reflected in the results of the concrete wall tests with the simulated vegetation and overhang causing the highest errors during the erosion volume calculations, whereas other factors such as roots or removing volume in an off-center location have a much smaller impact on the accuracy of erosion measurements. Another factor that can impact the accuracy of erosion measurements, but was not studied for the concrete wall tests was the decrease in range and thereby resolution of scans at lower meteorological visibility (Heritage and Large, 2009). Adverse weather conditions such as rain, severe cold, or high winds may shut down the scanner altogether (Charlton et. al, 2009). A potential source of error for the concrete block test, however, is that the board that was used as the backboard to cover the opening in the back of the wall was taller than the wall. While it stayed in the same place for most scans, when the plywood board was placed on the top of the concrete wall for the overhang tests, the backboard was pushed slightly backwards. This could explain some of the overestimation of erosion volume found in the overhang measurements. Direct sunlight can also impair the reflectance of the area of interest and reduce resolution (Charlton et. al, 2009).

Other factors that were found to change the accuracy of scans include the application of georeferencing, as seen in **Figure 16**, which demonstrates a directly proportional relationship between percent error and site size, with the smallest site having the smallest error and the largest site having a much larger error. Confounding factors such as overhanging banks and vegetation could potentially interfere with the establishment of a direct correlation between site

size and percent error. The impact of georeferencing on improved scan registration and merging accuracy has been demonstrated in previous studies (Alexiou et. al, 2021). Considering that the erosion volume calculation process involves two separate registration steps, having this extra accuracy in registration, even if it only means an improvement in point accuracy by a couple of millimeters, can significantly improve the accuracy of volume calculations. Another study found that georeferencing confers sufficient accuracy in LiDAR scans to detect minute trends in coastal erosion, which requires accuracy on the decimeter scale that could not be accomplished otherwise (Harwin et. al, 2012).

While it is known that all these factors can impact the resolution and thereby the quality of a point cloud significantly, few studies have attempted to quantify the impact of occlusion by vegetation or overhanging banks on the accuracy of erosion measurements. In a similar study of TLS accuracy, the listed point error (6-10 mm) and the impacts of vegetation on the accuracy of scans are reported, and the study discusses workflows that one can deploy to avoid dealing with the errors caused by vegetation, such as taking multiple or elevated scans (Li et. al, 2020). TLS scans were taken on a field plot, and error was estimated by comparing the volume of erosion measured and the mass of sediment captured from the field plot. Most of the uncertainty was attributed to scan angle or the number of scans taken (Li et. al, 2020). Another study cites vegetation as a major cause of error in measured bank erosion volume, even considering automatic registration tools that can filter out vegetation. The authors conclude that manual removal of vegetation either in the field or in the software can be tedious and subjective and therefore is not effective at completely mitigating vegetation impacts on erosion measurements (Day et. al, 2013). In their study, Day et. al used an algorithm that allows for points to be

compared in the direction of likely change rather than directly comparing points to one another, allowing for factors such as overhanging banks to be less problematic in erosion calculation (Day et. al, 2013). This algorithm is a workaround to the issues associated with measuring a change in topographical change on an organic surface. So, while in our study, we use a mesh, in this study, they use a predictive algorithm that superimposes point clouds not by matching the closest points, but instead by matching one point to the point closest to where the algorithm predicts that the next point will be. Sources of error such as irregular surfaces, alignment error, and removal of vegetation were discussed in this study (Day et. al, 2013). However, no analysis was performed to isolate these individual factors to estimate the contribution of each individual factor to measurement error (Day et. al, 2013). These insights align with sources of uncertainty discussed in other TLS papers, but there are limited studies trying to quantify how much any one factor might be impacting the quality of the erosion measurement. Although our tests confirm these limitations in the measurement technique, the low observed margin of error demonstrates that TLS is a highly reliable way to measure erosion providing a quantitative determination of mercury flux.

Overall, the cumulative method erosion measurements showed that the most upstream site at EFK 22 combined high erosion rates and high mercury concentrations, leading to the highest calculated mercury flux among all 9 sites. The highest mercury concentrations in bank soils were found at four other sites in the HRD zone (EFK19.34, 19.32, 19.07 and 19.02). While these sites experience lower erosion rates, the high mercury concentrations lead to higher mercury flux than the sites downstream of this area. For example, EFK 19.34 had an erosion rate low enough to be considered net deposition but still had a higher flux than EFK 5.4 or 16.41. It is

also important to consider with this result that the single method rather than cumulative method was used for these calculations, so sites that may have high simultaneous erosion and deposition leading to low net erosion values may still have high mercury flux.

All sites in the HRD zone are located along bends meaning they have a higher risk for erosion, which is consistent with their high BEHI values (Ayers and Wade, 2013) resulting in above average erosion rates. This trend agrees with the results of another bank erosion study in the South River, Virginia. The primary mode of channel change in this mercury-impacted river are river bends, which contribute to most of the erosion in this system (Rhoades, 2009). This effect is amplified in rivers that are meandering and tend to migrate (Rhoades, 2009). The study also found a positive correlation between bank height, bed slope and depth, flow velocity, and erosion (Rhoades, 2009). No correlation was able to be established between bank height, or other site-specific stability characteristics, and erosion trends in EFPC, as demonstrated in **Figure 19**. In addition, no measurements of bed slope and depth were conducted, while flow velocity has only been measured at two field sites. Nevertheless, both the erosion volume and mercury flux estimates are well below values previously calculated by erosion measurements (Watson et. al, 2016). The average erosion throughout the watershed was projected to be about 134 times higher per 100 meter reach than what was measured by TLS in the present study. This may be due to the overestimation of erosion associated with the use of erosion pins, which is supported by a previous study reporting that in EFPC, erosion pins estimated, on average 64 times more erosion than TLS (Collado, 2021). This interpretation is also supported by another study which found that while the installation of erosion pins can hold some sediments in place, the main impact of installation is a disturbance of the banks that leads to more erosion and overestimation of erosion

rates (Couper and Maddock, 2002). For these reasons, as well as the overall higher accuracy that TLS measurements have compared to erosion pin measurements, the use of TLS in a similar fashion to this pilot study may be appropriate for application throughout EFPC and other watersheds in which determining streambank retreat is important.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

This study was able to successfully measure the erosion of streambanks in several locations along EFPC and thereby generate estimates of erosion rates and mercury flux on a site-specific basis. Through a series of controlled tests, we were able to determine that common streambank factors, such as vegetation, thick roots, and overhanging banks have a negative impact on the accuracy of erosion estimates. However, despite the clear impact these factors can have on the accuracy of scans, several measures were identified that can help minimize uncertainty. The most significant improvements were achieved by georeferencing recorded point clouds and maintaining scan distance and angle within limits identified in this study. Overall, the maximum error identified for erosion volume measurement by TLS was 0.037 m. This demonstrates that despite some limitations with this sampling technique, we can be reasonably confident in the accuracy of the erosion volume data and flux calculations that are based on erosion rates. This allows us to establish confidence that the use of TLS is a viable method for measuring streambank erosion and comparison of erosion rates between different locations. This information can be used to help inform the allocation of remediation resources in East Fork Poplar Creek.

