Terrestrial Laser Scanning for Monitoring Streambank Retreat: Comparison with Traditional Surveying Techniques

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Abstract: Data concerning streambank retreat (SBR) rates are important for many different engineering applications such as stream restoration and total maximum daily load (TMDL) development. However, measurement of SBR can be time-consuming and is often characterized by large measurement and interpolation errors. These errors propagate into the calculation of sediment budgets for the development of TMDLs, creating uncertainty in source partitioning and overall load estimates. We compared two techniques for measuring SBR: (1) traditional surveying with a total station and (2) terrestrial laser scanning (TLS). An 11-m streambank on Stroubles Creek in Blacksburg, Virgina was surveyed six times over a 2-year period. The average SBR along the entire bank was estimated to be −0.15 m/year with TLS and −0.18 m/year with total station surveying. The resulting differences in median SBR estimates along five distinct cross sections between each of the survey dates ranged from −0.11 to +0.06 m. This error in SBR due to total station surveying would be significant when extrapolating to a reach- or watershed-scale estimate of sediment load due to SBR. In addition, TLS collects data across the entire streambank surface, rather than just at distinct cross sections, providing much more information concerning SBR volumes and spatial variability.

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Introduction

Stream morphology is measured for many hydraulic applications such as flood routing, habitat modeling, and sediment load estimation, as well as larger engineering projects such as stream restoration and total maximum daily load (TMDL) development. These projects have significant economic impacts, with approximately $1 billion spent annually on stream restoration (Bernhardt et al. 2005) and $16 billion spent on sediment damages (Osterkamp et al. 1998). Fluvial applications rely on effective surveying of stream morphology for engineers to produce cross section profiles or three-dimensional (3D) topographic models. Traditionally, the measurement of topography is performed by manual point surveying with laser levels or electronic total stations. However, these methods are limited by time-intensive field surveys, spatial resolution restrictions, and difficulties in surveying complex morphology such as undercut banks.

We applied ground-based lidar, also known as terrestrial laser scanning (TLS), to measure streambank retreat (SBR). SBR is a process affected by many different factors, including subaerial processes (climate-related events), fluvial entrainment (direct transport of soil material by streamflow), and mass failure (caused by bank instability) (Lawler 1992). Traditional methods for measuring this phenomenon, such as erosion pins and total station surveying, have limitations in point resolution and can be affected by sensor error and operator bias (Lawler 1993). In addition, both erosion pins and total station surveying can result in direct physical disturbance of the streambanks being measured (Pyle et al. 1997). Aerial photography has also been used for measuring SBR (Winterbottom and Gilvear 2000; Rhoades et al. 2009), but is limited by photogrammetric errors and assumptions such as vertical banks.

Along with measurement error, interpolation and generalization influence how SBR data and erosion rates are represented. It is common for many applications to use point measurements for calculating an average SBR rate (Knighton 1973; Davis and Gregory 1994), which loses information pertaining to the spatial variability of SBR. Studies have calculated SBR using the difference in repeated stream cross-sectional surveys (Agouridis et al. 2005) and the change in 3D surface models created from point measurements (Brasington et al. 2003). The combination of measurement error, interpolation error, and spatial generalization can lead to a high amount of total error. Propagation of these errors can result in extensive output uncertainty in geomorphologic and hydraulic models. In most applications involving average SBR rates and sediment load estimation, the amounts of uncertainty and variability in estimates are not adequately quantified (Green et al. 1999; Laubel et al. 1999; Lawler et al. 1999).

