Article

Measuring Streambank Erosion: a Comparison of Erosion Pins, Total Station, and Terrestrial Laser Scanner

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Abstract: Streambank erosion is difficult to quantify; models and field methods are needed to assess this important sediment source to streams. Our objectives were to 1) compare three techniques for quantifying streambank erosion: erosion pins, total station, and laser scanning; 2) spatially assess streambank erosion rates in the Indian Mill Creek watershed of Michigan, USA, and 3) relate results with modeling of nonpoint source pollution. Total station and laser scanner data were correlated, but neither erosion pins and total station nor erosion pins and laser scanner were correlated. The laser scanner collected high resolution data on clear, barren streambanks, but the erosion pin or total station techniques were more representative of complex vegetated banks. We estimate that streambank erosion contributes 28.5% of the creek’s total sediment load. These findings are important to address sources of watershed impairments related to sedimentation, as the applicability of each technique depends on streambank morphology.

Keywords: Streambank, erosion, lidar, stream, sediment, watershed

1. Introduction

Sediment pollution is a major concern for streams throughout the United States [1]. It causes widespread degradation of aquatic habitat and reduces suitability for fish and macroinvertebrate communities [1–3]. Sediment can enter a stream through many pathways, but the dominant pathway is often streambank erosion [4,5]. Streambank erosion is natural but can be accelerated by disturbances of changing watershed land use [1,2,6]. Successful management of sediment in a watershed requires an understanding of sources and entry pathways [7]. Understanding the dynamic nature of streambanks is important to shoreline landowners threatened by retreating banks, water quality managers, and geomorphologists [8]. It also is important for projects involving stream restoration and Total Maximum Daily Load development [9]. One difficulty with managing sediment pollution is that it is hard to quantify sediment loading from streambank erosion [4,10]. Various techniques could be used for this purpose including erosion pins, total station surveying, and terrestrial laser scanning, however a comparison study of all three methods is lacking. The scientific motivation for our study was that these three techniques had not been compared together over several streambanks in varying conditions; thus there were questions about the comparability of the techniques and their usefulness in different bank conditions.

1.1. Streambank Erosion Measurement Techniques

Erosion pins are narrow metal rods installed horizontally to measure the retreat of the streambanks over time [5]. They are commonly used in streambank erosion studies [5,11]. They are suitable for a wide range of fluvial environments, cheap, and simple to maintain with no special
A total station is an electronic surveying instrument that combines horizontal angle, vertical angle, and distance measurement to map a structure or terrain [9, 12]. Total station surveys can effectively show how the shape of a streambank changes over time from erosion or deposition [9, 12]. A total station can very accurately measure the location of a point on the streambank [9]. However, data can be coarse and lack point density needed to accurately model bank retreat and conditions [13]. Data collection with a total station can cause disturbance to the streambank [9]. Additionally, overhanging or undercut banks can make total station surveys difficult. There are no standard methods to account for the empty space below the overhang on topographic maps. Undercut banks have previously been ignored because of this difficulty, which causes error in the data [12]. This is important because urban streams experience a channel widening stage from increased storm flows and water velocities [2], which could cause more undercut banks.

A terrestrial laser scanner uses lidar technology to create high resolution scans of a surface showing three dimensional topography [9, 14]. Lidar works by combining laser-based distance measurements with precise orientation to model a three dimensional surface [15]. A main advantage of the laser scanner is that it can detect small erosion rates along a streambank, bluff, or gully with as high as one millimeter resolution [16–18]. This gives managers more of an ability to control sedimentation at a watershed scale by measuring small erosion rates spread over an extensive stream system [16]. Though the technique provides superior measurement precision, optical issues with water reflection [19] and obstruction by vegetation and crenulated surfaces [16] must be recognized. Terrestrial laser scanners have difficulties with measuring heavily vegetated streambanks [9, 20]. Data gaps can occur because of vegetation and other natural obstructions; interpolation could cause error so should only be used as a last resort [21]. Vegetation and other obstructions can be removed by special computer programs that classify the point cloud data from a terrestrial laser scanner into different classes. However, the complexity of natural surfaces and size of data files make vegetation classification difficult [21]. These large data files are difficult to process on desktop computer [16]. Heritage and Hetherington [20] recommend a field protocol for using a terrestrial laser scanner to study fluvial morphology. This includes positioning the scanner to minimize the shadowing of, placing targets for alignment in all three dimensions, and repeating scans from the same positions.

1.2. Prior Comparison Studies

Previous comparisons between techniques to measure streambank erosion have provided valuable insights into difference and error. Resop and Hesson [9] compared a total station and terrestrial laser scanner for measuring streambank erosion along an 11 meter streambank of Stroubles Creek, Virginia, USA with six readings over two years. The bank was bare, with little vegetation. Estimates of bank retreat rate were 0.15 m yr⁻¹ with the laser scanner and 0.18 m yr⁻¹ with the total station, thus a relative error of 20%. They found that the laser scanner was quicker to use and did not disturb the streambank like the total station. However, processing the laser scanner data was difficult because of the size and complexity of data files. By comparing data points between the two methods, they found a mean bank retreat difference of 0.018 m, standard deviation of 0.020 m, and that 63% of total station points were within 0.02 m of the laser scanner data. Estimates of volumes of soil erosion from streambanks between the two techniques had an average difference of 109%, with a range from 7% to 373%. The cause of these differences was likely because of the different resolutions of the total station and laser scanner. Aside from some instances where an undercut bank clearly affected total station data, Resop and Hesson did not find any systematic differences between the results of the total station and laser scanner on their bare bank.

