Georeferenced Video Mapping to Classify Streambank Erosion Susceptibility

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Abstract

Boat-mounted, georeferenced videos were used to develop a method to rapidly document streambank conditions and assess erosion susceptibility over long stream segments. Traditional streambank survey methods are often spatially limited, time-consuming, and expensive. A novel Streambank Video Mapping System (SVMS) comprised of a GPS receiver, two streambank-facing video cameras, and thalweg depth sensor gathered continuous georeferenced data on both streambanks in a single pass. A modification of the commonly applied Bank Erosion Hazard Index was used to classify streambank conditions. The modified index, named the Bank Erosion Susceptibility Index (BESI), was derived from a combination of the variables including bank angle, bank height, bankfull height, channel depth, bank surface protection, and riparian diversity. These variables were combined into a four-parameter model to estimate bank erosion susceptibility. Using the SVMS, two stream segments in Tennessee were surveyed. In 1.33 hours, 7.7 km of the New River and in 1.08 hours, 7.6 km of Beaver Creek were surveyed for an average collection rate of 6.3 km/h. Maps of streambank erosion susceptibility were developed and the streambank health of the two stream reaches were compared. For each streambank, variables were visually classified from the georeferenced video by five independent observers. To assess the accuracy of the SVMS approach site field measurements were physically collected and compared to the video assessments with average errors less than 5 percent.

Keywords

Streambank, erosion, video; GIS, rapid assessment

Introduction

        Sediment is one of the leading causes of water impairment in the U.S. (USEPA 2009; TDEC 2012). Identifying areas that are susceptible to streambank erosion within stream and river networks is an important step in understanding the source of instream sediment. Hydrologic processes, instream hydraulics, streambank geometry and structure, soil characteristics, riparian vegetation, and climatic conditions interactively control streambank erosion (Thorne and Tovey 1981). The mechanism of streambank erosion generally includes a combination of hydraulic-induced bank-toe erosion and bank mass failure (Simon and Collison 2002). Due to gravitational forces, streambank particles are more likely to be detached from steeper slopes and deposited on gentler slopes (Pfankuch 1975; Foster 2010). The presence, type, and abundance of riparian vegetation also affects streambank stability such that vegetation can provide reinforcement of the soil by root systems, reduce soil moisture content from increased interception and evapotranspiration, and regulate physical soil characteristics (Leh et al., 2018; Simon and Collison 2002; Singh and Saraswat, 2016; Thompson and Mostaghimi 2006).

        Many studies have been conducted to simulate conservation practices to reduce sediments, but before that it is important to predict the erosion as realistically as possible (Carling et al, 2001; Singh et al., 2018; Singh and Bhattarai, 2019). Numerous methods are available to document and/or predict streambank erosion that vary in type and number of parameters assessed (Rosgen 2001; Montgomery and MacDonald 2002; Simon 2006). In general, the most accurate methods use pins driven into the bank to allow detailed measurements of erosion or deposition rates (Lawler 1993). While highly accurate, these approaches are very difficult to apply over long stream segments due to their time-consuming deployment and thus are best relegated to applications in specific locations of concern.

        More rapid approaches usually employ a combination of observed streambank conditions that correlate to estimates of sedimentation rate. Of the more rapid methods, a commonly used approach is the Bank Erosion Hazard Index (BEHI) (Rosgen 2001). The BEHI employs direct measurements of five parameters including: 1) bank height to bank full height ratio, 2) root depth measured as a percentage of bank full height, 3) root density percentage, 4) surface protection percentage, and 5) bank angle in degrees. The resultant measurement for each parameter is categorized into six groups from very low to extreme potential for erosion and then combined into an overall score for an index of bank erosion hazard. In addition to describing areas that are at risk of erosion, the BEHI has also been used to estimate annual sediment loads resulting from streambank erosion (Van Eps et al. 2004).

