ITERATIVE BANK-STABILITY AND TOE-EROSION MODELING FOR PREDICTING STREAMBANK LOADING RATES AND POTENTIAL LOAD REDUCTIONS

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Abstract Sediment emanating from streambank erosion can often be the dominant source of sediment in unstable stream systems. Contributions of sediment from streambank erosion are however, often difficult to ascertain and are often estimated by indirect methods such as interpretation of time-series aerial photographs. The Bank-Stability and Toe-Erosion Model (BSTEM) developed by the USDA-ARS, National Sedimentation Laboratory has been applied to this problem in a variety of geomorphic settings across the country to quantify streambank-loading rates, lateral retreat, and potential reduction in sediment loadings under different bank-mitigation measures. BSTEM evaluates the force-equilibrium factor of safety of either planar- or cantilever-shear failure in a layered streambank. The resisting forces comprise the cohesive and frictional strengths of the soil, forces due to positive and negative pore-water pressures and a component of the hydrostatic confining force afforded by water in the channel. The driving forces comprise the weight of the failure block reduced by a component of the hydrostatic confining force. A global search algorithm was employed to search for the minimum factor of safety. An advanced root-reinforcement model based on fiber-bundle theory was applied to quantify the increase in bank strength due to assemblages of riparian vegetation. The hydraulic-erosion component of BSTEM estimates the applied shear stress along the bank toe and bank face and to erode these surfaces perpendicular to the existing geometry.

The purpose of this paper is to demonstrate the application of BSTEM as a viable tool for indentifying and quantifying the controlling bank-slope conditions for a range of stream-restoration objectives. In this research, the model is used iteratively to simulate the effects of hydraulic toe erosion on bank stability for a series of storm flows, generally over an annual hydrograph. Unit loadings values (at a site) obtained by iteratively modeling annual hydrographs representing the 99th, 95th, 90th, 75th, 50th, and 25th percentile flow years are weighted by the percent of time these flows are likely to occur to obtain a long-term, average streambank loading for each site. Results are then extrapolated spatially by multiplying the unit loadings values by the “percent of reach failing” and by the length of the respective reach. Total loadings values are then compared to measured data from USGS gauging stations or from other sources. Iterative modeling runs were conducted at several locations across the USA: three streams draining into Lake Tahoe, CA, the Lower Tombigbee River, AL, and the Big Sioux River, SD. Results of these studies have shown that the relative contribution of suspended sediment emanating from the streambanks can vary considerably, ranging from as low as 12% in the predominantly low gradient, agricultural watershed of the Big Sioux River, SD to as high as 47% on the steep forested watershed of Ward Creek, CA. Modeling of streambank mitigation strategies has also shown that the addition of toe protection to eroding streambanks can reduce overall volumes of eroded sediment up to 85-100%, notwithstanding that hydraulic erosion of the toe makes up only 15-20% of total bank erosion.

INTRODUCTION

Sediment is one of the leading contributors to water-quality impairment in surface waters of the United States through its adverse effects on downstream water-quality and aquatic life-support processes. Streambank erosion by mass failure represents an important form of channel adjustment and a significant source of sediment in disturbed streams, often contributing 60-80% of the suspended-sediment load (Simon and Rinaldi, 2006).

Given the relatively important role of streambank erosion in watershed sediment yields and channel adjustment, it is surprising that little, if any quantitative information is available on the effectiveness of bank treatments on reducing erosion. Bank failures generally occur by a combination of hydraulic processes that undercut bank toes and geotechnical processes causing bank collapse by gravity. The variables and processes that control streambank erosion need to be predicted accurately under existing and remediated conditions to evaluate bank-stabilization designs, existing streambank-derived sediment loads and the potential to alter sediment loadings from streambanks. The fundamental premise to reduce loadings from streambank erosion is, therefore, to either reduce the hydraulic and downslope forces and/or to increase the resistance of the bank toe to hydraulic forces and the resistance of the bank mass to downslope (gravitational) forces. Mitigation measures to reduce bank erosion might include some combination of bank-toe protection to increase resistance to hydraulic forces, planting of vegetation on the bank top and face to increase the cohesive strength of the bank materials and be more resistant to mass failure, or re-grading the bank slope to a flatter angle to reduce the overall driving downslope force. All of these processes and conditions can be simulated with the deterministic Bank-Stability and Toe-Erosion Model (BSTEM; Simon *et al*., 2000).

BSTEM has been used statically to test for relative stability of a bank under given pore-water pressure and vegetation conditions (Pollen and Simon, 2005; Pollen-Bankhead and Simon, 2009), to test for stable bank-slope designs (Simon *et al*., 2008), and to determine the importance of seepage undercutting relative to bank strength, bank angle, pore-water pressure and root reinforcement (Cancienne *et al*., 2008). With time-series pore-water pressure data, the model has been used quasi-dynamically to evaluate the important variables controlling bank stability (Simon *et al*., 2000) and the mechanical and hydrologic effects of riparian vegetation (Simon and Collison 2002; Simon *et al*., 2006). Most recently, BSTEM has been used iteratively to simulate hydraulic erosion at the bank toe and bank stability during a series of flow events for the purpose of evaluating current (existing) and potential changes in failure frequency and streambank-derived loadings (Simon *et al*., in press).