Based on the results of this study, it is recommended that TLS data should be ideally obtained on overcast days, from banks with little or minimal dense vegetation, and when water levels are low. Meeting these conditions might necessitate field data collection during the winter season or physical removal of vegetation from banks; however, it is important to note that vegetation removal can cause additional erosion. Considering the number of creek banks that

presented challenges due to root networks, dense vegetation, or soil overhang at the top of the bank, prioritizing locations where these issues are less prevalent is advisable.

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APPENDIX

Table 3: Net erosion volumes calculated over time at all field sites

		cumulative volume (m3/m2)								
		202008- 202010	202010- 202101	202101- 202107	202107- 202204	202204- 202301	202301- 202310	202310- 202402	202403- 202411	202411- 202502
5.4	**	-0.1863	-0.1692	-0.5083	0.3574	0.0104	-0.1348	0.2271	0.1058	-0.0187
14.	56		0.0296	0.021	0.0105	-0.0283	0.1206	-0.0558	-0.0055	-0.0134
16.	41	0.0704	0.0992	-0.0285	0.1142	-0.0117	-0.0071	0.0841	0.0055	-0.0543
19.	02	0.0158	-0.0566	0.1496	-0.08	-0.0923	0.0401	-0.0167	-0.0041	-0.0355
19.	07	0.0112	-0.0942	0.0285	0.0299	-0.0831	0.0095	-0.0635	-0.024	-0.0187
19.	32	-0.0022	-0.0198	0.0428		0.0942	0.0242	0.0198	-0.0016	-0.0274
19.	34	-0.0013	-0.0213	0.0006	0.0386	0.0494	-0.0545	-0.036	-0.009	0.0016
20.	27	0.0007	-0.0042	-0.0041	0.0049	-0.0215	-0.0037	-0.0398	-0.008	-0.0252
22		-0.1185	-0.1791	-0.2382	0.1374	-0.1876	-0.1521	-0.0774	-0.0412	-0.4292
5.4		-0.1863	-0.3555	-0.8638	-0.5064	-0.496	-0.6308	-0.4037	-0.2979	-0.3166
14.	56	0	0.0296	0.0506	0.0611	0.0328	0.1534	0.0976	0.0921	0.0787
16.	41	0.0704	0.1696	0.1411	0.2553	0.2436	0.2365	0.3206	0.3261	0.2718
19.	02	0.0158	-0.0408	0.1088	0.0288	-0.0635	-0.0234	-0.0401	-0.0442	-0.0797
19.	07	0.0112	-0.083	-0.0545	-0.0246	-0.0246	-0.1077	-0.0982	-0.1857	-0.2044
19.	32	-0.0022	-0.022	0.0208	0.0208	0.115	0.1392	0.159	0.1574	0.13
19.	34	-0.0013	-0.0226	-0.022	0.0166	0.066	0.0115	-0.0245	-0.0335	-0.0319
20.	27	0.0007	-0.0035	-0.0076	-0.0027	-0.0242	-0.0279	-0.0677	-0.0757	-0.1009
22		-0.1185	-0.2976	-0.5358	-0.3984	-0.586	-0.7381	-0.8155	-0.8567	-1.2859

Table 4: The surface areas of each cumulative mesh used to calculate normalized volume

Surface area (m3)										
	2020 08- 2020 10	202010- 202101	202101- 202107	202107- 202204	202204- 202301	202301- 202310	202310- 202402	202403- 202411	2024 11- 2025 02	AVG
5.4	9.84	10.91	9.85	9.33	8.34	9.51	10.26	9.56	10.15	9.75
14.56	7.19	0.00	8.70	8.29	10.62	9.32	10.39	9.84	10.02	8.26
16.41	6.85	7.15	5.63	4.84	6.59	6.66	5.70	6.62	6.48	6.28
19.02	13.5 3	12.64	12.53	13.09	12.06	15.43	12.18	11.11	12.01	12.73
19.07	14.7 6	14.39	13.77	13.54	16.14	17.62	10.28	15.98	16.41	14.77
19.32	7.25	6.96	8.56	0.00	9.13	9.38	9.36	10.06	9.81	7.83
19.34	6.12	5.51	5.30	6.14	6.08	7.51	7.13	7.04	6.32	6.35
20.27	5.48	5.65	5.43	5.28	5.96	5.99	5.85	6.63	6.05	5.81
22	20.0 1	21.48	22.12	22.60	24.25	23.61	21.63	22.09	25.14	22.55

Table 5: Normalized cumulative volumes

Norm Cumulative volume (m3/m2)										
	202008	202008 - 202010	202010 - 202101	202101 - 202107	202107 - 202204	202204 - 202301	202301 - 202310	202310 - 202402	202403 - 202411	202411 - 202502
5. 4	0	-0.0189	-0.0326	-0.0877	-0.0543	-0.0595	-0.0664	-0.0393	-0.0311	-0.0312
14. 5 6	0	0.0000	0.0041	0.0058	0.0074	0.0031	0.0165	0.0094	0.0094	0.0079
16. 4 1	0	0.0103	0.0237	0.0251	0.0527	0.0370	0.0355	0.0562	0.0493	0.0419
19. 0 2	0	0.0012	-0.0032	0.0087	0.0022	-0.0053	-0.0015	-0.0033	-0.0040	-0.0066
19. 0 7	0	0.0008	-0.0058	-0.0040	-0.0018	-0.0015	-0.0061	-0.0095	-0.0116	-0.0125
19. 3 2	0	-0.0003	-0.0032	0.0024	0.0000	0.0126	0.0148	0.0170	0.0156	0.0079
19. 3 4	0	-0.0002	-0.0041	-0.0041	0.0027	0.0109	0.0015	-0.0034	-0.0048	-0.0050
20. 2 7	0	0.0001	-0.0006	-0.0014	-0.0005	-0.0041	-0.0047	-0.0116	-0.0114	-0.0167
22	0	-0.0059	-0.0139	-0.0242	-0.0176	-0.0242	-0.0313	-0.0377	-0.0388	-0.0512