Day et al. [22] compared a terrestrial laser scanner with analyses of georeferenced aerial photography for measuring erosion of bluffs in the Le Sueur watershed of Minnesota, USA. Eroding banks were digitized from aerial photographs for 243 bluffs, while laser scans were taken of 15
bluffs, and results were extrapolated to 480 bluffs. These bluffs were large enough to be identified using 3 m resolution elevation data and with a height up to 160 m. The study found an average erosion rate of 0.20 m yr\(^{-1}\) with the laser scanner and 0.14 m yr\(^{-1}\) from aerial photographs. It also found an average difference of 36% between sediment loading measurements from the two techniques. Eltner et al. [23] compared a terrestrial laser scanner with photogrammetry on an unmanned aerial vehicle (UAV) for measuring bank erosion in two European catchments. They found that the point clouds of the laser scan and UAV photogrammetry differed by an average 3.1 to 18.0 mm, depending on the camera and software used for photogrammetry. Although we did not interpret aerial photography or include photogrammetry data in our analysis, the findings of Day and Eltner are relevant because they demonstrate the comparability of laser scanning with traditional techniques. Ours is the first study to compare erosion pins, a total station, and a terrestrial laser scanner on the same banks.

1.3. Objectives

Our objectives were to 1) evaluate and compare three techniques for quantifying streambank erosion: erosion pins, total station surveyor, and laser scanning, 2) assess the spatial distribution of streambank erosion rates in the Indian Mill Creek watershed of Michigan, USA, and 3) estimate the annual rate of sediment loading in the watershed from streambank erosion and compare with modeled estimates. This research benefits watershed managers in addressing fish and macroinvertebrate community impairments in Indian Mill Creek and other watersheds that are degraded by excessive sediment. An ability to better quantify erosional bank loss is also important for owners of houses, farms, sewer lines, roads, and other infrastructure along streams who need to realize how much bank they’re losing to protect themselves from damages due to eroding banks.

2. Materials and Methods

2.1. Study Area

Indian Mill Creek in Kent County, Michigan, USA (HUC 040500060504) is a tributary to the Grand River and is 18.5 km long with a 44 km\(^2\) watershed. The creek resides in the Southern Michigan Northern Indiana Till Plains ecoregion, characterized by irregular plains, cropland, pasture, and oak/hickory/beech/maple forests [24]. The watershed land cover is predominately urban (43%) and agricultural (39%), with commercial and residential development in the lower watershed, natural and urban lands in the middle watershed, and farmland and orchards in the upper watershed [25]. This land cover pattern affects the distribution of erosion risk in the watershed. The National Weather Service classifies the area as a humid continental climate with distinct summers and winters and fairly even distribution of precipitation throughout the year (www.weather.gov). A total of 28.5 km of streams were identified in the watershed using a Geographic Information System (GIS).

2.2. Site Design

Nine sites were chosen for this study (Figure 1). Four sites were in the lower urbanized parts of Indian Mill Creek, three sites were in the upper farmlands, and two sites were on tributaries. Within each property, an 18 meter section of stream was chosen, based on a balance between an open channel for laser scanning and being representative of the reach, and then split into the left and right banks while looking in a downstream direction. Erosion pins were installed at all eighteen banks (minimum = 4 pins, average = 7.3 pins, maximum = 20 pins per bank), total station surveys were performed at sixteen, and laser scanning was performed at ten. The reason that laser scans were performed at fewer banks is that we were limited by time and financial resources to scan ten banks, while we had greater liberty with erosion pins and the total station coverage. The presence/absence of undercut banks and heavy vegetation at each bank also was noted.
2.3. Erosion Pins

A total of 137 erosion pins were installed at the eighteen banks following the design of prior studies [5,11,26]. Prior to installing erosion pins, the 18 meter stream section was divided into three six-meter subsections using a measuring tape. Erosion pins were carefully installed in the middle of each subsection on both banks. One to three pins were installed at each location evenly spaced up the bank, with one pin for approximately every meter of bank height. Extra pins were installed if there were visible changes not captured by the design, such as the vertical transition between an undercut bank and vegetated slope.

Erosion pins were measured from tip of the pin to streambank using a measuring tape to the nearest 0.5 cm. The average of measurements from the top and bottom of the pin was used to account for bank slope. Where there was a horizontal angle to the bank, the left and right sides of the pin were also included in the average. Erosion pins were measured monthly from May to September 2017, with two additional measurements following rain storms, then April to May 2018. The spread of erosion pin data at each site was analyzed using R3.3.2 [27]. The volume of soil loss was estimated following methods of Palmer [28] and Zaimes et al. [29]. Change in bank volume per meter of stream length was calculated for each bank at each site by multiplying the average erosion pin value by the bank height from total station data. Overall change in bank volume was estimated by multiplying this rate by the 18 meter site length.

2.4. Total Station

The first step of the total station surveys was to set four control points at each site using a Trimble Geo7x Global Positioning System (GPS) with Zephyr external antenna. These control points tie into the NAD 1983 UTM Zone 16N projected coordinate system and orient the total station. Control points were two foot rebar stakes driven into the ground and marked with orange tape or a...
TerraSync 5.86 software was used to collect data. All GPS data were post-processed in Pathfinder Office using data from the Grand Rapids Continuously Operating Reference Station.