        Another rapid approach for assessing bank stability is included in the Rapid Bioassessment Protocol (RBP) developed by the EPA. The RBP is a monitoring framework that integrates several biological population measurements with functional habitat parameters to evaluate stream impairment (Barbour et al. 1999). Sampling reaches are divided into high gradient or low gradient reaches, and physical habitat assessment parameters are adjusted accordingly. The ten parameters measured include epifaunal substrate/available cover, embeddedness, velocity/depth combinations, sediment deposition, channel flow status, channel alteration, frequency of riffles and/or

frequency of bends (sinuosity), bank stability, bank vegetative protection, and riparian vegetative zone width. The RBP involves rating these 10 parameters as optimal, suboptimal, marginal or poor (Barbour et al. 1999). Doll et al. (2015) developed Stream Performance Assessment (SPA), a visual rapid assessment technique, to evaluate eco-geomorphological conditions of restored streams. A 110-point system was established that included both instream habitat and fluvial geomorphology and correlated well with macroinvertebrate metrics.

When attempting to interpret geomorphic dynamics over long stream segments, it is often necessary to develop an inventory of morphological conditions from river reconnaissance surveys (Downs and Thorne 1996). River reconnaissance approaches have the advantage of providing qualitative yet broadly descriptive data over long stream segments and can cost-effectively be used to guide subsequent restoration engineering efforts (Downs and Thorne 1996). The tradeoff with cost and time efficiency in qualitative river reconnaissance approaches is a lack of detailed site measurements for consistent measure of streambank erosion.

In general, there is a trade-off between site-specific precision and broad spatial coverage. Many estimates of streambank erosion contribution to instream sediment implicitly assume that a single measurement or rating can be applied over a wide geomorphic area with no regard to spatial or temporal variability (Montgomery and MacDonald 2002; Singh and Kumar, 2017). However, a particular measurement or channel rating can have very different implications depending on the stream type and location in the channel network (Montgomery and MacDonald 2002). Process-response feedback mechanisms operating in the fluvial system require the extension of geomorphic assessment upstream and downstream of a project reach, as these interactions may be significant (Downs and Thorne 1996). The application of accurate and precise site-specific data to a long stream segment can result in inaccurate estimates of streambank erosion over the segment if the site-specific data is not representative of the range and proportion of conditions found throughout the stream segment. Therefore, there is a need for geomorphological assessment to be both intensive and extensive (Downs and Thorne 1996).

Methods of monitoring and assessing streambanks have improved over the last two decades in terms of accuracy and effectiveness. However, most current assessments are limited in their utility because they are made at specific locations, which may not accurately represent the entirety of a segment, fail to characterize the full spectrum of conditions, and fail to identify critical areas of bank instability. Georeferenced video is an emerging concept that has proven effective in aquatic habitat assessment (McConkey 2009). Candlish (2010) developed large-scale instream habitat maps to promote watershed management of aquatic resources by utilizing georeferenced video mounted on a kayak. This approach was used to survey up to 16 km of instream habitat per day. Continuously surveyed attributes of substrate size, embeddedness, depth, and habitat type were tagged to GPS locations and used to create relatively high-resolution maps over long stream segments (Candlish 2010).

The goal of this study was to quantify streambank erosion susceptibility continuously over long stream segments using a system of combining GPS, video, and depth sensors. Specific objectives included: 1) development of a georeferenced video mapping system to quickly capture continuous streambank erosion indicators; 2) creation of an index based on observable parameters correlated to areas of high erosion susceptibility; 3) application of the index to classify erosion susceptibility throughout long stream segments 4) validation of the video assessments against field data and; 5) comparison of the consistency of video interpretation among observers.

Methodology

Equipment

The Streambank Video Mapping System (SVMS) consisted of a sit-on-top kayak (Wilderness Systems Tarpon 100); three GPS-enabled video cameras (Contour cameras) mounted facing forward, left, and right (90°); a flush-mounted depth sensor (Cruz-Pro ATU-120S); a National Marine Electronics Association multiplexer; and a GPS receiver (Trimble 132) (Figure 1). The GPS receiver provided sub-meter GPS accuracy and outputted time and location data at 1Hz. The GPS data was combined with the depth data within the multiplexer and then was recorded onto a flash drive. The Contour GPS cameras included a Neo-6 GPS module and recorded video at 1280 by 720-pixel resolution. The georeferenced video was combined with the GPS and depth data such that each data point is associated with Coordinated Universal Time (UTC) and coordinate information.