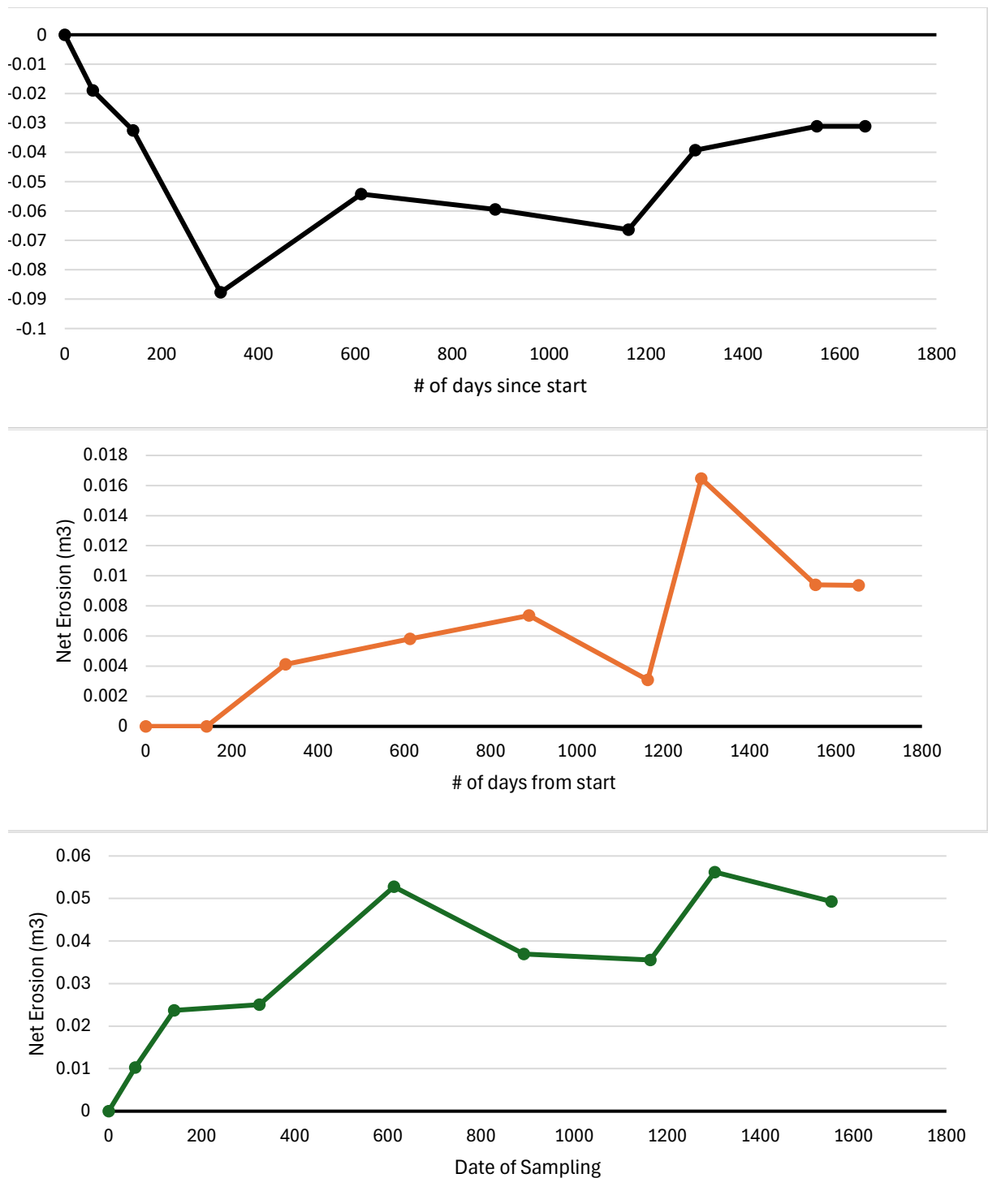


Figure 20: Cumulative erosion graphs for EFK 5.4-16.41

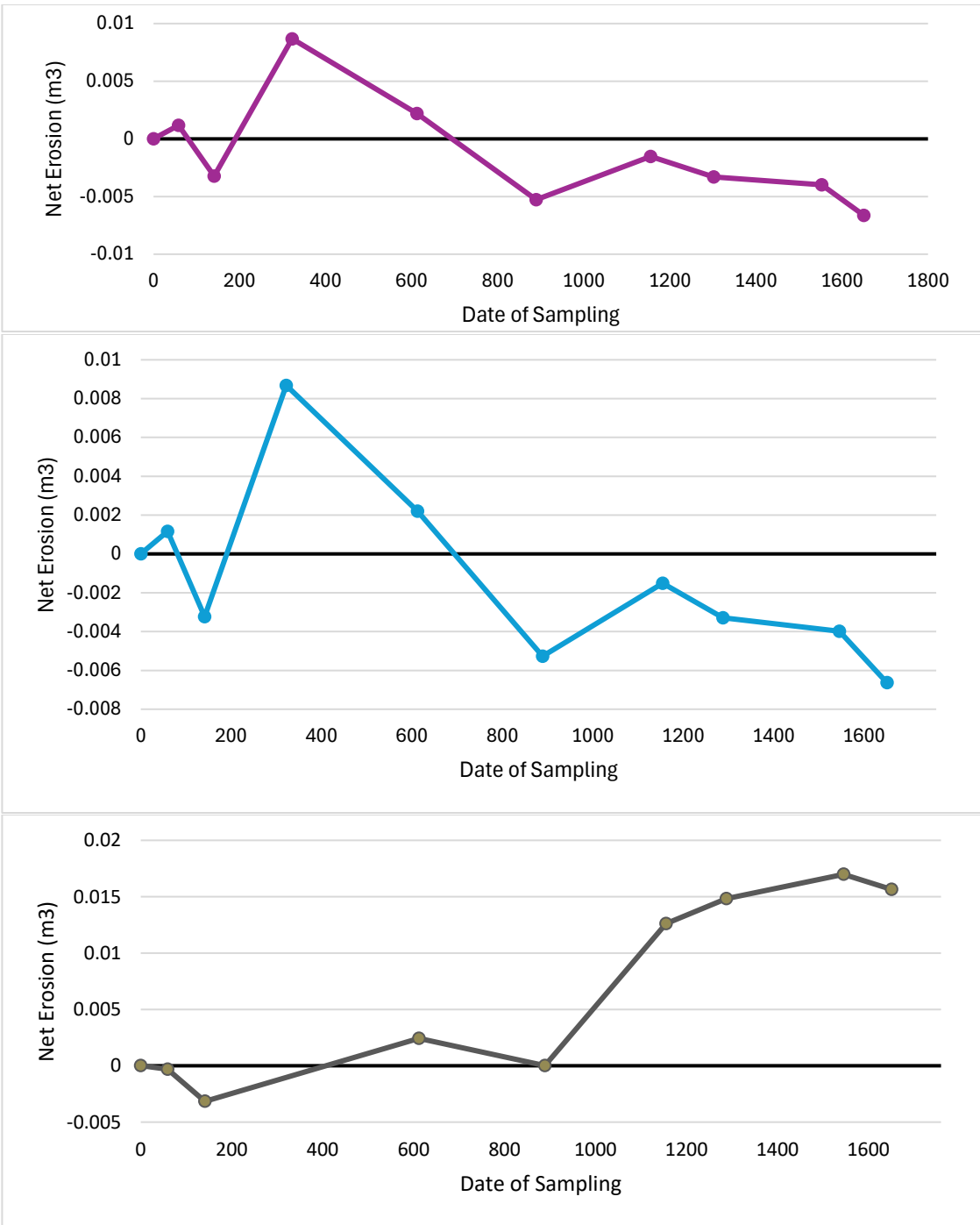


Figure 21: Cumulative erosion graphs for EFK 19.02-19.32

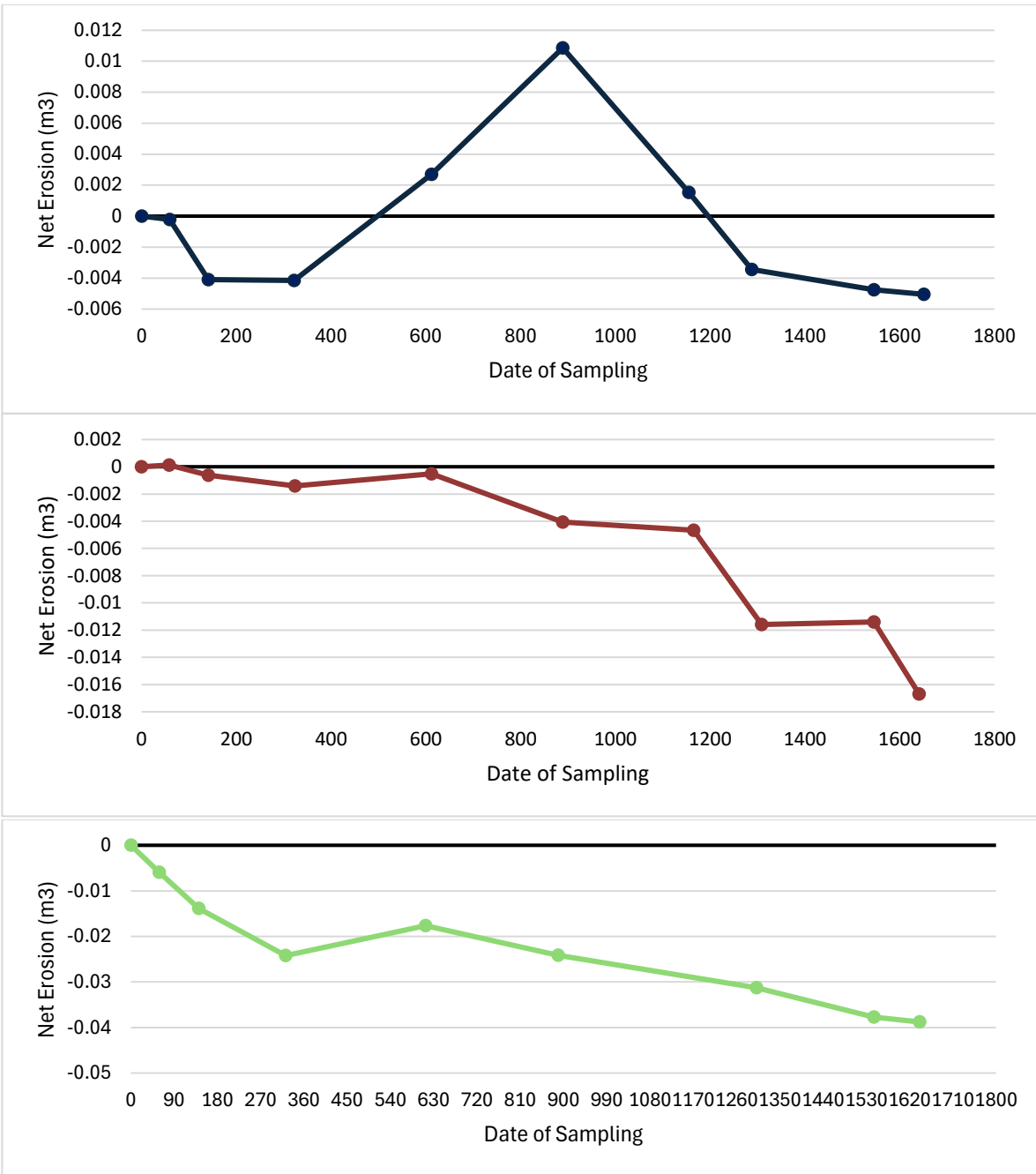


Figure 22: Cumulative erosion graphs for EFK 19.34-22

Table 6: Data for all the single method erosion measurements that are part of a full one