The purpose of this paper is to demonstrate the application of BSTEM as a viable tool for indentifying and quantifying the controlling bank-slope conditions for a range of stream-restoration objectives. Iterative application of the model in diverse environments such as Big Sioux River, South Dakota; Tombigbee River, Alabama and three streams in the Lake Tahoe Basin, Nevada and California will be demonstrated.

Bank Stability and Toe-Erosion Model (BSTEM) The original model developed by Simon *et al*. (1999; 2000) is a Limit Equilibrium analysis in which the Mohr-Coulomb failure criterion is used for the saturated part of the streambank, and the Fredlund *et al*. (1978) criterion is used for the unsaturated part. The latter criteria indicates that apparent cohesion changes with matric suction (negative) pore-water pressure, while effective cohesion remains constant. In addition to accounting for positive and negative pore-water pressures, the model incorporates complex geometries, layered soils, changes in soil unit weight based on water content, and external confining pressure from streamflow. The model divides the bank profile into five user-definable layers, each with unique geotechnical properties. The enhanced BSTEM (Version 5.3) includes a sub-model to predict bank-toe erosion and undercutting by hydraulic shear. This is based on an excess shear-stress approach that is linked to the geotechnical algorithms. Complex geometries resulting from simulated bank-toe are used as the new input geometry for the geotechnical part of the bank-stability model. If a failure is simulated, that new bank geometry can be exported back into either sub-model to simulate conditions over time by running the sub-models iteratively with different flow and water-table conditions. In addition, the enhanced bank-stability sub-model automatically selects between cantilever and planar-failure modes and allows for inclusion of the mechanical, reinforcing effects of riparian vegetation (Simon and Collison, 2002; Micheli and Kirchner, 2002; Pollen and Simon, 2005).

Bank-Toe Erosion Sub-Model The Bank-Toe Erosion sub-model is used to estimate erosion of bank and bank-toe materials by hydraulic shear stresses. The effects of toe protection are incorporated into the analysis by changing the characteristics of the toe material in the model. The model calculates an average boundary shear stress from channel geometry and flow parameters using a rectangular-shaped hydrograph defined by flow depth and the duration of the flow (steady, uniform flow). The assumption of steady, uniform flow is not critical insomuch as the model does not attempt to rout flow and sediment and is used only to establish the boundary shear stress for a specified duration along the bank surface. The model also allows for different critical shear stress and erodibility of separate zones with potentially different materials at the bank and bank toe. The bed elevation is fixed because the model does not incorporate the simulation of bed sediment transport. Toe erosion by hydraulic shear is calculated using an excess shear approach. The average boundary shear stress (τ_o) acting on each node of the bank material is calculated using:

$$\tau_o = \gamma_w R S \qquad (1)$$

where τ_o = average boundary shear stress (Pa), γ_w = unit weight of water (9.81 kN/m^3), R = local hydraulic radius (m) and S = channel slope (m/m).

The average boundary shear stress exerted by the flow on each node of the bank profile is determined by dividing the flow area at a cross-section into segments. The line dividing the bed- and bank-affected segments is assumed to bisect the average bank angle and the average bank-toe angle. The hydraulic radius (R) of the flow on each segment is the area of the segment (A) divided by the wetted perimeter of the segment (P_n). Thus the shear stress varies along the bank surface according to equation 1 as parameters comprising the segmented areas change.

An average erosion rate (in m/s) is computed for each node by utilizing an excess-shear stress approach (Partheniades, 1965). This rate is then integrated with respect to time to yield an average erosion distance in centimeters. This method is similar to that employed in the CONCEPTS model (Langendoen, 2000), except that here, erosion is assumed to occur normal to the local bank angle, and not horizontally:

$$E = k\, \Delta t\, (\tau_0 - \tau_c) \qquad (2)$$

where E = erosion distance (cm), k = erodibility coefficient (cm^3/N-s), Δt = time step (s), τ_0 = average boundary shear stress (Pa), and τ_c = critical shear stress (Pa).

Resistance of bank-toe and bank-surface materials to erosion by hydraulic shear is handled differently for cohesive and non-cohesive materials. Originally, for cohesive materials the relation developed by Hanson and Simon (2001) using a submerged jet-test device (Hanson, 1990; 1991) was used:

$$k = 0.2\, \tau_c^{-0.5} \qquad (3)$$

This relation has been recently updated based on hundreds of tests on streambanks across the United Sates (Simon *et al.*, in press, this volume):

$$k = 1.62\, \tau_c^{-0.838} \qquad (3a)$$

The Shields (1936) criteria is used for resistance of non-cohesive materials as a function of roughness and particle size (weight), and is expressed in terms of a dimensionless critical shear stress:

$$\tau* = \tau_o / [(\rho_s - \rho_w)\, g\, D] \qquad (4)$$

here $\tau*$ = critical dimensionless shear stress, ρ_s = sediment density (kg/m^3), ρ_w = water density (kg/m^3), g = gravitational acceleration (m/s^2), and D = characteristic particle diameter (m).