The use of TLS for measuring stream morphology is still in its early stages of research. TLS for geomorphologic applications has ranged in scope from measuring individual rock breakdown (Bourke et al. 2008) to monitoring landslides (Bitelli et al. 2004; Hsiao et al. 2004; Teza et al. 2008). Most TLS research to date has involved calculating the difference in digital elevation models

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Fig. 1. Image of streambank showing locations of scan targets (T's) and cross sections (X's)

(DEMs) over time to detect change. There has been some research involving TLS for measuring erosion from streambanks and coastal cliffs at a relatively large scale (bank heights ranging from 14 to 65 m and resolutions ranging from 0.03 to 0.1 m) (Lim et al. 2005; Rosser et al. 2005; Collins and Sitar 2008). The potential, however, for using TLS for recording undercut banks and small-scale changes has been noted by Rosser et al. (2005). Heritage and Hetherington (2007) used TLS to scan a 150-m stream reach at 0.01-m resolution. When the data were compared to 257 independent survey points, they found a mean error of 0.004 m with a standard deviation of 0.17 m and 55% of the survey data within ± 0.02 m of the TLS data.

The objectives of this study were (1) to compare the measurements of traditional total station surveying and TLS for monitoring SBR in a small stream with little riparian vegetation and complex undercut banks, and (2) to make observations about the measurement and interpolation error of traditional surveying. TLS provides a means of estimating the error associated with measuring SBR with point measurements by using it as a reference data set.

Methods

Study Site

The study was conducted on a streambank along Stroubles Creek located downstream of Virginia Tech's main campus in Blacksburg, Va. Stroubles Creek has been identified as an impaired stream with both urban and agricultural impacts (Benham et al. 2003) and is currently undergoing a TMDL implementation plan for reducing sediment loads (Yagow et al. 2006). It is a gravel-bed stream with cohesive banks ranging in height from 1.0 to 1.3 m and an average baseflow depth of 0.2 m (Wynn et al. 2008). The stream reach has a watershed drainage area of approximately 17.1 km^2 and is located in a pasture with dairy cattle access. The bank face is bare with little vegetation and is undercut along much of its length (Fig. 1). Topographic measurements were taken along the 11-m streambank on six dates between May 2007 and May 2009. Two different surveying methods were used: surveying with an electronic total station and TLS. Both methods were used on the same day each time, first using TLS and then the total station.

Field Methods

Total station surveying was performed using a Leica TC 307. Five cross sections were measured over the length of the streambank (Fig. 1). Points were surveyed on both sides of the stream focusing on slope breaks. On average, five points were measured at each cross section on the target eroding streambank, or one point every 0.25-m change in elevation over the 1-m-tall streambank. Along each cross section, points were measured at the top of bank, the edge of water, and the location of existing erosion pins, which also acted to spatially align the repeated cross sections over time. The erosion pins were installed as part of a separate study.

The ground-based laser scanner used for this study was an Optech ILRIS-3D. This is a nonpanning system with a 40° field of view. Three scans were taken of the target streambank from three different locations on the opposite bank ranging from 6 to 10 m from the target bank. The average point spacing on the target bank was 1 cm. Both first and last returns were measured to limit the effect of shading due to vegetation on the streambanks. The scanner has a footprint diameter of 13.7 mm at a distance of 10 m (based on a beam divergence of 0.00974°) and an accuracy of 7–8 mm at 100 m (Lichti and Jamtsho 2006; Optech 2009).

Permanent references using 0.6-m rebar were placed into the ground for spatial alignment over time. For the total station measurements, the top of each rebar was surveyed. For TLS, 0.3-m square metal plates placed on the rebar were used as scanner targets (Fig. 1).

Data Analysis

The total station data were processed by converting the easting, northing, and elevation values to distance from the total station

Table 1. Number of Topographic Points Measured by Each Method and the Mean Absolute Point Differences

	05/07	08/07	12/07	05/08	12/08	05/09
Survey points	23	24	25	27	28	25
TLS points	360,042	40,339	52,328	96,175	105,806	101,019
Mean absolute difference (m)	0.017	0.015	0.016	0.020	0.024	0.014