		202010	202101	202107	202204	202301	202310	202403	202411	202502
5.4	0	-0.1863	-0.4305	0.6508	0.236	-0.2443	-0.1092	-0.3261	-0.6421	-0.0223
14.56	0		0.0296	-0.1889	0.2329	0.4107	-0.0341	-0.1235	0.0507	-0.0659
16.41	0	0.0704	0.1612	-0.0029	0.1449	0.1157	-0.1362	0.1572	0.0915	0.0514
19.02	0	0.0158	-0.2763	-0.5355	-0.8762	0.7018	-0.7423	-0.2486	-0.1256	-0.0502
19.07	0	0.0112	-0.483	-0.1424	0.4259	-0.5886	-0.3682	-0.4879	-0.448	-0.0922
19.32	0	-0.0022	-0.1069		0.1545	-0.3988	-0.1988	-0.5363	0.1527	-0.0784
19.34	0	-0.0013	-0.0961	-0.1295	0.2634	0.0755	0.03	0.025	0.036	0.0075
20.27	0	0.0007	-0.0433	0.0319	-0.0192	-0.0729	0.0116	-0.0194	-0.0071	0.0003
22	0	-0.1185	-1.9764	0.3066	2.5532	-0.885	-1.2336	-0.7991	-1.4384	-0.2554