Bank Stability Sub-Model The bank stability sub-model combines three limit equilibrium-methods to calculate a Factor of Safety (F_s) for multi-layered streambanks. The methods simulated are horizontal layers (Simon and Curini, 1998; Simon *et al*., 2000), vertical slices for failures with a tension crack (Morgenstern and Price, 1965) and cantilever failures (Thorne and Tovey, 1981).

For planar failures without a tension crack, the Factor of Safety (F_s) for both the saturated and unsaturated parts of the failure plane is given by:

$$F_s = \frac{\sum_{i=1}^{I}\left(c_i' L_i + S_i \tan\phi_i^b + \left[W_i \cos\beta - U_i + P_i \cos(\alpha - \beta)\right]\tan\phi_i'\right)}{\sum_{i=1}^{I}\left(W_i \sin\beta - P_i \sin[\alpha - \beta]\right)} \qquad (5)$$

where c_i' = effective cohesion of ith layer (kPa), L_i = length of the failure plane incorporated within the ith layer (m), S_i = force produced by matric suction on the unsaturated part of the failure surface (kN/m), ϕ^b = angle representing the rate of increase in shear strength with increasing matric suction (°), W_i = weight of the ith layer (kN), U_i = the hydrostatic-uplift force on the saturated portion of the failure surface (kN/m), P_i = the hydrostatic-confining force due to external water level (kN/m), β = failure-plane angle (degrees from horizontal), α = bank angle (degrees from horizontal), ϕ' = angle of internal friction (°), and I = the number of layers.

The cantilever shear failure algorithm is a further development of the method employed in the CONCEPTS model (Langendoen, 2000). BSTEM can utilize the different failure algorithms depending on the geometry and conditions of the bank. Determining whether a failure is planar or cantilever is based on whether there is undercutting and then comparing the factor of safety values. The failure mode is automatically determined by the smaller of the two values. The model is easily adapted to incorporate the effects of geotextiles or other bank stabilization measures that affect soil strength. This current version (5.3) of the model assumes hydrostatic conditions below the water table. Matric suction above the water table (negative pore-water pressure) is calculated by linear interpolation.

Root Reinforcement (RipRoot) Sub-Model Waldron (1977) extended the Coulomb equation for root-permeated soils, by assuming that all roots extended vertically across a horizontal shearing zone, and that the roots act like laterally loaded piles, with tension transferred to them as the soil is sheared. In the Waldron (1977) model, the tension developed in the root as the soil is sheared is resolved into a tangential component resisting shear and a normal component increasing the confining pressure on the shear plane. ΔS can be represented by:

$$\Delta S = T_r\,(\sin\,\theta + \cos\,\theta \tan\,\phi)\,(A_R/A) \qquad (6)$$

where T_r is the average tensile strength of roots per unit area of soil (kPa), $A_R\,/A$ is the root area ratio (dimensionless), and θ is the angle of shear distortion in the shear zone.

Gray (1974) reported that the angle of internal friction of the soil appeared to be affected little by the presence of roots. Sensitivity analyses carried out by Wu et al. (1979) showed that the value of the first angle term in equation 6 is fairly insensitive to normal variations in θ and ϕ (40-90°, and 25-40°, respectively) with values ranging from 1.0 to 1.3. A value of 1.2 was therefore selected by Wu et al. (1979) to replace the angle term and the simplified equation becomes:

$$\Delta S = 1.2\ T_r\ (A_R\,/A) \qquad (7)$$

According to the simple perpendicular root model of Wu *et al.* (1979), the magnitude of reinforcement simply depends on the amount and strength of roots present in the soil. However, Pollen *et al.* (2004) and Pollen and Simon (2005), found that these perpendicular root models tend to overestimate root-reinforcement due to the inherent assumption that the full tensile strength of each root is mobilized during soil shearing, and that the roots all break simultaneously. This overestimation was largely corrected by Pollen and Simon (2005) by constructing a fiber-bundle model (RipRoot) to account for progressive breaking during mass failure. Validation of RipRoot versus the perpendicular model of Wu *et al*. (1979) was carried out by comparing results of root-permeated and non-root-permeated direct-shear tests. The direct-shear tests revealed that accuracy was improved by an order of magnitude by using RipRoot estimates (Pollen and Simon, 2005; Mickovski et al., 2009).