A Topcon GPT-3107W total station theodolite on tripod with SurveyPro software was used to survey streambank shape. The instrument was set on one of the control points and backsighted to the farthest point for the most accurate orientation. When the instrument needed to be moved, a temporary control point was created by pushing a marker into the ground, and the previous point was checkpointed to determine error during movement. A reflector prism was used on top of a staff with bubble level to collect points. For undercut banks, the horizontal distance between the prism staff and the back of the undercut was noted. However, data for undercut banks were not incorporated into erosion estimates because virtual models could not account for overhanging bank shape.

The site design for the total station surveys was based on methods of Keim et al. [12] and Resop and Hession [9]. Seven transects were performed along each bank over the 18 meter site, at the 0, 3, 6, 9, 12, 15, and 18 meter marks. The 3, 9, and 15 meter marks coincided with erosion pin locations. In each transect, sideshots for the top of the bank and toe were collected. Then, two to three shots were taken evenly spaced along the bank, depending on its size and variability. These shots were taken at erosion pins during the 3, 9, and 15 meter transects; at the location where the pin met the streambank.

Total station data were exported as a CSV file with Windows Mobile Device Center 6.1 and imported into ArcMap software. Then, xy data were displayed and exported as a shapefile. A separate file was created for each streambank using the Select tool of ArcToolbox. A 3D TIN file was created using Create TIN with Delaunay Triangulation. The TINs were cropped using the Delineate TIN Data Area Tool of 3D Analyst to remove superfluous data. The volume of soil gain or loss between 2017 and 2018 TIN streambank models was then calculated using the Surface Difference Tool of 3D Analyst. The volume was divided by site length to estimate change in volume per meter of stream per year.

2.5. Terrestrial Laser Scanner

One to two banks were surveyed at each site with a FARO Focus3D terrestrial laser scanner in 2017 and a Trimble TX8 scanner in 2018. Ten total banks were chosen to incorporate representative conditions and have clear visibility. Three survey markers were placed along each bank, as far apart as possible without sacrificing visibility. Target spheres were placed on these markers. These markers act as control points, and were surveyed with the total station so laser scan results can be projected in a Geographic Information System (GIS). To ensure all three spheres were visible to the scanner, brush was pushed aside, cut with a knife or machete, held back, or sat on.

Next, a preliminary low-quality scan was taken to adjust the horizontal and vertical scan limits. Prior to the full scan, the resolution and quality were set. We used 1:1 resolution and 2x quality and color image for the FARO scans, and Level 3 quality for the Trimble scans. These levels were chosen because they were successfully used by the Annis Water Resources Institute previously (Kurt Thompson, personal communication) or recommended for the purposes of our study (Mark Tenhove, personal communication) as a balance between high quality data and manageable file size. Laser scans from both instruments were processed using CloudCompare software, although Trimble scans first had to be exported to a compatible .LAZ format using Trimble RealWorks 10.4.3. The FLS plugin was used to import FARO files to CloudCompare. Excess data was cut out and scans were aligned by target spheres. At the IMC7 and IMC1 sites, target markers disappeared so the alignment incorporated sturdy points on wood or metal structures, and manual alignment was needed for IMC7. The CANUPO plugin [21] and veget_LongRange.prm filter [30] with 0.1 m filtering resolution were then used to filter vegetation from the scans. This gave the most accurate classification of filters and filtering resolutions we experimented with and was within processing capabilities of our computer. Other filters we experimented with were otiRa_vegetsuper.prm and otiRa_vegetsemi.prm [21], as well as vegetRangiCliff.prm and vegetTidal.prm [30]. After processing, the 2017 scans had a
median of 2,696,052 data points representing streambank, while the 2018 scans had a median of 1,302,523 data points representing streambank.

Volume change of streambanks between 2017 and 2018 was calculated in Trimble RealWorks using the Volume Calculation tool with horizontal difference and 10 cm resolution. The percent of laser scan coverage from these volume outputs was calculated by dividing the scan area occupied by bank in both 2017 and 2018, facing the bank directly and horizontally from the stream, by the total gridded area of the file. The difference in laser scan coverage between banks with and without heavy vegetation was analyzed using a Shapiro-Wilk test to confirm normal distribution (p=0.110 without vegetation, p=0.547 with vegetation), followed by a t-test in R 3.3.2.

2.6. Statistical Comparisons and Visualization

Statistical tests were performed in R 3.3.2 using data from the ten banks that had laser scans. The IMC6 right bank was removed because it was deemed an outlier for the laser scan tests, being 4.3 times higher than the second highest measurement, and affecting the normality. Shapiro-Wilk Tests were used on the erosion pin, total station, and laser scanner volume change estimates to determine normality. Data from all three techniques were found to be normally distributed (p = 0.977, 0.964, and 0.746). Differences between techniques were tested using ANOVA with randomized complete block design, with estimates of erosion rate as values, techniques as groups, and sites as blocks. Plots of normal Q-Q and residuals vs. fitted values were interpreted and suggested that the ANOVA was appropriate to use over data transformations or nonparametric alternatives. A similar ANOVA test was used by Purvis and Fox [31] to analyze the influence of riparian buffers and time period on erosion rates. Correlations between techniques were tested using Pearson Tests with Holm p-value adjustments for multiple comparisons. Percent differences between volume results of the laser scanner and total station techniques were calculated following the methods of Resop and Hession [9], who took the difference between laser scan and total station results, divided by the laser scan result. We calculated the percent difference for laser scan and erosion pin results, and for erosion pin and total station results, in the same fashion. The IMC4 (L) bank was removed from the percent difference analysis because it was an outlier with high total station error and less than 1% laser scan coverage after vegetation filtering.