Figure 1 Streambank video mapping system

Development of Bank Erosion Susceptibility Index

The Bank Erosion Susceptibility Index (BESI) method was created based on modifications to the Bank Erosion Hazard Index (BEHI) (Rosgen 2001). Although other erosion models and habitat assessments were considered, the BEHI approach was selected because it is a commonly applied approach that uses a number of parameters that could be estimated from video. The intent was not to validate the BEHI approach for use in streams, but rather to see if an index could be created based primarily on visually classifiable parameters of effectively document erosion potential.

Five variables classified from the video were bank angle, bank height, bankfull height, surface protection, and riparian diversity. Stream depth was recorded from the georeferenced depth sensor flush mounted to the base of the kayak. These variables were combined to create four parameters for the BESI approach and the parameters were bank angle, bank height to bankfull height ratio, surface protection, and riparian diversity (Connell 2012). Bank angle (BA) was visually estimated to fall in one of four categories.

- 0-60 degrees received a BESI score of 2.45
- 61-80 degrees received a BESI score of 4.95
- 81-90 degrees received a BESI score of 6.95
- >91 degrees received a BESI score of 9

Bank height and bankfull height were determined by visual assessment separately as the observer focused on the distance from the water surface to bank height elevation. To increase accuracy and efficiency during video assessment, the seven height categories used in this study were 0-1 ft., 1-3 ft., 3-6 ft., 6-9 ft., 9-12 ft., 12-18 ft., and > 18 ft. Each GPS point was associated with a bank height, bankfull height, and stream depth, and a ratio value (RV), $\frac{(\text{Bank Height} + \text{Depth})}{(\text{Bankfull Height} + \text{Depth})}$, was calculated for each location. Surface protection (SP) (%) was visually categorized into one of four groups which relate to how much soil is exposed to moving water and rainfall directly on the stream bank.

- 55-100 percent surface protection received a BESI score of 2.45
- 30-54 percent surface protection received a BESI score of 4.95
- 15-29 percent surface protection received a BESI score of 6.95
- <14 percent surface protection received a BESI score of 9

Evaluation of root depth and root density, included in the BEHI (Rosgen 2001), was excluded from the BESI because of challenges presented by measurement of these parameters in video assessment. In lieu of using these parameters, the BESI included riparian diversity as a parameter that reflected the potential soil holding strength of riparian vegetation. In general, BESI used the assumption that the larger the trees and more complex the understory in the riparian zone, the greater the root development to resist erosion into the bank. Riparian diversity (RD) scores were defined as:

- Optimal- Surrounding area consists of several sizes of trees, shrubs, and grasses of all sizes. High diversity is presumed to be indicative of very high root depth and density. BESI score = 2.45.

- Sub-Optimal- Surrounding area consists of low diversity trees with some understory and grasses. Sub-Optimal is presumed to be indicative of good root depth and density. BESI score = 4.95.

- Marginal- Surrounding area consists of a few trees with a few shrubs and grass. Marginal is presumed to be indicative of moderate root depth and density. BESI score = 6.95.

- Poor- Surrounding area consists of short grass or bare soil. Poor is presumed to be indicative of poor root depth and density. BESI score = 9.

Unlike the BEHI (Rosgen 2001) with its six hazard categories, only four categories were included in the BESI. Low and very low scores were combined into a single evaluation category and very high and extreme scores were also combined. The four BESI categories corresponding to low, moderate, high, and very high, changed at values of 18.5, 24.4, and 30.2, and an overall range of 9.8 to 36. The intent of the simplification of the number of categories was to improve the ability of users to effectively categorize the visual assessments. Similar to the Rosgen (2001) BEHI, Table 1 shows the Bank Erosion Susceptibility Ratings used with the SVMS.