A further paper by Pollen (2007) investigated the forces required to pull out roots in a field study, and the RipRoot model was modified to account for both root-failure mechanisms. The addition of pullout forces allowed for estimations of spatial variability in root-reinforcement with changes in soil texture, and temporal changes with changes in soil water. In the RipRoot model currently embedded in BSTEM 5.3, a vegetation assemblage can be created by accessing the species database contained in the sub model; the user enters species, approximate vegetation ages, and approximate percent cover of each species at each site to estimate root density. This database includes tests performed across the United States. Root-reinforcement values are then calculated automatically using RipRoot's progressive breaking algorithm.

METHODS

Using BSTEM for iterative modeling The selected annual hydrographs for each river were first discretized into a series of steady-state rectangular-shaped discharge events (Figure 1), where the peak of each rectangular hydrograph was set to be 90% of the actual hydrograph peak for each storm event. The reason for this reduction in flow peak for each part of the discretized hydrograph was so that the discretized peaks represented the average value occurring over that time period, with, in reality, some parts of the real hydrograph having lower flows and some having higher flows.

Discharge values for each flow event were then converted to a series of flow depths, based on a stage-discharge relation developed for the closest USGS gage to each site. As water table height information was unavailable for the channels studied, for bank stability modeling purposes it was assumed that water table height equaled flow height at the peak of each hydrograph, with drawdown conditions (receding water level, with high water table) also being modeled. The discretized hydrographs were then iteratively input into BSTEM using the following approach to run the toe erosion and bank stability algorithms in BSTEM:

1. The effects of the first flow event was simulated using the toe-erosion sub model to determine the amount (if any) of hydraulic erosion and the change in geometry in the bank-toe-region.
2. The new geometry was exported into the bank-stability sub-model to test for the relative stability of the bank.
    a. If the Factor of Safety (F_s) was greater than 1.0, geometry was not updated and the next flow event was simulated.
    b. If F_s was less than 1.0, failure was simulated and the resulting failure plane became the geometry of the bank for simulation of toe erosion for the next flow event in the series.
    c. If the next flow event had a stream stage elevation lower than the previous one, the bank-stability sub-model was run again using the new lower stream stage elevation and higher ground water table elevation to test for stability under drawdown conditions. If F_s was less than 1.0, failure was simulated and the new bank geometry was exported into the toe-erosion sub-model for the next flow event.
3. The next flow event in the series was simulated.

Depending on the project needs, iterative model runs were made to represent different flow year conditions: a 99th percentile flow year represented a very wet year and, therefore, potential worst case conditions for erosion, bank failures and suspended sediment loadings. A range of flow years was also modeled in two of the case studies presented herein so that the suspended sediment loadings from an average annual year could be calculated. In addition, BSTEM was run with different mitigation strategies to see how, for example, the effect of placing rock at the bank toe or growing different types of vegetation on the banks, might affect bank stability and sediment delivery to the channel. The following sections outline the results of three studies carried out using iterative runs of BSTEM. The flow years and mitigation strategies modeled varied according to the river system being studied and the project objectives.

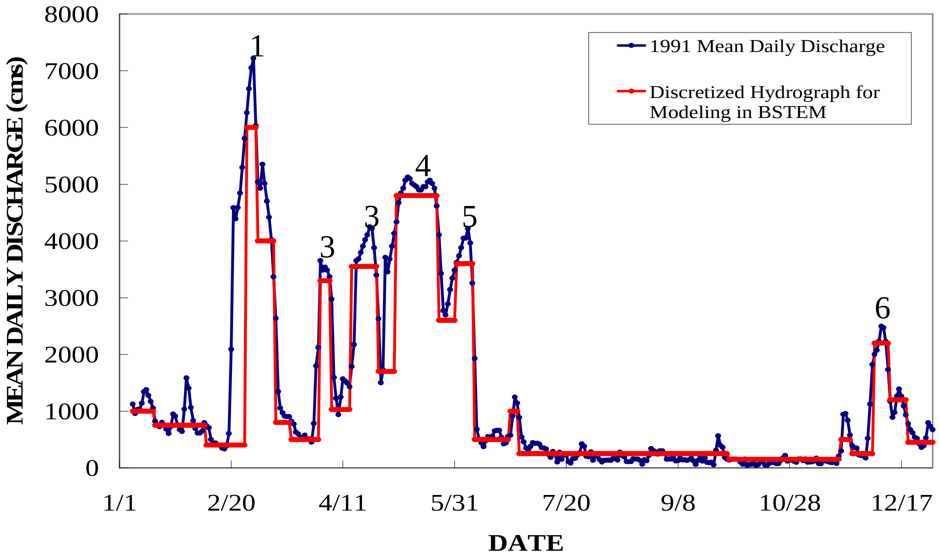

Figure 1 Discretized hydrograph for 90th percentile flow year at Coffeeville Dam, showing the six steady-state, rectangular shaped flow events modeled in BSTEM.