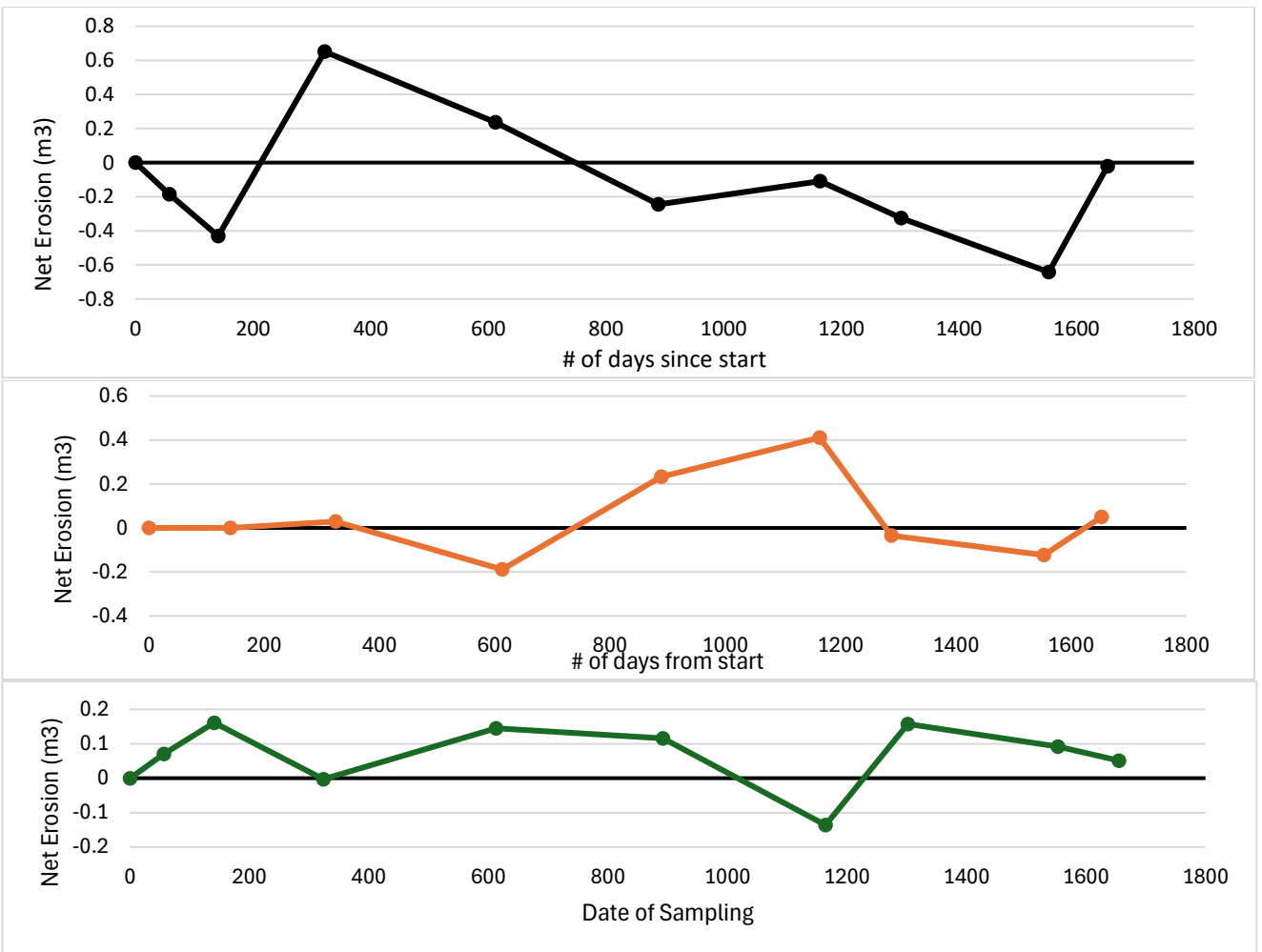


Figure 23: Single method point erosion measurements over time for EFK 5.4-16.41

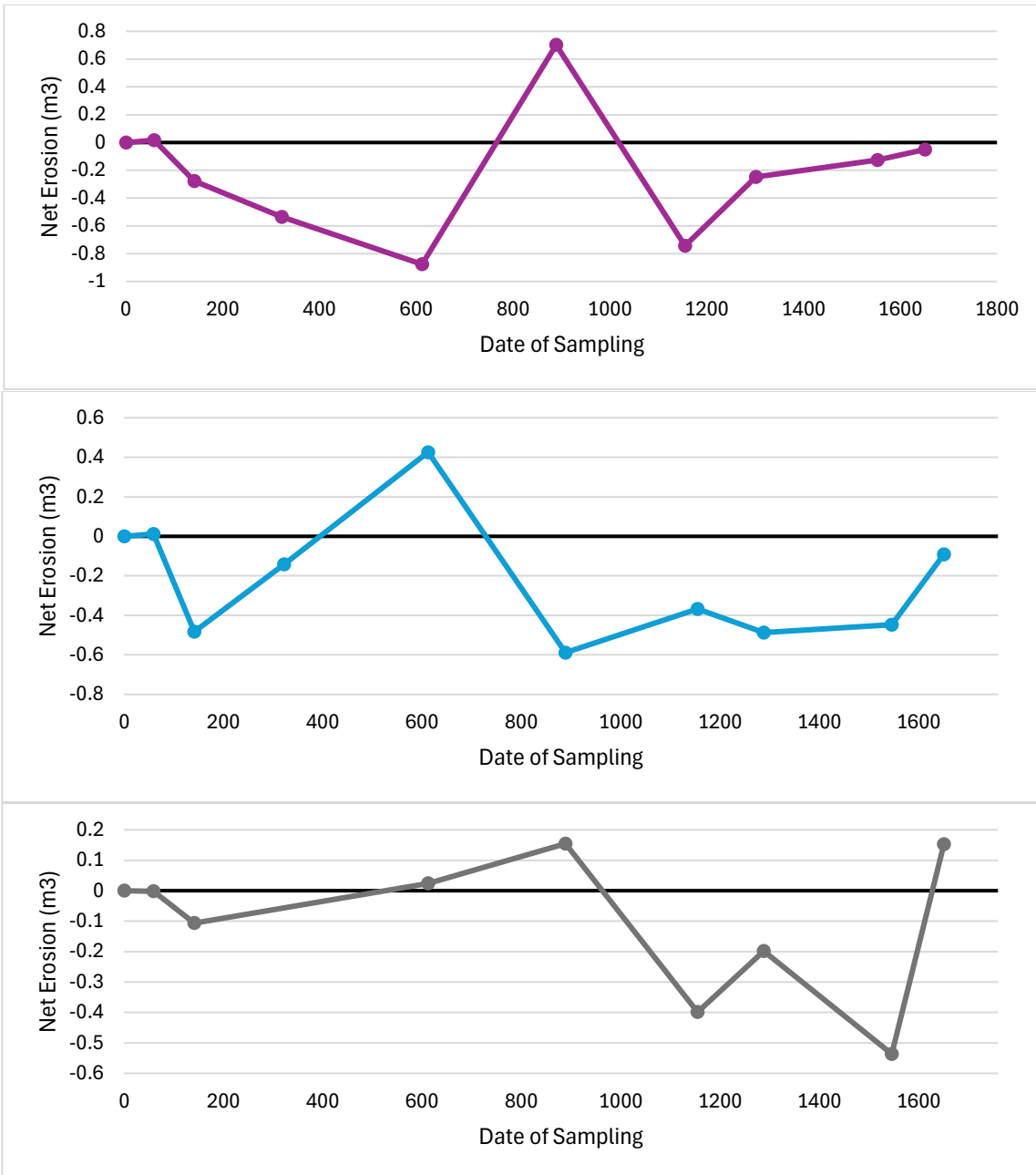


Figure 24: Single method point erosion measurements over time for EFK 19.02-19.32

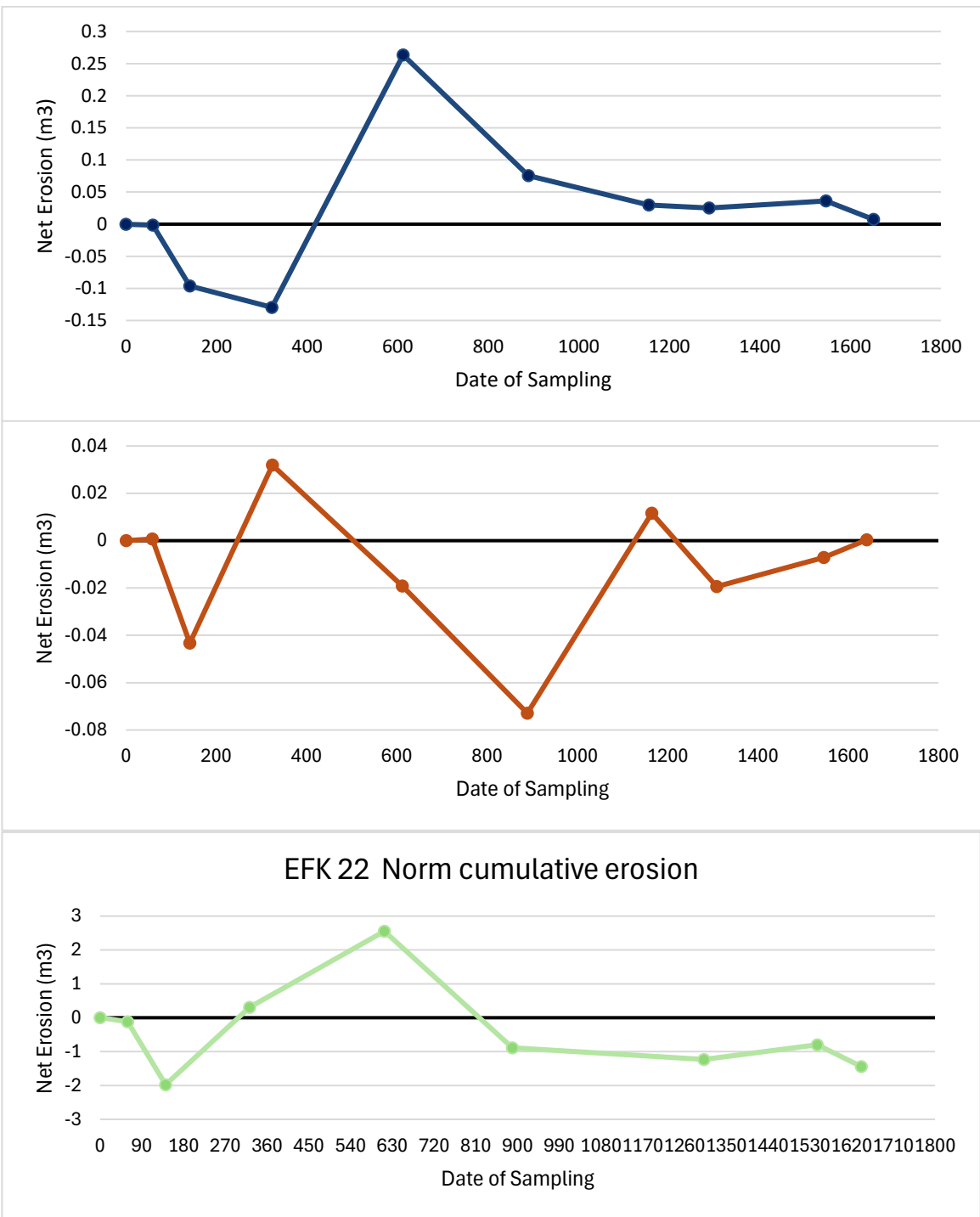


Figure 25: Single method point erosion measurements over time for EFK 19.34-22

Table 7: The data for the concrete wall tests, displayed in a heatmap of accuracy, duller colors are closer to accurate, while brighter colors are farther. Orange colors are above the correct erosion amount, and blue colors are below the amount.