Table 1. Bank erosion susceptibility ratings

Bank Erosion Susceptibility Rating		BankHeight to Bankfull Height (Ratio)	Riparian Diversity (%)	Bank Angle (Degrees)	Surface Protection (%)	Index Totals
Low	Value	1.0-1.19	Optimal	0-60	55-100	
	Index	2.45	2.45	2.45	2.45	9.8-18.5
Moderate	Value	1.2-1.5	Sub Opt	61-80	30-54	
	Index	4.95	4.95	4.95	4.95	18.6-24.4
High	Value	1.6-2.0	Marginal	81-90	15-29	
	Index	6.95	6.95	6.95	6.95	24.5-30.2
Very high	Value	>2.1	Poor	>91	<14	
	Index	9	9	9	9	30.3-36.0

Field Studies

The New River, which flows into the Big South Fork National River and Recreational Area (BISO), was surveyed on December 3, 2011 using the SVMS. The primary land use adjacent to the survey reach was a mixture of pasture and small-scale agriculture. River discharge was 25.5 m3/s on the survey date. Surveys began at the River Road Bridge (36.38926° N, 84.48787° W) south of Huntsville, TN and ended at Low Gap Road (36.38429° N,

84.52813° W) just upstream of the BISO. The SVMS survey covered 7.7 km in 1.33 h and included video of both streambanks with corresponding location, time, and depth data.

Beaver Creek located approximately 24 km north of Knoxville, TN, was surveyed with the SVMS on September 8, 2011. Beaver Creek, a tributary of the Clinch River, drains an urbanizing watershed of 224 km2 located between Copper Ridge and Black Oak Ridge. Stream discharge was 14.1 m3/s on the survey date. The surveys began at the Solway Bridge (35.96475° N, 84.17852° W) and concluded at the confluence with the Clinch River (35.949190° N, 84.200752° W). A total of 7.6 km was surveyed in 1.08 h and included video of both streambanks and associated GPS and stream depth data.

Direct field measurements of the variables were made at 38 random locations (10 meters in length) to compare with the SVMS results. Connell (2012) describes the protocol for site selection and field measurements. On New River, both the left and right banks of ten random locations were measured on site for bank angle, bank height, surface protection, and riparian diversity. For Beaver Creek, both left and right banks of nine locations were also measured on site for bank angle, bank height, surface protection, and riparian diversity. Beaver Creek differed in that a stratified random method was used for site location to increase the range of BESI scores observed (Connell 2012). For this study, measures from the right and left bank were considered independent locations. While not hydraulically independent, opposite banks' conditions could vary substantially based on local variability. For example, one site may be on an inside bend and the other on an outside bend or one site may be forested while the other is bordered by a cow pasture. The video estimates of the primary author were compared to the field measurement using a contingency table for each parameter and the overall BESI score.

Analysis

All data were collected, organized, and classified for the SMVS and field validation efforts by the lead author. For consistency, the observer evaluated one parameter at a time, and each observation was georeferenced by linking the video VTR code with the UTC time and thus the corresponding GPS locations. Classified results were then mapped in ArcGIS 9.3 to view the data and the extent of streambank length was determined for each BESI class. Streambank length was determined as the horizontal distance between GPS points. The videos collected from the 38 random sites on both the New River and Beaver Creek were also visually classified by four additional independent observers.

To better understand the strengths and weakness of the SVMS approach, several different comparisons were made between the results of the SVMS and direct field measurements. To test for site-specific measurement accuracy, direct field measurements of the Bank Erosion Susceptibility Index (BESI) parameters were compared to the video assessment results. From the classified data, ten second clips of streambank video were created centered around the 38 10-meter field validation sites. The ten second video clips were then visually classified by four

independent observers. For consistency, these observers evaluated one parameter at a time. After the video classification score sheets were completed, each individual parameter and the overall BESI score was calculated for each observer. To test for consistency among observers, results from the five independent observers were compared to each other.