CASE STUDY 1: Lower Tombigbee River, AL: Effects of mitigation strategies modeled for a 90th percentile flow year (Bankhead et al., 2008) Streambank erosion is prevalent along the Lower Tombigbee River, with aerial reconnaissance indicating that more than 50% of all banks along the study reach (RM 72 to 259) have experienced recent bank failures. Associated with this erosion is the loss of land and property. Taking the average widening rate of 1.2m/y over the 29-year period of air-photo analysis and multiplying by the length of the study reach (187 miles; 301 km) provided an estimate of the total land loss over the period. This was equivalent to 1044 hectares, or 2580 acres. Given this considerable amount of land loss from bank instabilities, it was reasonable to investigate potential strategies that could be used to reduce the magnitude and frequency of bank failures along the study each.

As an example, a series of alternative strategies to reduce the magnitude and frequency of bank failures was simulated for the site at RM 114.7. Given that the BSTEM model simulates failures in two dimensions (height and width), a reach length of 100 m was assumed to provide results in m^3. The simulations were conducted in such a way as to be able to quantify the reduction in the frequency of failures and the volume of material delivered to the channel by bank failures. Using mean-daily discharges from a high-flow year (1991; 90^{th} percentile flow year) to represent worst-case flow conditions and a bed slope of 0.000088 m/m, the toe-erosion and bank-stability sub-models were run iteratively for the six major flow events of that year. The iterative modeling was carried out for each of the following four bank conditions:

1. Existing conditions, no mitigation;
2. Rock placement along the bank toe;
3. Rock placement at the bank toe and 5-year old woody vegetation on the bank top; and
4. Rock placement at the bank toe, 5-year old woody vegetation on the bank top, grading the bank to a 45^o (1:1) slope, and 5-year old woody vegetation on the re-graded slope.

For each set of conditions, the total number of bank failures and the volume associated with each failure was summed and then compared to the other alternatives to quantify the effectiveness of each treatment. Overall, this approach proved successful in evaluating the effectiveness of each treatment. For the initial case with existing bank conditions, 11 failures were simulated, resulting in about 55,000 m^3 of eroded bank sediment. Although the number of bank failures was only reduced by one (to 10) for the case with toe protection, the amount of lateral retreat and volume of failed material was drastically reduced (by about 500%) to about 9500 m^3. This was because the toe protection did not allow the bank to be undercut at its base, thereby reducing the size of subsequent failures. The addition of bank-top vegetation provided additional cohesive strength to the top 1.0 m of the bank and resulted in a further reduction of failure frequency (to 8) and failure volume (8500 m^3). This effect would probably be more pronounced if older specimens were simulated because of greater root density and diameters. Alternative 4, which includes rock at the bank toe, grading the bank slope to 1:1 and placing woody vegetation on the bank top and face, greatly reduced failure frequency (to 3) and showed the smallest failure volume of all cases (about 3200 m^3). Results from each of the alternative strategies are shown in graphic form in Figure 2.

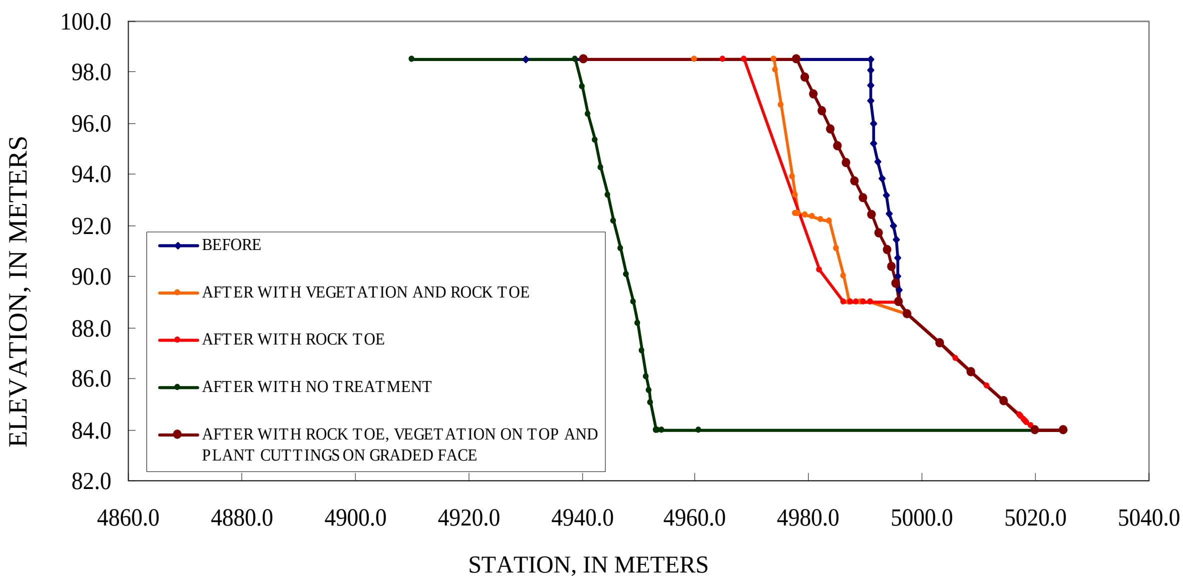

Figure 2 Summary of iterative modeling results for alternative mitigation strategies showing the volume of failures for each bank condition.