2.7. Basinwide Estimates

Basinwide estimates of sediment loading from bank erosion were calculated separately from erosion pin, total station, and laser scanner data. These were calculated by multiplying the bank erosion rate per meter of stream length (m³ m⁻¹ yr⁻¹) by the entire length of streams in the watershed (28,500 m) by an average soil bulk density of eroding streambanks 1,500 kg (m³⁻¹) [32]. We used erosion pin data to compare basinwide estimates with other studies because the erosion pins had more sites and no limitations in coverage due to vegetation or other obstacles.

3. Results

3.1. Site Conditions, Erosion, and Deposition

Our study documented streambank conditions, volumetric changes using three erosion measurement techniques, and coverage of the laser scan data (Table 1). Negative bank volume change represents net erosion over the study period, while positive change represents net deposition. NA’s exist in total station and laser scanner data where a bank was not surveyed for logistical reasons. There was no discernible relationship between undercut banks and total station results biased toward deposition, possibly because the bias from undercut banks was relatively small compared to the spread of the data.
### Table 1. Site Conditions, volumetric results, and laser scan coverage for study streambank in the Indian Mill Creek watershed.

<table>
<thead>
<tr>
<th>Site (Bank)</th>
<th>Undercut Banks</th>
<th>Heavy Vegetation</th>
<th>Erosion Pins</th>
<th>Total Station</th>
<th>Laser Scanner</th>
<th>Laser Coverage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMC7 (L)</td>
<td>No</td>
<td>No</td>
<td>0.081</td>
<td>0.264</td>
<td>0.015</td>
<td>21.4%</td>
</tr>
<tr>
<td>IMC7 (R)</td>
<td>No</td>
<td>No</td>
<td>0.027</td>
<td>0.081</td>
<td>0.022</td>
<td>29.8%</td>
</tr>
<tr>
<td>IMC6 (L)</td>
<td>Yes</td>
<td>No</td>
<td>-0.004</td>
<td>-0.065</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>IMC6 (R)</td>
<td>Yes</td>
<td>No</td>
<td>-0.082</td>
<td>-0.111</td>
<td>0.155</td>
<td>60.1%</td>
</tr>
<tr>
<td>IMC5 (L)</td>
<td>Yes</td>
<td>No</td>
<td>-0.105</td>
<td>-0.078</td>
<td>0.004</td>
<td>24.4%</td>
</tr>
<tr>
<td>IMC5 (R)</td>
<td>Yes</td>
<td>No</td>
<td>-0.065</td>
<td>0.098</td>
<td>0.008</td>
<td>38.6%</td>
</tr>
<tr>
<td>IMC4 (L)</td>
<td>Yes</td>
<td>Yes</td>
<td>-0.034</td>
<td>0.047</td>
<td>-0.001</td>
<td>0.5%</td>
</tr>
<tr>
<td>IMC4 (R)</td>
<td>No</td>
<td>No</td>
<td>0.078</td>
<td>0.424</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>IMC3 (L)</td>
<td>No</td>
<td>No</td>
<td>-0.070</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>IMC3 (R)</td>
<td>No</td>
<td>No</td>
<td>-0.048</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>IMC2 (L)</td>
<td>No</td>
<td>Yes</td>
<td>-0.003</td>
<td>-0.018</td>
<td>0.001</td>
<td>5.6%</td>
</tr>
<tr>
<td>IMC2 (R)</td>
<td>Yes</td>
<td>No</td>
<td>-0.066</td>
<td>-0.111</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>IMC1 (L)</td>
<td>Yes</td>
<td>Yes</td>
<td>-0.034</td>
<td>-0.055</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>IMC1 (R)</td>
<td>Yes</td>
<td>Yes</td>
<td>-0.052</td>
<td>-0.273</td>
<td>-0.036</td>
<td>11.9%</td>
</tr>
<tr>
<td>WD (L)</td>
<td>No</td>
<td>Yes</td>
<td>0.003</td>
<td>0.046</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>WD (R)</td>
<td>Yes</td>
<td>Yes</td>
<td>-0.024</td>
<td>-0.186</td>
<td>-0.008</td>
<td>29.0%</td>
</tr>
<tr>
<td>BC (L)</td>
<td>No</td>
<td>No</td>
<td>-0.016</td>
<td>0.100</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>BC (R)</td>
<td>Yes</td>
<td>No</td>
<td>-0.011</td>
<td>0.383</td>
<td>0.033</td>
<td>20.5%</td>
</tr>
</tbody>
</table>

#### 3.2. Statistical Comparisons between Techniques

The ANOVA showed that there were no detectable differences between streambank erosion measurement techniques (df=2/23, F=0.457, p=0.639). Correlation tests found no significant correlations between erosion pin and total station data ($R^2=0.26$, $p=0.330$) or erosion pin and laser scanner data ($R^2=0.16$, $p=0.330$; Figure 2). However, there was a significant correlation between total station and laser scan data ($R^2=0.79$, $p=0.003$).