Concrete wall error overlap tests					
Treatment	TSI	SVR	MSVR	SVF	MSVF
Known volume:	0.0149	0.0149	0.0149	0.0149	0.0149
Low volume 1	0.0134	0.0175	0.0179	0.0174	0.0184
Low volume 2	0.0101	0.0134	0.0129	0.0157	0.0146
Low volume 3	0.018	0.0165	0.0186	0.0171	0.0167
Low vol average	0.013833	0.0158	0.016467	0.016733	0.016567
Control 1	0.0155	0.015	0.0141	0.0161	0.0166
Control 2	0.0158	0.0162	0.0146	0.0178	0.0179
Control 3	0.0158	0.0163	0.0165	0.0177	0.0185
Control average	0.0157	0.015833	0.015067	0.0172	0.017667
Veggie (No crop) 1	0.0159	0.017	0.0154	0.0279	0.028
Veggie (No crop) 2	0.0057	0.0142	0.0144	0.0175	0.0218
Veggie (No crop) 3	0.0162	0.0152	0.0163	0.021	0.0259
Veggie (no crop) average	0.0126	0.015467	0.015367	0.022133	0.025233
Veggie (Crop) 1	0.0143	0.015	0.0149	0.0158	0.0168
Veggie (Crop) 2	0.0145	0.0156	0.0151	0.0163	0.0182
Veggie (Crop) 3	0.0149	0.0155	0.0146	0.0166	0.0169
Veggie (crop) average	0.014567	0.015367	0.014867	0.016233	0.0173
Roots 1	0.0043	0.0139	0.0137	0.0098	0.0076
Roots 2	0.0121	0.015	0.0152	0.0162	0.0132
Roots 3	0.0129	0.0145	0.0135	0.0144	0.0155
Roots average	0.009767	0.014467	0.014133	0.013467	0.0121
Big Overhang 1	0.0257	0.0268	0.0232	0.0286	0.0297
Big Overhang 2	0.0231	0.0259	0.0219	0.0268	0.0228
Big Overhang 3	0.0255	0.0246	0.0218	0.0293	0.0231
Big overhang average	0.024767	0.025767	0.0223	0.028233	0.0252
Short overhang 1	0.0234	0.0262	0.0222	0.0274	0.0231
Short overhang 2	0.0236	0.0258	0.022	0.0268	0.0223
Short overhang 3	0.0246	0.0259	0.0226	0.02	0.0199
Short overhang average	0.023867	0.025967	0.022267	0.024733	0.021767
Veggie (No back, crop) 1	0.0029	0.0032	0.0044	0.0063	0.007
Veggie (No back, crop) 2	0.0029	0.0047	0.0032	0.0052	0.0032
Veggie (No back, crop) 3	0.0031	0.0044	0.0044	0.0037	0.0038
Veggie (No back, crop) average	0.002967	0.0041	0.004	0.005067	0.004667