Obviously these treatments represent a broad range of options and costs. Recognizing that these findings represent only one site, similar results are expected at other sites within the study reach. It is important to recognize, however, that both the absolute frequency and volume of failures likely represents an overestimate of what actually took place during 1991. This is because once failure is simulated, the model does not account for the fate of this material, which may be deposited at the bank toe, providing a buttressing (stabilizing) effect and serving to build-up the bank toe region. What is relevant is the relative differences between the exiting case (no mitigation) and the various alternatives.

C**ASE STUDY 2: Lake Tahoe: Contribution of suspended sediment from bank erosion during a 99th percentile flow year, possible mitigation strategies, and cost analysis (Simon et al., 2009)** The project objectives in this study were similar to those of the Lower Tombigbee River study, with a 99th percentile flow year being modeled with and without various mitigation strategies. In this case, an additional objective of the study was to calculate the percent contribution of streambank sediment to overall suspended sediment in the streams under investigation. Under existing conditions at a site at rkm 13.1 on the Upper Truckee River, CA, a total of 1288 m^3 of material was predicted to be eroded using iterative BSTEM runs, during 12 periods of hydraulic erosion and 4 mass failure episodes. Toe erosion represented just 7% of the total bank erosion in the reach. The addition of toe protection virtually eliminated bank steepening by hydraulic erosion at the bank toe and total bank erosion was reduced by about 89% to 137 m^3 over the same period. Similar results were obtained for all other paired simulations at additional sites. The finding that load reductions of 87% can be realized with added toe protection highlights the important relation between hydraulic erosion at the toe that steepens bank slopes and subsequent bank instability. Under existing conditions, toe erosion accounted for an average of 13.6% of the total streambank erosion, yet control of that process resulted in a total sediment-load reduction from bank erosion of almost 90%.

To obtain an estimate of the total load reduction that could be anticipated for the entire length of each stream, modeled results were combined with observations of the longitudinal extent of recent bank failures along the main-stem lengths of each stream. Rapid geomorphic assessments (RGAs) that use diagnostic characteristics of channel form to infer dominant active processes were conducted along each stream as part of earlier research (Simon *et al.*, 2003). The longitudinal fraction of banks experiencing recent failures was noted for each bank in a reach (6-20 channel widths in length) and expressed as one of five percentage ranges (0-10%, 11-25%, 26-50%, 51-75%, 76-100%) (Table 1). The midpoint of the range for each bank (left and right) was used to determine a local mean failure extent. This was then classified as low, moderate or high in order to apply different unit loads along each stream. Unit loads associated with each class were selected by comparing bank-derived sediment volumes estimated by the numerical simulations with the results of RGAs. For reaches classified as low, a load an order of magnitude lower than the moderate value was used. Unit loads were multiplied by a weighting factor representing the total length of banks (left and right) that had recently failed in a reach to obtain total streambank-derived sediment loads for the stream. The average extent of bank failures (in percent) was then broken into low, medium and high groupings to apply different unit loading rates along each stream according to the following procedure. Loadings were calculated for each reach by applying the appropriate total loading rate (high or moderate) to those classed as high or moderate. For reaches classified as low, a value an order of magnitude lower than the moderate rate was used. Fine-grained loadings for each reach were calculated using the measured percentage of fines (<0.063mm) for the site. Table 1 shows a worked example for Blackwood Creek.

To address the cost of potential management scenarios for fine-grained load reduction by toe protection, three options were considered which included treating all reaches (All), treating only those reaches eroding at high rates (H), and treating only those reaches eroding at high and moderate rates (H+M) (Table 2). A cost for rock placement of $984 per meter was used as the cost basis (obtained from local sources) that was then multiplied by the length of reach represented by each treatment option. A median load reduction of 86.8% was used to determine the cost per metric tonne of load reduction. Total load reductions ranged from 33% to 87% depending on the treatment option (length treated). The unit cost (in $/T) of performing this type of rehabilitation similarly varied from $267/T to almost $2,500/T (Table 2).

Table 1 Example calculation of total-streambank loads for Blackwood Creek. Results of RGAs (columns 2 to 3) permitted a mean percentage of each reach experiencing bank failures to be estimated. The mean of consecutive failure extents was multiplied by the reach length to estimate the weighting factor. Fine-grained loads were determined by multiplying the fraction of fines in each reach by the estimated total load. Color coding refers to high (36,170 m^3/km), moderate (4,720 m^3/km) and low (472 m^3/km) streambank-derived unit loads.