![Figure 2](image_url). Correlations of bank volume change rate estimates between [A] erosion pins and total station ($R^2=0.26$, $p=0.330$), [B] erosion pins and laser scanner ($R^2=0.16$, $p=0.330$), and [C] total station and laser scanner ($R^2=0.79$, $p=0.003$) for nine sites in the Indian Mill Creek watershed. Solid line indicates significant correlation.
3.3. Vegetation Filtering

The terrestrial laser scanner performed well on barren streambanks with clear line of sight. It collected high resolution, quality data for these banks. However, for vegetated and obscured streambanks, the laser scanner had large data gaps. Banks with heavy vegetation had significantly lower average laser scan coverage after vegetation filtering (11.75%) than other banks (32.5%, p = 0.047). These banks were most common in agricultural headwaters, which had substantial herbaceous plant growth, even in the spring when we surveyed. Laser scanner data could be underestimating change in bank volume because erosion of banks behind vegetation, roots, and other obstructions was not accounted for. This is especially true at the IMC4 (L) bank (Figure 3 g), where only 0.5% of the bank had coverage. This site was characterized by large masses of roots and overhanging vegetation that obscured the bank and were removed by the vegetation filter. The low rate of volume change for this bank from laser scanner data could be an effect of the low coverage because it is unclear what change in bank shape is occurring under the vegetation. The ability for the laser scanner to produce high coverage along vegetated streambanks is a significant limitation of the technique. As far as we know, there is no standard for when coverage becomes too small to reliably use laser scan data. The site with the highest percent laser coverage, IMC6 (R), was a steep bank under forest canopy that was mostly clear of small vegetation growth and other obstructions. The IMC7 (R) bank was assigned a classification of no heavy vegetation because open banks were observed; however, shrubs and exposed roots could be responsible for low laser scan coverage. NA's exist where a bank was not surveyed for logistical reasons.

Figure 3. Photos of the 18 study streambanks in the Indian Mill Creek watershed, labeled by figure letter, site and left (L) or right (R) bank. Photos (a) through (h) are in the lower watershed through urban and forested land cover, (i) through (n) are in the upper watershed through farmland, and (o) through (r) are on tributaries.
3.4. Comparative Analyses of Techniques and Sites

Study streambanks experienced net deposition (positive volume change), net erosion (negative), little change in bank volume (points near zero), or a mixture depending on the technique (Figure 4). Sites are labeled with name and left (L) or right (R) bank and are ordered from lowest reach (IMC7) to headwaters (IMC1), followed by the two tributary sites. The presence of heavy vegetation (HV) or undercut banks (UB’s) is noted under the site name to visualize the effects of these conditions on estimates of bank volume change. The following analysis of the chart is split into lower watershed, upper watershed, and tributary sites. Percent differences between techniques were substantial, with an average difference of 650% between erosion pins and total station data, 596% between the laser scanner and erosion pins, and 1,275% between the laser scanner and total station (Table 2). Bank photos are presented for reference in Figure 3.

Figure 4. Comparison of results from techniques used to measure streambank erosion in the Indian Mill Creek watershed 2017-2018. Positive values indicate net deposition while negative values indicate net erosion being measured. Presence of heavy vegetation (HV) or undercut banks (UB’s) is noted under site names.
Table 2. Percent difference in volume results for techniques to measure streambank change in the Indian Mill Creek watershed, calculated only for sites that had all three techniques used, following methods in Resop and Hession [9]. Reference Table 1 for absolute values.

<table>
<thead>
<tr>
<th>Site (Bank)</th>
<th>Erosion Pins and Total Station</th>
<th>Laser Scanner and Erosion Pins</th>
<th>Laser Scanner and Total Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMC7 (L)</td>
<td>226%</td>
<td>449%</td>
<td>1,692%</td>
</tr>
<tr>
<td>IMC7 (R)</td>
<td>205%</td>
<td>22%</td>
<td>271%</td>
</tr>
<tr>
<td>IMC6 (R)</td>
<td>35%</td>
<td>153%</td>
<td>171%</td>
</tr>
<tr>
<td>IMC5 (L)</td>
<td>26%</td>
<td>3,003%</td>
<td>2,260%</td>
</tr>
<tr>
<td>IMC5 (R)</td>
<td>251%</td>
<td>904%</td>
<td>1,111%</td>
</tr>
<tr>
<td>IMC4 (L)</td>
<td>238%</td>
<td>2,511%</td>
<td>3,715%</td>
</tr>
<tr>
<td>IMC2 (L)</td>
<td>448%</td>
<td>466%</td>
<td>2,106%</td>
</tr>
<tr>
<td>IMC1 (R)</td>
<td>430%</td>
<td>43%</td>
<td>661%</td>
</tr>
<tr>
<td>WD (R)</td>
<td>668%</td>
<td>191%</td>
<td>2,136%</td>
</tr>
<tr>
<td>BC (R)</td>
<td>3,559%</td>
<td>134%</td>
<td>1,070%</td>
</tr>
</tbody>
</table>

3.5. Lower Watershed Sites (IMC7, IMC6, IMC5, and IMC4)

Sites in the lower watershed experienced either a positive volume change (deposition) or negative (erosion) depending on the bank and technique. Erosion pins, total station, and laser scanner all documented deposition of sediment at both IMC7 banks (Figure 3a and b), although there was considerable percent difference between rates. Erosion pin and total station results were similar for the IMC6 (L) site, showing only slight bank erosion. At the IMC6 (R) site, the laser scanner measured high deposition of sediment on the bank, while the total station and erosion pins both measured substantial erosion. The high laser scanner measurement at this site caused the percent differences to still be under 200%, as it is in the denominator of the calculation. The difference in measurements here could be because erosional areas were shadowed by leafy shrubs.