To compare sampling efficiency between the SVMS and direct field measurement approaches, the rate at which each method collected and classified the data was compared. For the SVMS and BESI approach, the time to collect the field data and then time to watch the video for each of the five measured variables for each bank was determined. For consistency of comparison, it was assumed that observers watched the video at real time speed so that a single variable for a single bank would take the same amount of time as the field data collection. For the direct field measurement, amount of time in the field for both surveys was combined and then two hours was added to it for the time to add the recorded field data into the computer. Time for travel and analysis of the data was considered to be identical for both techniques so times for these activities were excluded from the comparison.

Results and Discussion

SVMS georeferenced field measurements

The SVMS collected GPS, depth, and video data for the two test stream segments at 1 second intervals. Classification of the video was completed for the entirety of both streambanks for each of the two stream segments. Areas of varying erosion susceptibility were determined and displayed using thematic mapping within ArcGIS. In the New River segment, 78% of the streambank length received a low erosion susceptibility rating, 21% scored moderate, and the remaining 1% was identified as high erosion susceptibility (Figure 2). The total distance of streambank that was rated as high erosion susceptibility was 135 meters, with a maximum score of 25.0 determined. Average BESI score for the entire reach was 15.3, giving it a low streambank erosion susceptibility score. Similar to the New River segment, the Beaver Creek survey documented limited areas of high erosion susceptibility (Figure 3). In Beaver Creek, a total length of 190 meters was classified with high erosion susceptibility, which represents approximately 1% of the surveyed reach. With 81% low, 18% moderate, and an average BESI score of 14.0, Beaver Creek also received an overall low erosion susceptibility score. The BESI scores for the New River and Beaver Creek reaches are shown in Figure 4, providing a visual of the total streambank health in terms of erosion susceptibility.
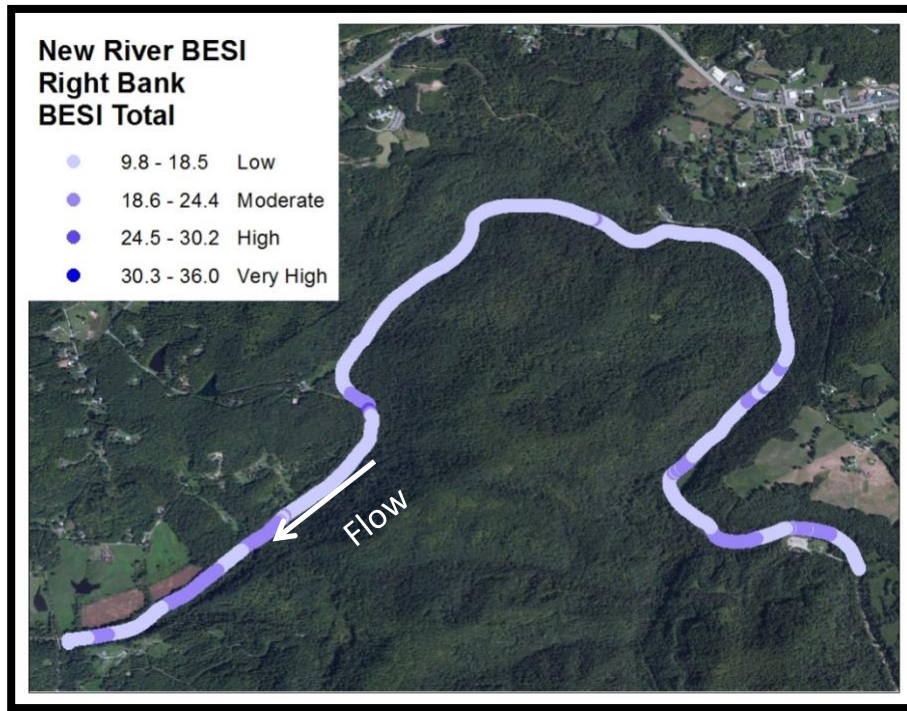
Figure 2 New River segment right bank erosion susceptibility index score
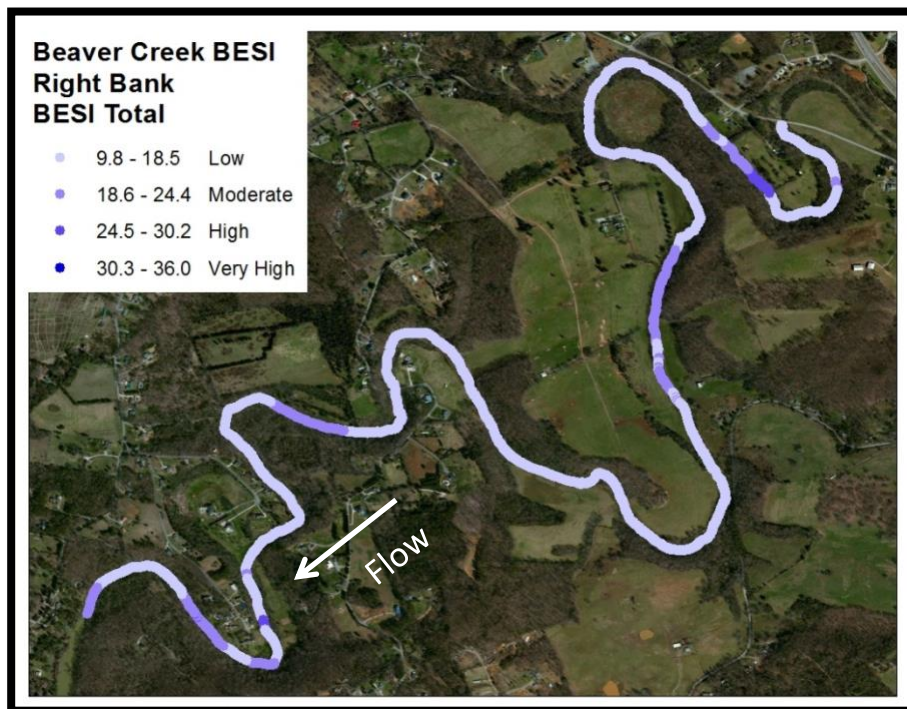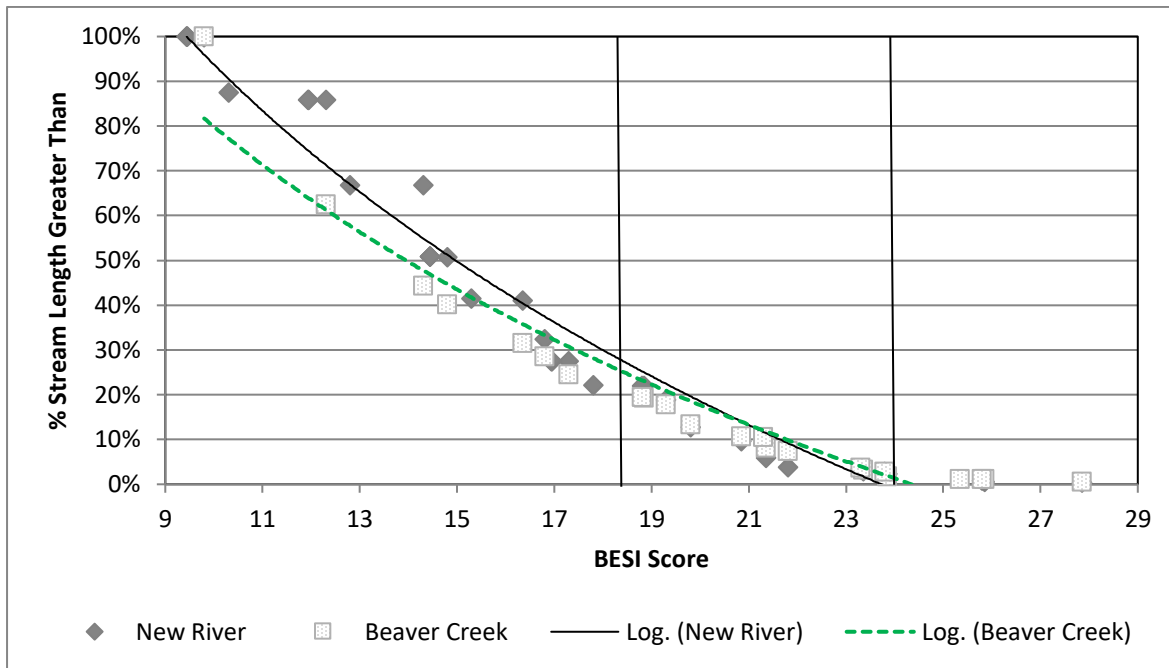