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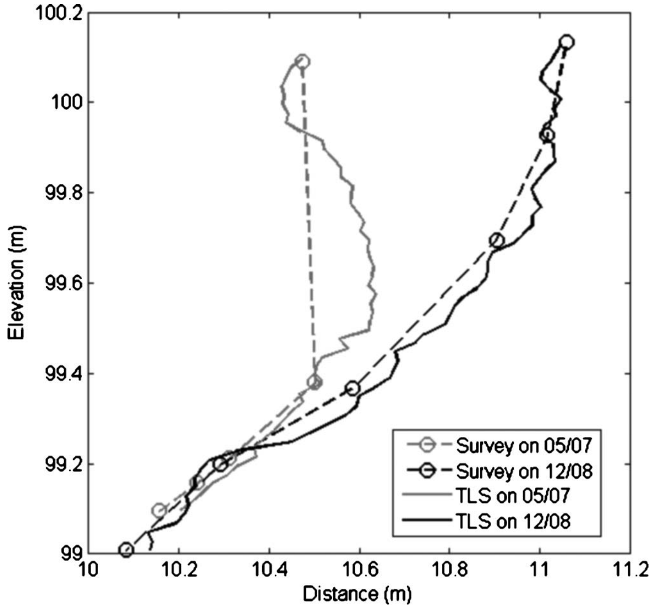

Fig. 2. Cross Section 4 of the streambank measured by both total station surveying and TLS

and elevation. The TLS scans for a particular study date were aligned together using the IMAlign tool in InnovMetric PolyWorks, which has an iterative algorithm that best-fits the point clouds to within a mean error of ± 0.0001 m. The point clouds for different study dates were then aligned using reference points selected from the three scan targets (the stationary metal plates). After alignment, the data were manually edited to remove vegetation. The points between the top of bank and the edge of water were then exported into MATLAB for further analysis.

Three metrics were used to measure the differences between the total station and TLS data: (1) individual point differences; (2) median SBR at each cross section; and (3) volume change over the entire streambank surface. The first metric was calculated for each of the six survey dates by comparing the total station and TLS data from individual dates. The second and third metrics were calculated using differences in surveys between each of the six survey dates (where negative change represents SBR).

Individual point differences were determined by first aligning the survey and TLS data for each study date manually in IMAlign using the benchmarks and targets. The point differences between each of the survey points and the TLS point cloud were calculated using the IMInspect tool in PolyWorks that identified the closest point in the TLS data to each survey point and calculated the point-to-point distance.

For the total station surveys, median SBR was calculated by interpolating every 2 cm from the top of bank to the edge of water, and determining the lateral change between cross sections. Volume change was calculated from the total station data sets as the weighted average of cross-sectional area change multiplied by the overall bank length.

For TLS, the data were first divided into two sections (to minimize error due to the curvature of the stream). Both sections were projected to a plane behind the bank surface (parallel to streamflow). The points were then converted to a 2-cm DEM with respect to the two planes by taking the minimum point-to-plane distance within each cell (to filter out vegetation). SBR was then calculated as the change in DEMs over time. Volume change was calculated numerically as the SBR at each 2-cm grid cell over the entire bank area.

Results

Individual Point Differences

Over the six study dates, a total of 152 points were measured with the total station compared with 755,709 points with TLS. Using TLS in the field was faster than the total station and did not physically disturb the topography of the bank. While postprocessing the TLS data presented a challenge due to its size and complexity, with proper alignment software and high-speed computers the postprocessing time of both data sets was comparable. The mean absolute point difference between the two methods was 0.018 m with a standard deviation of 0.020 m and 63% of survey points within ± 0.02 m of the TLS data. The number of points for each method and the point differences for each study date are shown in Table 1.

An example cross section is shown in Fig. 2 comparing the topographic measurements from both methods. The total station measurements were fairly accurate where points were surveyed and in general they captured the trend of the cross section topography (Fig. 2). The higher-resolution TLS provided a more accurate and complete measurement of streambank topography. The difference between the cross sections measured by both methods illustrates the interpolation error inherent in taking limited point measurements.