At both IMC5 banks, the laser scanner documented very little change in bank volume, even though there was substantial undercutting and slumping along both banks (Figure 3 e and f), documented by erosion pins. The total station estimate was fairly consistent with erosion pin data (26% difference). However, for the IMC5 (R) bank, there was a 251% difference. A likely reason for the disparity is that the entire right bank was undercut and the lip had been pushed up; erosion pins were still able to collect data in the undercut, but the total station with was only able to collect data on the top of the bank.

At the IMC4 (L) bank, erosion pins estimated slight erosion, while the total station estimated slight deposition. This difference could once again be the undercuts that extend the entire length (Figure 3 g). Low laser scan coverage from roots and vegetation (0.5%) likely explains the low estimate of bank change from the laser scanner. The IMC4 (R) bank had a disparity where the total station measured heavy sediment deposition, but the erosion pins only measured slight deposition. This could be because erosion pins are limited in their ability to measure localized sediment deposition (Figure 3 h).

3.6. Upper Watershed Sites (IMC3, IMC2, and IMC1)

Agricultural sites in the upper watershed primarily experienced bank erosion. The IMC3 site had substantial bank erosion measured by erosion pins along both banks (Figure 3 i and j). At this site, a constricting culvert under a driveway, large willow fallen across the creek, and runoff from upstream farmland could be altering the local hydrology to scour the banks. At the IMC2 site, the left bank had consistent measurements of bank change, showing slight erosion, although it is likely that the low estimates inflated the percent difference between techniques. This low erosion rate made sense because the site has a vegetated riparian buffer of approximately ten meters to protect...
the banks. Erosion pin and total station estimates for the IMC2 (R) bank both showed erosion. This bank was along a lawn with no riparian buffer and was visibly eroding (Figure 3 l).

The IMC1 site also had visible erosion that was documented by all three techniques at the right bank, and both techniques used at the left. The total station estimated a much higher erosion rate at the right bank than the laser scan and erosion pins (difference of 661% and 430%), which could be because of the resolution and coverage of the data. This bank was heavily vegetated and had laser scan coverage. Differences could also be due to the shape of the bank, which was complex with many bends, slumps, and large barren areas (Figure 3 m and n). Differences could also be caused by a high checkpoint error of the total station, possibly due to unstable soil conditions for the tripod.

3.7. Tributary Sites (WD and BC)

Small tributaries had a mixture of erosion and deposition. The WD site was along a meander, which explains why the left bank inside the bend had measured deposition, while the right bank on the outside of the bend had measured erosion (Figure 3 o and p). The total station could have estimated more erosion for the WD (R) bank than the pins and laser scans (differences of 668% and 2,136%) because the laser scans had data gaps due to shrubs and herbaceous vegetation, and because the erosion pins had coarser data that could miss eroding areas. The BC site banks had erosion from the pin data, but substantial deposition by total station data. The laser scanner data on the right bank showed small deposition. We observed deposition of sediment on the bed of Brandywine Creek and the toe of the banks at the BC site, as well as evidence of powerful flows during storms that pushed down grass in the creek’s floodplain. Undercut banks could also explain why the total station estimated more deposition (Figure 3 q).

3.8. Estimates of Error

Total station end checkpoint error data show that measurements can vary by millimeters or centimeters (Table 3), with an average error of 5.5 cm (standard deviation 11.7 cm). The high 2018 checkpoint elevation error introduces uncertainty into the total station results for the IMC4 site. We presume that this error occurred because the tripod was set in soft muddy soil, causing the instrument to tilt during the survey. It could also have been a recording error because both the northing and easting error were small. Laser scanner alignment had an average of 0.7 cm error (standard deviation = 0.4 cm).

<table>
<thead>
<tr>
<th>Site</th>
<th>Checkpoint Error 2017 (m)</th>
<th>Checkpoint Error 2018 (m)</th>
<th>Target Alignment Error (m)</th>
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</thead>
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<td>IMC7</td>
<td>Northing 0.008</td>
<td>Easting 0.006</td>
<td>Elevation 0.064</td>
</tr>
<tr>
<td>IMC6</td>
<td>Northing 0.004</td>
<td>Easting 0.001</td>
<td>Elevation -0.004</td>
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<tr>
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<td>No data</td>
<td>No data</td>
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<tr>
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<td>Easting 0.021</td>
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<tr>
<td>BC</td>
<td>No data</td>
<td>No data</td>
<td>No data</td>
</tr>
</tbody>
</table>

3.9. Basinwide Estimates

Overall, an average bank volume change rate of -0.024 m$^3$ m$^{-1}$ yr$^{-1}$ (standard deviation 0.049) was estimated from erosion pin data (Table 1). Both the total station and the laser scanner showed
more deposition of sediment on streambanks, with an average bank volume change of 0.034 and 0.019 m³ yr⁻¹, and standard deviation of 0.187 and 0.049. The high standard deviation and bank change rate from total station data is due in part to the right bank of the IMC4 site (Figure 3 h). This bank is the inside of a meander bend with heavy deposition of sediment visible. This deposition was also documented with erosion pin data. It is possible that deposition of sediment on most banks from laser scanner data was due vegetation and other obstructions shadowing eroding areas.