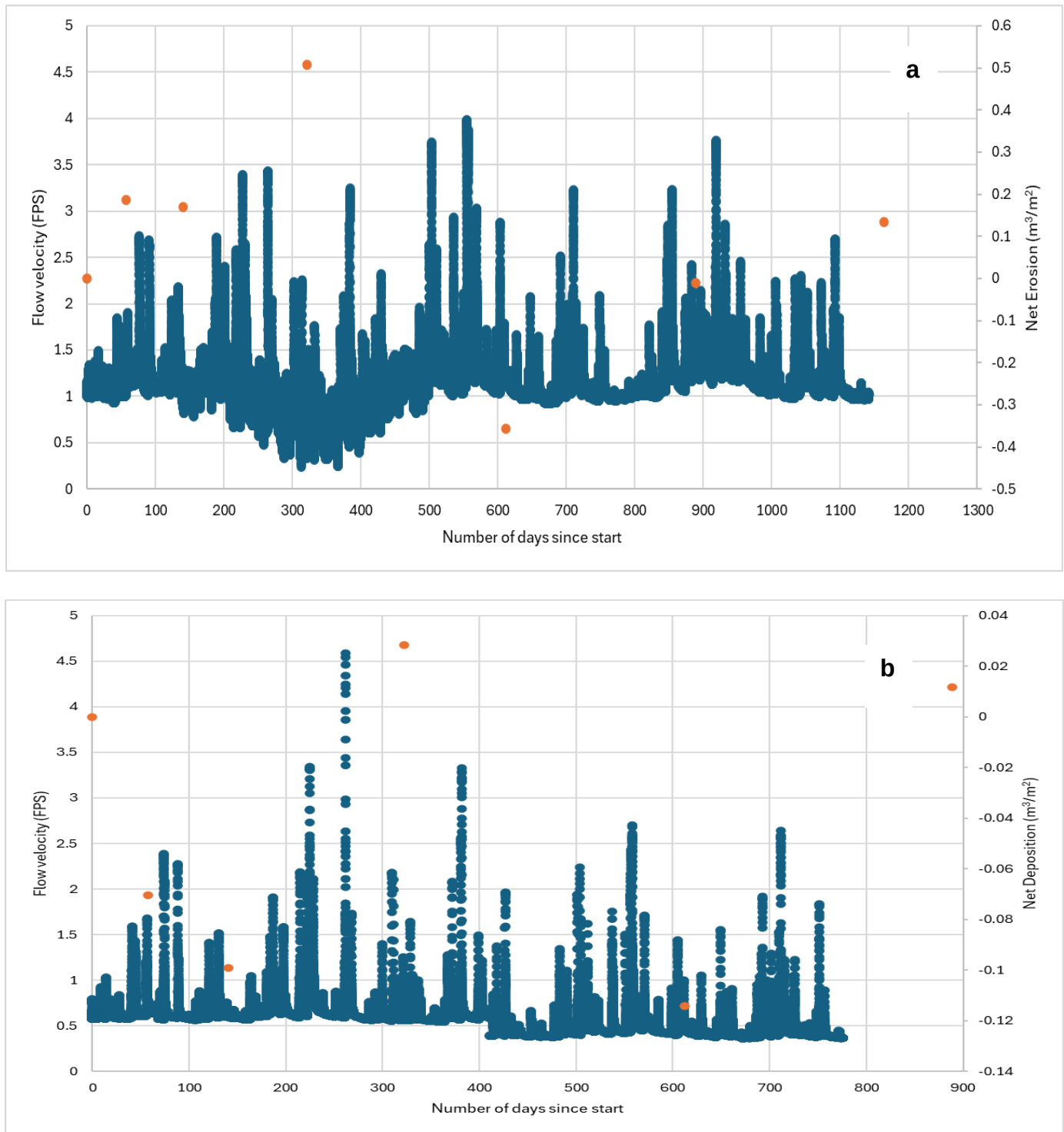


Figure 26: Comparison between net erosion and flow at EFK 5.4 (a) and flow and net deposition at EFK 16.4 (b)

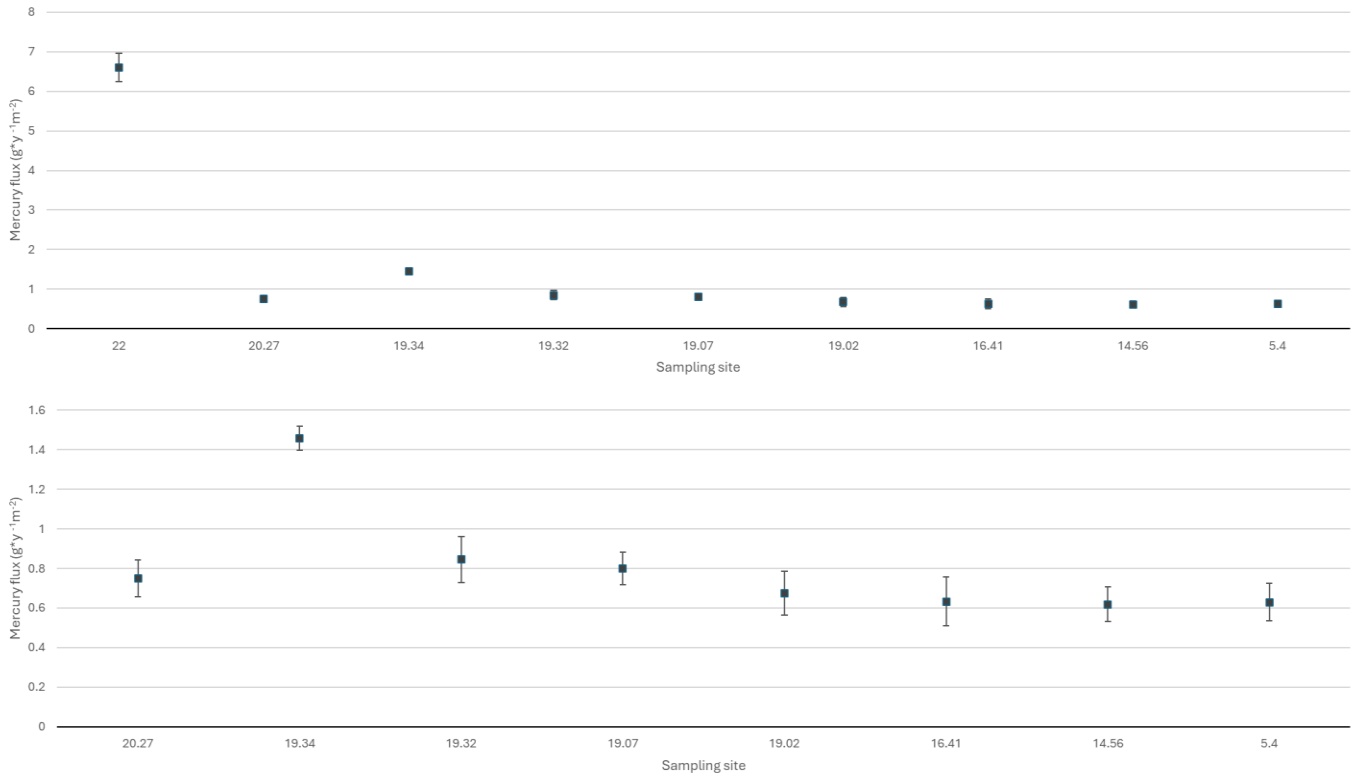


Figure 27: The normalized yearly mercury flux at (a) all sites with their respective error intervals applied and (b) a focused view without EFK 22 to facilitate comparisons, calculated with the cumulative method calculations

Table 8: The comparison between the erosion pin erosion volumes and TLS erosion volumes/100m

Field Site	Erosion pin (kg*yr ⁻¹)	Bulk (g*kg ⁻¹)	LiDAR Erosion (m ³ /m ²)*100	Erosion (kg*yr ⁻¹)	Reach Sum
22	240297	1.5	2.149	711.704	711.704
20		1.74	2.759	1059.819	
19.34	220066	1.57	2.165	750.231	
19.32		1.42	2.946	923.411	
19.07		1.28	2.405	679.549	
19.02		1.44	3.415	1085.558	4498.568
16.41	345076	1.53	0.815	275.380	
14.56		1.36	2.115	634.837	910.217
5.4	301657	1.6	6.075	2145.692	2145.6921

VITA

Tyler Musante was born on January 30, 2001, and grew up in Danville, California. Ever since he was young, he had a great appreciation for nature and the environment, spending his free time backpacking, running, snowboarding, and exploring the outdoors in general. He brought this passion for the environment to his study of Environmental Science at Elon University and the School for Field Studies, and study of Water Resources Engineering here at the University of Tennessee. He looks to continue to follow his passion for environmental service in a career of Water Resources Engineering and/or Environmental Remediation and Stream Restoration.