Distance (km)	Extent of failures (%)			Reach length (km)	Reach failing (%)	Weighting factor	Total volume (m^3)	Fraction <0.063 mm (%)	Fines volume (m^3)
	Left	Right	Mean	1	2	(1)*(2)/100			
8.29	0-10	0-10	5.0	-	-	-	-	-	-
8.19	0-10	26-50	21.5	0.10	13.25	0.0133	62.5	5.8	3.6
7.69	11-25	11-25	18.0	0.50	19.75	0.0987	46.6	0.00	0.00
7.18	11-25	11-25	18.0	0.51	18	0.0918	43.3	26.0	11.3
7.17	11-25	76-100	53.0	0.01	35.5	0.0035	128	26.0	33.4
6.84	0-10	11-25	11.5	0.33	32.25	0.1064	50.2	26.6	13.4
6.51	0-10	51-75	34.0	0.33	22.75	0.0751	354	22.1	78.3
6.03	0-10	26-50	21.5	0.48	27.75	0.1332	629	20.0	125.7
5.55	0-10	26-50	21.5	0.48	21.5	0.1032	487	7.9	38.5
5.08	0-10	51-75	34.0	0.47	27.75	0.1304	616	23.5	144.7
4.15	26-50	11-25	25.5	0.93	29.75	0.2767	1306	3.6	47.0
3.95	0-10	76-100	46.5	0.20	36	0.0720	2604	21.4	557.3
2.80	51-75	0-10	34.0	1.15	40.25	0.4629	2185	12.3	268.7
1.97	26-50	11-25	25.5	0.83	29.75	0.2469	1165	24.8	289
1.77	11-25	51-75	40.5	0.20	33	0.0660	2387	16.6	396.3

Table 2 Loads and costs for performing bank-toe protection assuming a unit cost of $984/m for placement of stone at the bank toe. H+M refers to reaches designated as high and moderate.

Stream	**Loads (T)**				**Total Cost ($)**			**Unit Cost ($/T of Load Reduction)**		
	Existing	**Toe Protection**			**Toe Protection**					
		All	**H + M**	**H**	**All**	**H + M**	**H**	**All**	**H + M**	**H**
Blackwood Creek	4432	585	623	2920	8,159,449	6,840,551	403,543	2,121	1,796	267
Load reduction (%)		**86.8**	**85.9**	**34.1**						
Upper Truckee River	5691	751	914	3789	20,911,417	10,735,138	2,601,378	4,233	2,247	1,368
Load reduction (%)		**86.8**	**83.9**	**33.4**						
Ward Creek	2956	390	451	910	6,358,661	3,120,669	1,731,594	2,478	1,246	846
Load reduction (%)		**86.8**	**84.7**	**69.2**						
Totals	**13079**				**35,429,527**	**20,696,358**	**4,736,515**			

CASE STUDY 3: Big Sioux River, SD: Contribution of suspended sediment from bank erosion during different percentile flow years, an average annual year, and possible mitigation strategies (Bankhead and Simon, 2009) Similar to the Lake Tahoe study discussed in case study 2, the objective of this study was also to determine rates and loadings of sediment from streambank erosion along the study reach, and to determine the effects of possible mitigation strategies where necessary. In this case, however, a series of flow years ranging from a very wet year (90th percentile flow year) to a very dry year (10th percentile flow year) were modeled. The volumes of sediment eroded during each percentile flow year modeled were then weighted so that the suspended sediment volume emanating from the banks during an average annual year could be estimated. Results were extrapolated spatially for the entire study reach, and then validated against suspended sediment gage data available from USGS gages along the study reach.

Bank stability and toe erosion analysis were carried out using the model BSTEM, at five study sites along the study reach, for a range of percentile flow years (90th, 75th, 50th, 25th and 10th). These model results showed that predicted eroded volumes of sediment emanating from streambanks decreased non-linearly from the 90th percentile flow year to the 10th percentile flow year. Predicted volumes of sediment eroded from the streambanks at each site ranged from 169 to 1359 m^3 of sediment per 100 m reach during the 90th percentile year, under existing conditions where the banks have a cover of native grasses. These volumes of eroded sediment were predicted to fall to 0 to 21 m^3 per 100-m reach during the modeled 10th percentile flow year, again, assuming a cover of native grasses. Bank failures were generally only predicted to occur during the 90th percentile flow year modeled at each site, indicating that during lower percentile flow years, hydraulic scour at the bank toe was the predominant erosion process, rather than mass wasting of the banks by geotechnical failure. It therefore followed that the addition of toe protection (up to 1m) to banks with existing native grass cover greatly reduced the volume of bank material predicted to erode at each site during an average annual flow year (calculated by appropriately weighting the loadings from each percentile flow year). This reduction was a result of the protection of the base of the banks from hydraulic scour and thus over-steepening (Figure 3). Model runs indicated that even when the contribution to total erosion from toe scour was not that great (for example, only 16 to 50% of total erosion came from toe scour during years where bank failures did occur), if the toe scour was prevented, the overall volume of eroded bank material was reduced by 87 – 100%.