Figure 3 Beaver Creek segment right bank erosion susceptibility index score

Figure 4 Comparison of New River and Beaver Creek bank erosion susceptibility index scores
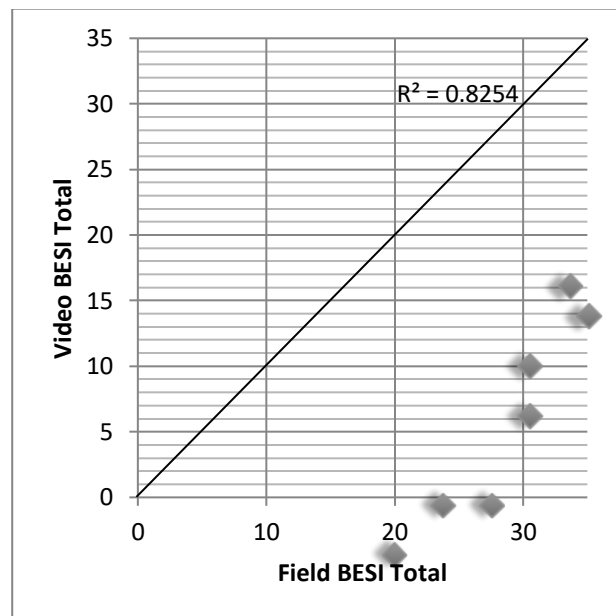
Accuracy comparison between SVMS and direct field measurements

Details of the variation in the BESI scores by the five observers at the 38 field validation sites are presented by Connell (2012). In summary, the average percent error of the total BESI scores for all observers were all less than 5% from the field measured values. This indicates both consistency among individual observers in scoring the video and correlation with the field validation scores.

Given that the majority of the segment was determined to be in the low BESI range, the randomly selected field validations sites did not represent the full range of BESI documented throughout the reach. Therefore, nine of the field validation sites along the Beaver Creek right bank were chosen using stratified random selection to pick 3 sites near each of the low, medium and high BESI score ranges (Connell 2012). The field validation conducted at these sites provided comparison in a larger range of BESI scores. Table 2 shows the results when comparing the field measurements to the video assessment at these nine stratified random locations. Figure 5 displays the field measurements compared to video interpretation for total BESI scores on a 1:1 ratio expressing a strong correlation.

Table 2 Individual bank erosion susceptibility scores for the stratified random sites on Beaver Creek. Bank Angle (BA), Surface Protection (SP), Riparian Diversity (RD), Ratio Value (RV)