Assuming the average erosion rate of our eighteen study banks from erosion pin data (0.024 m³ m⁻¹ yr⁻¹) represents the average bank erosion rate for the 28.5 km of streams of the Indian Mill Creek watershed, we estimate from erosion pin data that bank erosion contributes 1,346.5 cubic meters of sediment per year to Indian Mill Creek. Multiplying by an average soil bulk density of eroded sediment of 1,500 kg (m³⁻¹) [32], we estimate that streambank erosion contributes an annual load of 2,020 Mg of sediment per year to Indian Mill Creek.

4. Discussion

4.1. Comparison of Techniques

We evaluated and compared three techniques for measuring streambank erosion: erosion pins, total station, and terrestrial laser scanner. We were unable to detect significant differences between measurement techniques and found a significant correlation only between total station and laser scanner data. Percent differences between techniques were large. Thus, when designing a streambank erosion study, results between different techniques could have limited comparability, and thoughtful selection of a technique is very important depending on riparian conditions.

Our results show that selection of a streambank erosion measuring technique should be dependent on the goals of the project, resources available, desired resolution of data, and site conditions. Terrestrial laser scanning has high resolution and can detect small erosion rates with sub-centimeter error, especially on open streambanks with little vegetation. The scanner itself is easy to use, requiring little effort for a high resolution scan. However, the cost of the laser scanner would make it unusable for many watershed studies. Additionally, training with special point cloud processing software, and ideally Geographic Information Systems, is necessary to process the laser scanner data. This software often requires computers that are more powerful than the typical home desktop. The terrestrial laser scanner performed well on clear barren streambanks, such as the right bank of IMC6. However, there were large data gaps and limited coverage when vegetation or other obstructions obscured the bank. This introduces uncertainty into the estimates of bank erosion because it is unclear how the bank is changing behind the vegetation. We recommend using the laser scanner only for bare banks with limited vegetation cover. If vegetated banks must be scanned, we recommend scanning them in early spring directly after snowmelt before vegetation has become established. We do not recommend physically removing vegetation from the banks because this could affect bank stability.

The total station or erosion pins are preferable techniques for vegetated banks. The pointed staff and reflector of the total station allowed us to collect data for points obstructed by vegetation. Similarly, erosion pins can be installed and measured on vegetated banks without loss of data. In general, erosion pins are the cheapest and easiest technique to measure streambank erosion. They can be installed and monitored for $1-2 per pin and do not require expensive equipment or familiarity of special software. However, they provide very low spatial resolution; our transects were spaced three meters apart with approximately one pin per meter bank height. We also observed that there can be minor destabilization of the bank while installing and checking the pins. The total station works effectively for barren or vegetated streambanks. However, it requires skill with surveying, familiarity with the instrument and special software, and may not always be available to researchers. Additionally, minor bank destabilization can occur when using the staff and prism to collect data.

The total station does not work for undercut banks using the methods we performed, ignoring the space under the overhang in its entirety. Undercut banks were documented at the IMC6, IMC5,
IMC4, IMC2, IMC1, WD, and BC sites. Although it is unclear how strongly they affected erosion estimates, these undercuts shifted total station data at these sites toward deposition because the undercutting erosion was ignored in the TIN model. Total station results also had a larger spread of data than the other techniques. While results from the laser scanner and erosion pins tended to show change less than 0.1 m$^3$ m$^{-1}$ yr$^{-1}$, the total station results were more variable, estimating changes in bank volume up to 0.2 to 0.4 m$^3$ m$^{-1}$ yr$^{-1}$ (Table 1, Figure 4). The BC site right bank, IMC7 left bank, and IMC4 right bank all had high deposition documented with a total station that was not consistent with laser scanner or erosion pin results. The lack of erosion measurements from undercut banks could contribute to these high deposition estimates. On the other hand, the IMC1 right bank and WD right bank had relatively high erosion rates from total station data. An explanation for these rates could be from heavily eroding banks that were measured with the total station, but could have been between erosion pin transects or hidden from the laser scanner behind vegetation. Resop and Hession [9] noted that measurement of bank erosion can involve large errors and uncertainty. They did not find any systematic differences between results of total station surveys and laser scans, aside from some instances where the total station could not collect data beneath an undercut bank. Our study supports this, as the ANOVA was unable to detect significant differences between the laser scanner, total station, and erosion pins. Resop and Hession found that volumes of soil erosion from their study streambank estimated by the total station and laser scanner had an average difference of 109%, with a range from 7% to 373%. That is much smaller than what we experienced between the laser scanner and total station, which had an average difference of 1,275% with a range from 171% to 2,260%. Vegetation and other complexities along our banks are likely responsible for this greater range of differences; the bank that Resop and Hession studied was bare, with little vegetation.