Table 2. Median SBR (m) at Each Cross Section and Overall Volume Change (m^3) by Both Methods (Negative=Retreat)

Cross section	05/07 to 08/07		08/07 to 12/07		12/07 to 05/08		05/08 to 12/08		12/08 to 05/09	
	Survey	TLS	Survey	TLS	Survey	TLS	Survey	TLS	Survey	TLS
(a) Median SBR (m)										
1	−0.03	0.00	−0.03	−0.07	−0.06	−0.12	0.00	0.02	−0.13	−0.12
2	0.01	0.02	−0.11	−0.13	−0.15	−0.13	0.03	0.01	−0.13	−0.17
3	−0.12	−0.02	0.04	−0.02	−0.13	−0.13	0.00	0.01	−0.19	−0.17
4	−0.11	0.00	−0.03	−0.05	−0.17	−0.16	0.00	0.00	−0.13	−0.11
5	−0.01	0.02	0.00	−0.02	−0.15	−0.11	−0.03	−0.03	−0.01	0.06
(b) Volume change (m^3)										
	−0.71	0.26	−0.33	−0.42	−1.71	−1.92	−0.06	0.17	−1.38	−1.29

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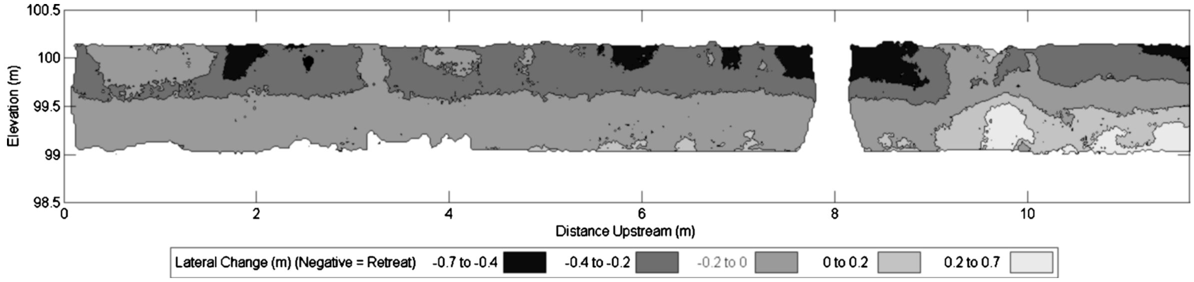

Fig. 3. TLS measured lateral change over the bank surface from 05/07 to 12/08 (the gap in the data at 8-m upstream is a result of the way the data were projected)

Cross-Sectional SBR

The median cross-sectional SBR values between each of the survey dates from both total station surveying and TLS are shown in Table 2. There was a positive correlation between the median SBR for both methods ($r=0.81$), indicating general agreement. The difference between surveying and TLS calculations of median SBR at individual cross sections ranged from -0.11 to $+0.06$ m or from 0 to 3,000% relative to TLS with a mean relative error of 248%. Only 12 of the 25 median SBR measurements had relative errors less than 50%. Over the 2-year study the relative error between surveying and TLS for measuring median SBR at each cross section ranged from 12 to 157% with a mean of 49%. The average SBR per year over the entire bank was -0.18 and -0.15 m/year from surveying and TLS, respectively, a relative error of 20% compared to TLS. The relative errors show that while there is a large variability of SBR error between two surveys, as expected, the error decreases as the measurement time increases and more surveys are performed.

Volume Change

The volume change for each method between the six study dates is provided in Table 2 (negative represents retreat). The difference between surveying and TLS ranged from 7 to 373% of the total retreat measured by TLS with a mean of 109%. The average yearly retreat rates were measured to be -2.1 and -1.6 $m^3/year$ by surveying and TLS, respectively, a relative error of 31% compared to TLS. The relative error in volume was slightly more than the relative error for average SBR (20%), likely since errors are added over the bank face when calculating volumes rather than averaged as in the case with cross-sectional SBR rates. The largest error occurred during the first two survey dates, likely due to the total station being unable to measure a section of the bank that was deeply undercut during the first survey date (Fig. 2), resulting in an overestimation of retreat. Aside from cases such as this where an undercut bank results in less retreat measured by TLS, there does not seem to be a systematic difference between the results of the two methods. The rest of the difference between the two methods was likely the result of the higher spatial resolution of TLS (about 4,400 times that of surveying in this study).