Rating	Site	Viewer BA	Field BA	%E	Viewer SP	Field SP	%E	Viewer RD	Field RD	%E	Viewer RV	Field RV	%E	Viewer BESI	Field BESI	%E
High	1	9.00	9.00	0.00	6.95	4.95	28.78	4.95	2.45	50.51	2.45	2.45	0.00	23.35	18.85	19.27
Low	2	2.45	2.45	0.00	2.45	2.45	0.00	2.45	2.45	0.00	4.95	4.95	0.00	12.30	12.30	0.00
Medium	3	2.45	2.45	0.00	4.95	4.95	0.00	6.95	6.95	0.00	2.45	2.45	0.00	16.80	16.80	0.00
Medium	4	4.95	4.95	0.00	4.95	4.95	0.00	4.95	4.95	0.00	6.95	4.95	28.78	21.80	19.80	9.17
Low	5	2.45	2.45	0.00	2.45	4.95	-102.04	2.45	2.45	0.00	4.95	4.95	0.00	12.30	14.80	-20.33
Low	6	2.45	2.45	0.00	2.45	2.45	0.00	2.45	2.45	0.00	2.45	2.45	0.00	9.80	9.80	0.00
High	7	6.95	9.00	-29.50	6.95	9.00	-29.50	6.95	9.00	-29.50	4.95	4.95	0.00	25.80	31.95	-23.84
High	8	6.95	9.00	-29.50	6.95	6.95	0.00	9.00	9.00	0.00	4.95	4.95	0.00	27.85	29.90	-7.36
Medium	9	2.45	2.45	0.00	4.95	2.45	50.51	6.95	6.95	0.00	4.95	4.95	0.00	19.30	16.80	12.95
Avg.				-6.55			-5.81			2.33			3.20			-1.12

Figure 5 Individual field vs. video total bank erosion susceptibility index scores

Comparison between SVMS and direct field rate of data collection

  The BEHI method is a point data collection, while the BESI/SVMS method provides more continuous data collection. If total streambank erosion or health is to be determined than a continuous streambank data collection is needed. When comparing the rate of data collection between methods, unsurprisingly data collected using SVMS was faster than direct field measurement. What was surprising was the magnitude of the collection rate and classification difference. Streambank erosion data was collected and classified at a rate of 1.15 km per hour using the SVMS approach compared to only 10 meters per hour with the direct field measurements. This equates to a data

collection and classification rate 109 times faster for the SVMS approach compared to the direct field measurements.

Conclusion

       The objective of this project was to develop a Streambank Video Mapping System (SVMS) to document streambank erosion susceptibility rapidly over long stream segments. The SVMS was used successfully to meet the objective of acquiring continuous GPS, stream depth, and video of each streambank quickly. The chosen parameters of Bank Erosion Susceptibility Index (BESI) proved applicable for visual assessment from the georeferenced video. Maps for New River and Beaver Creek developed from the SVMS/BESI approach visually documented the location and extent of areas of high erosion susceptibility. Dependent on flow rates and other stream/river navigation factors, the SVMS surveyed an average of 6.3 km/hour of streambank (3.15 km/hour of linear stream channel) while capturing continuous, high definition georeferenced streambank video and stream depth.

       The kayak mounted SVMS used in this research has passed numerous Class III rapids while collecting data with all the sensitive equipment safely stowed in a waterproof box. Anything bigger than a Class III rapid and all dams require portaging for safety. The described SVMS approach is most applicable in streams and small rivers. The use of two kayaks may be useful for larger rivers where each kayak could collect data for each streambank by staying approximately 5 to 10 meters from the streambank to allow for better streambank video resolution. In the case of high-water situations, surveying is still possible however a portion of the shoreline will be inundated and affect a proper assessment score.

       The SVMS and BESI were shown to be an efficient method of landscape-scale, erosion susceptibility mapping. Compared to traditional erosion assessments which tend be costly, isolated, restricted by access, and at times inaccurate due to extrapolation, the SVMS surveys more streambank, in less time. Stream reconnaissance provides the basis for scientific studies of channel form and process that embrace the collection and analysis of both qualitative information and quantitative data on the fluvial system (Downs and Thorne 1996).

       While the SVMS approach may not be as accurate or precise at a specific location when compared to direct field measurement, the SVMS approach greatly reduced data collection time and provided a spatially continuous output. If the goal of a survey is to better understand the extent, location, spatial distribution, and potential causes of streambank erosion over a long stream segment, the SVMS approach was superior to traditional point or transect approaches. While further refinement may be necessary to improve classification accuracy, the SVMS approach improves data collection speed, decreases sampling costs, and provides a valuable video archive of stream conditions when conducting streambank assessment over long stream segments. Future work should explore how well the BESI/BEHI predicts empirically documented streambank erosion in this region.

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