Contributions of sediment from streambank erosion along the study reach of the Big Sioux River were found to be in the range of 10 – 25% of the total suspended-sediment load. Average, annual contributions of sediment from streambank erosion for the entire study reach (6,340 T) were shown to be about 15%. During a particularly wet, high-flow year as occurred in 1994, streambank contributions were consequently greater (27,000 T), comprising 25% of the total suspended-sediment load over the 300 km study reach. The data further indicated that streambank contributions were generally greater in the lower half of reach than average, annual bank contributions upstream of Brookings and at the 90th percentile flow were about 16% and 10%, respectively.

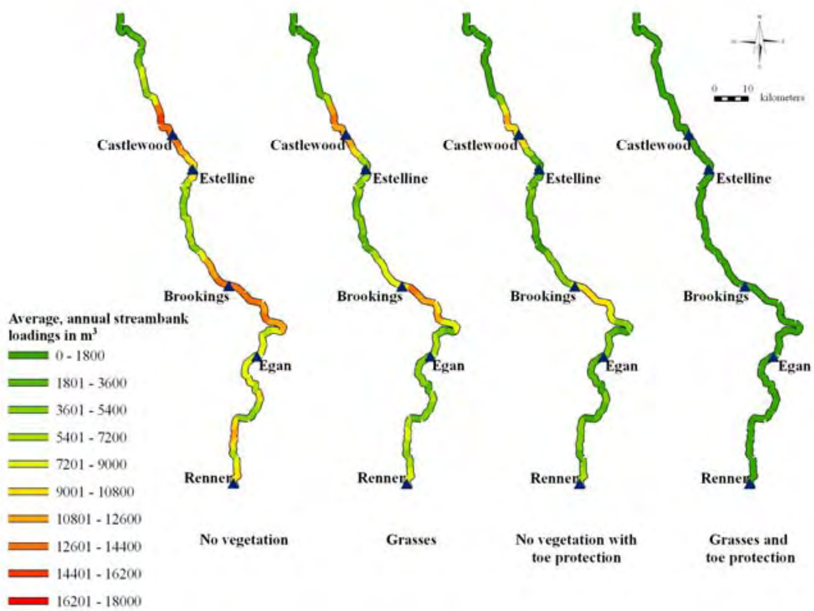

Figure 3 Spatial illustration of average annual streambank loadings (m^3), for a range of mitigation strategies and bank conditions.

The final part of the study on the Big Sioux investigated the effect of extrapolating the iterative modeling results over the 300 km length of the study reach, for the mitigation strategies tested. As expected, the bare-bank simulations displayed greater average, annual loadings along the entire study reach, with total loadings of 503,000 m^3 (8,810 T). The effect of top-bank grasses (or an assemblage of grasses and young cottonwood trees) was a reduction in average, annual streambank loadings of 28% (to 362,000 m^3 or 6,340 T); 20% for the 90th percentile flow. The addition of bank-toe protection to the grassed bank resulted in a total reduction in average, annual loadings (from the bare-bank case) of 97% (to 15,200 m^3 or 267 T). The important role of toe protection was further apparent by comparing the difference in streambank loadings between the bare-bank case and the mitigation strategy that incorporated toe protection alone. Here, average, annual streambank loadings were reduced 51% from 503,000 m^3 (8,810 T) to 243,000 m^3 (4,250 T); 84% for the 90^{th} percentile flow. Results of potential mitigation strategies can also be shown spatially (Figure 3). Maps such as those in Figure 3 can be used to illustrate that different mitigation strategies may be suitable for different parts of a reach. For example, in some of the yellow reaches in the map with no vegetation or mitigation, addition of grasses to the bank top may provide enough stability to reduce sediment loading to the required level in that particular reach. In the reaches that are shown in red in the first map, addition of vegetation may not be sufficient, with those reaches also requiring further mitigation, such as rock toe protection, to reduce bank erosion and resulting suspended sediment loadings.

CONCLUSIONS

Overall, the iterative use of BSTEM 5.3 over a series of hydrographs proved to be successful in evaluating toe erosion and bank failure frequency and thus the volume of sediment eroded from a bank over a given period of time. In addition, the model has been shown to be very useful in testing the effect of potential mitigation measures that might be used to reduce the frequency of bank instability and decrease sediment loadings emanating from streambanks. Finally, the results of iterative BSTEM analysis can be used to spatially extrapolate bank-derived volumes of sediment, from individual sites to entire reaches when used in conjunction with Rapid Geomorphic Analyses (RGA's) conducted at regular intervals along the study reach. Results of these three case studies have shown that the relative contribution of suspended sediment from streambanks can vary considerably, ranging from as low as 12 % in the predominantly low gradient, agricultural watershed of the Big Sioux River, SD to as high as 47 % on the steep forested watershed of Ward Creek, CA. Modeling of streambank mitigation strategies has also shown that the addition of toe protection to eroding streambanks can reduce overall volumes of eroded sediment up to 85-100 %, notwithstanding that hydraulic erosion of the toe makes up only 15-20% of total bank erosion. Vegetation also provided a stabilizing effect to the streambanks modeled, but sufficient time must be factored into any restoration design involving vegetation as a mitigation measure, to allow sufficient development of root networks.

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