Discussion

One of the advantages of TLS data over total station point data is that much more information can be learned about the spatial variability of SBR. Total station surveying is limited to calculating the average SBR value for an entire bank or looking at retreat and advance along stream cross sections. TLS on the other hand is capable of creating a change map over the entire bank surface allowing for the identification of areas of retreat and advance (Fig. 3). This type of information could be invaluable for studies where the spatial variability of retreat is critical, such as studying microscale streambank erosion processes.

The high accuracy of TLS allows for measuring topography of streambanks nondestructively at a previously unattainable resolution. However, there are many improvements that must be made to the scanning and data-processing methodology before TLS can be an effective tool for many stream applications. The analysis of TLS data can be complex and time intensive due to the size of the data sets. There are also limitations such as the inability to scan underwater topography and difficulties with measuring heavily vegetated surfaces.

Most applications involving measuring fluvial topography rely on total station surveys due to their familiarity and cost effectiveness. Our future research efforts will focus on the propagation of surveying error to larger-scale analyses such as reach- and watershed-scale sediment load estimates. Until TLS technology is more readily available and postprocessing techniques more accessible, research and management projects will continue to rely on total station surveys. In the meantime, TLS can help us estimate the error in topographic measurements from more standard techniques so that uncertainty can be quantified for TMDL sediment load estimates and other geomorphologic applications.

Summary and Conclusions

In this technical note we discussed the methodology of using TLS in the field to collect high-resolution streambank topography data, and then processed that data to calculate median SBR and volume change. The differences in these calculations were then found between total station data and TLS data. While total station surveying can be accurate for measuring single points, the error is much greater when looking at interpolated SBR values and overall retreat volume, particularly when measuring undercut banks and other complex topographies. TLS also has an advantage over point measurements in the ability to quantify the spatial variability of retreat and advance over the entire streambank surface.

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References

Agouridis, C. T., et al. (2005). "Streambank erosion associated with grazing practices in the humid region." *Trans. ASAE*, 48(1), 181–190.

Benham, B., et al. (2003). "Benthic TMDL for Stroubles Creek in Montgomery County, Virginia." *Submitted October 16, 2003 to the Virginia Dept. of Environmental Quality and Virginia Dept. of Conservation and Recreation*, Richmond, Va., ⟨http://www.deq.virginia.gov/tmdl/apptmdls/newrvr/stroub.pdf⟩ (Sept. 1, 2009).

Bernhardt, E. S., et al. (2005). "Synthesizing U.S. river restoration efforts." *Science*, 308, 636–637.

Bitelli, G., Dubbini, M., and Zanutta, A. (2004). "Terrestrial laser scanning and digital photogrammetry techniques to monitor landslide bodies." *Proc., 20th ISPRS Congress*, International Archives of the Photogrammetry, Remote Sensing, and Spatial Information Sciences, Istanbul, Turkey, 246–251.

Bourke, M., Viles, H., Nicoli, J., Lyew-Ayee, P., Ghent, R., and Holmlund, J. (2008). "Innovative applications of laser scanning and rapid prototype printing to rock breakdown experiments." *Earth Surf. Processes Landforms*, 33(10), 1614–1621.

Brasington, J., Langham, J., and Rumsby, B. (2003). "Methodological sensitivity of morphometric estimates of coarse fluvial sediment transport." *Geomorphology*, 53, 299–316.

Collins, B. D., and Sitar, N. (2008). "Processes of coastal bluff erosion in weakly lithified sands, Pacifica, California, USA." *Geomorphology*, 97, 483–501.

Davis, R. J., and Gregory, K. J. (1994). "A new distinct mechanism of river bank erosion in a forested catchment." *J. Hydrol.*, 157, 1–11.

Green, T. R., Beavis, S. G., Dietrich, C. R., and Jakeman, A. J. (1999). "Relating stream-bank erosion to in-stream transport of suspended sediment." *Hydrolog. Process.*, 13, 777–787.