4.2. Spatial Distribution of Bank Erosion

We assessed the spatial distribution of streambank erosion in the Indian Mill Creek watershed. The lower watershed experienced net deposition of sediment along the banks (Figure 5), as noted by researchers who observed heavy sand deposition on the IMC7 banks. The IMC4 site in the middle watershed experienced erosion on the left bank but deposition on the right. This is likely because the site was along a meander bend, with the outside on the left and inside on right. The WD site, also along a meander, experienced erosion on the right bank but deposition on the left. All other sites experienced net bank erosion and contributed to sediment loading in the Indian Mill Creek watershed. The highest rates of bank erosion from erosion pin data were at the IMC6 and IMC5 sites, which are along a high gradient reach of the creek as it descends the Grand River valley.
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Figure 5. Spatial distribution of erosion (red) and deposition (yellow) rates for study streambanks using erosion pin results.

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4.3. Estimation of Sediment Loading

We estimated the total load of sediment entering Indian Mill Creek from streambank erosion and compared it to results from a concurrent study of field and streambank erosion rates. This concurrent study used the Enhanced Generalized Watershed Loading Functions (GWLF-E) model [32] for the time period 1997-2010. The model predicted that average annual sediment loading from streambank erosion in the watershed during that time period was 1,031.3 Mg yr⁻¹, while annual sediment loading from field erosion was 5,077.9 Mg yr⁻¹. Our estimate of the contribution of sediment loading to Indian Mill Creek from the erosion pin data was 2,020 Mg yr⁻¹. This is roughly double the streambank erosion predictions of the GWLF-E model. The difference between our estimate and modeled predictions could be because the GWLF-E model was validated by watersheds in Pennsylvania that could have different conditions than Indian Mill Creek. Stream discharge data collected with a flow meter suggest that GWLF-E, although not calibrated to Indian Mill Creek, follows the same pattern of increasing discharge toward its outlet, but may be overestimating discharge in subbasins by a factor of 2.8 to 11.0. The difference could also be that our eighteen study banks sample only a small proportion of the overall length of bank in Indian Mill Creek. We decided not to use estimates of sediment loading from the total station and laser scanner because they incorporated fewer sites than erosion pins and had more uncertainties due to undercut banks, issues of the tripod on squishy soil, and bank coverage. Both these techniques estimated an average bank volume change in the watershed that was positive, suggesting that more sediment was deposited on streambanks than was removed by streambank erosion, which seems unlikely and could be an effect of the uncertainties and limitations of the techniques. Our best estimate of sediment loading from bank erosion in relation to the GWLF-E field erosion estimate suggests that streambank erosion contributes 28.5% of the annual total sediment load to Indian Mill Creek. This is...
a substantial portion of the sediment load and is almost certainly affecting the quality of aquatic habitat, fish, and macroinvertebrate communities in the Indian Mill Creek watershed.

Previous studies have demonstrated that streambank erosion can be a large source of sediment loading in a watershed [33]. Kiesel et al. [5] estimated for a lowland catchment in Germany that 71% of the sediment load was from streambank erosion. The catchment was relatively flat but had a large amount of agriculture along the creek. Kiesel found this estimate to be plausible because it was similar to estimates for other European catchments. Evans et al. [32] modeled the contribution of streambank erosion to 28 Pennsylvania watersheds using the GWLF-E model and estimated that eroding banks contribute between 4.8% and 78.6% of the total sediment loads to those watersheds, with an average of 17.9%. Fox et al. [4] reviewed fourteen studies and found that bank erosion contributions range from 7% to 92% of the suspended sediment load in the study watersheds. Beck et al. [34] estimated that bank erosion contributes 4% to 44% of annual suspended sediment load in an Iowa, USA watershed. Our estimate that 28.5% of the total sediment load in Indian Mill Creek comes from eroding banks is reasonable compared with these studies.

5. Conclusions

Sediment pollution is a major concern for streams throughout the United States. One difficulty in managing sediment pollution in streams is that it is difficult to quantify sediment from streambank erosion. We evaluated three techniques for measuring streambank erosion at nine sites in the Indian Mill Creek watershed: erosion pins, total station surveyor, and terrestrial laser scanner. We were unable to detect significant differences between measurement techniques, and found a significant correlation only between total station and laser scanner data. Percent differences between techniques were large. Each technique had advantages and disadvantages for measuring eroding streambanks, suggesting their application is highly dependent on watershed and site specific conditions. Erosion pins and total station surveying can be used in vegetated banks but have coarse resolution, while laser scanning has high resolution but cannot measure through dense streambank vegetation even employing the vegetation filter. Ultimately, the choice of technique depends on the goals of the project, bank conditions, desired resolution, and the resources available. We also assessed how streambank erosion rates varied spatially throughout the watershed, with the most deposition occurring in the lower reaches of Indian Mill Creek, and the most erosion in middle to upper reaches. Overall, we estimate that streambank erosion contributed 2,020 Mg of sediment each year to Indian Mill Creek, which is 28.5% of modelled sediment loads. This estimate shows that bank erosion is a substantial portion of the total sediment load and is almost certainly affecting the quality of aquatic habitat, fish, and macroinvertebrate communities in the Indian Mill Creek watershed.

Supplementary Materials: The erosion pin, total station, and terrestrial laser scanner data used in this study is published through Mendeley Data at http://dx.doi.org/10.17632/th48ctg5ww.1 under a Creative Commons Attribution 4.0 International license.

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