Heritage, G., and Hetherington, D. (2007). "Towards a protocol for laser scanning in fluvial geomorphology." *Earth Surf. Processes Landforms*, 32(1), 66–74.

Hsiao, K. H., Liu, J. K., Yu, M. F., and Tseng, Y. H. (2004). "Change detection of landslide terrains using ground-based lidar data." *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.*, 35(B7), 617–621.

Knighton, A. D. (1973). "Riverbank erosion in relation to streamflow conditions, River Bollin-Dean, Cheshire." *East Midland Geographer*, 5, 416–426.

Laubel, A., Svendsen, L. M., Kronvang, B., and Larsen, S. E. (1999). "Bank erosion in a Danish lowland stream system." *Hydrobiologia*, 410, 279–285.

Lawler, D. M. (1992). "Process dominance in bank erosion systems." *Lowland floodplain rivers: Geomorphological perspectives*, P. A. Carling and G. E. Petts, eds., Wiley, New York, 119–141.

Lawler, D. M. (1993). "The measurement of river bank erosion and lateral channel change: A review." *Earth Surf. Processes Landforms*, 18, 777–821.

Lawler, D. M., Grove, J. R., Couperthwaite, J. S., and Leeks, G. J. L. (1999). "Downstream change in river bank erosion rates in the Swale-Ouse system, Northern England." *Hydrolog. Process.*, 13, 977–992.

Lichti, D. D., and Jamtsho, S. (2006). "Angular resolution of terrestrial laser scanners." *Photogramm. Rec.*, 21(114), 141–160.

Lim, M., Petley, D. N., Rosser, N. J., Allison, R. J., and Long, A. J. (2005). "Combined digital photogrammetry and time-of-flight laser scanning for monitoring cliff evolution." *Photogramm. Rec.*, 20(110), 109–129.

Optech. (2009). "Technical overview—ILRIS-3D specifications." ⟨http://www.optech.ca/i3dtechoverview-ilris.htm⟩ (Sept. 1, 2009).

Osterkamp, W. R., Heilman, P., and Lane, L. J. (1998). "Economic consideration of a continental sediment-monitoring program." *Int. J. Sediment Res.*, 13(4), 12–24.

Pyle, C. J., Richards, K. S., and Chandler, J. H. (1997). "Digital photogrammetric monitoring of river bank erosion." *Photogramm. Rec.*, 15(89), 753–764.

Rhoades, E. L., O'Neal, M. A., and Pizzuto, J. E. (2009). "Quantifying bank erosion on the south river from 1937 to 2005, and its importance in assessing Hg contamination." *Appl. Geogr.*, 29, 125–134.

Rosser, N. J., Petley, D. N., Lim, M., Dunning, S. A., and Allison, R. J. (2005). "Terrestrial laser scanning for monitoring the process of hard rock coastal cliff erosion." *Q. J. Eng. Geol. Hydrogeol.*, 38, 363–375.

Teza, G., Pesci, A., Genevois, R., and Galgaro, A. (2008). "Characterization of landslide ground surface kinematics from terrestrial laser scanning and strain field computation." *Geomorphology*, 97(3–4), 424–437.

Winterbottom, S. J., and Gilvear, D. J. (2000). "A GIS-based approach to mapping probabilities of river bank erosion: Regulated River Tummel, Scotland." *Regul. Rivers: Res. Manage.*, 16, 127–140.

Wynn, T. M., Henderson, M. B., and Vaughan, D. H. (2008). "Changes in streambank erodibility and critical shear stress due to subaerial processes along a headwater stream, Southwestern Virginia, USA." *Geomorphology*, 97, 260–273.

Yagow, G., Benham, B., Wynn, T., and Younos, T. (2006). "Upper Stroubles Creek watershed draft TMDL implementation plan, Montgomery County, Virginia." *VT-BSE Document No. 2005-0013*, Virginia Dept. of Environmental Quality and Virginia Dept. of Conservation and Recreation, Richmond, Va.

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