A PRACTICAL METHOD OF COMPUTING STREAMBANK EROSION RATE

By

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Abstract: Accelerated streambank erosion is a major cause of non-point source pollution associated with increased sediment supply. A quantitative prediction of streambank erosion rate provides a tool to apportion sediment contribution of streambank sediment source to the total load transported by a river. A method for developing quantitative prediction of streambank erosion rates and examples of its implementation are presented. The prediction model presented utilizes a rational estimation, process-integration approach. A streambank erodibility index and calculated near-bank stresses are utilized in the prediction model. Streambank characteristics involving measurements of bank heights, angles, materials, presence of layers, rooting depth, rooting density and per cent of bank protection, are used to develop the streambank erodibility index. Measured data are converted to a normalization index for application for a wide range of channel sizes and types. Near-bank stress requires calculation of vertical velocity profiles and shear stress for subsequent distribution of energy calculations in the near-bank region.

The measured field values, converted to prediction indices, were tested against measured annual streambank erosion rates. The results of an analysis of variance performed on two independent data sets from two varied hydro-physiographic regions indicated a highly significant relation. Application in regions other than those used to develop the relations are also presented.

Applications in river and riparian management, stream channel stability analysis, streambank stabilization programs, river restoration, and sediment studies are presented. This model was also used to compare geologic erosion with anthropogenic sources and the consequence of riparian vegetation changes on streambank erosion rates. The model has particular advantages when used for stream channel stability departure analysis and sediment TMDL's.

INTRODUCTION

The significance of streambank erosion processes that contribute sediment to the total annual sediment transport has often been overlooked or misunderstood. Most studies on sediment supply have been directed to surface erosion processes, which in many disturbed landscapes are the major sediment sources. Streambank erosion contributions were shown to be the majority of total sediment supply in the West Fork Madison River, Montana (Rosgen, 1973, 1976). Restoration work and subsequent bedload and suspended sediment measurements conducted by the author on the East Fork River, Colorado has shown that three miles of unstable, braided channel was contributing 49% of the total sediment yield of a 140 km^2 watershed. This study involved the comparison of total sediment yield measurements upstream versus downstream due to streambank erosion acceleration from willow removal. More recent studies in the loess area of the Midwest United States, indicated that streambank material contributed as much as 80% of the total sediment load eroded from incised channels (Simon et al, 1996). Streambank erosion varies from 1.5 m/yr on the Obion/Forked Deer drainages in West Tennessee (Simon, 1989), to 14 m/yr in the Cimmaron River in Kansas (Schumm and Lichty, 1963), 50 m/yr. In the Gila River, Arizona 100 m/yr on some reaches of the Toutle River, Washington (Simon, 1992). Recent programs by several Federal agencies including the Natural Resources Conservation Service and U.S. Fish and Wildlife Service, have been providing financial assistance to private landowners for riparian management and protection in an effort to; decrease bank erosion rates, reduce downstream impacts associated with increased sediment supply, help aquatic and terrestrial habitats and protect land from erosion.

The adverse consequence of increased streambank erosion results not only in accelerated sediment yields, but also to changes in stream channel instability and associated stream type changes. Stream types can evolve in over a wide range of scenarios from meandering to braided, to incised channels due to various processes (see evolution scenarios Rosgen, 2001 In Press, Interagency Sediment Conf.). These instabilities and consequential shifts in stream type not only produce higher sediment yields, but can degrade the physical and biological function of rivers.

PRINCIPLES

Streambank erosion can be traced to two major factors: stream bank characteristics (erodibility potential) and hydraulic/gravitational forces. The predominant processes of stream bank erosion include: surface erosion, mass failure (planar and rotational), fluvial entrainment (particle detachment by flowing water, generally at the bank toe), freeze-thaw, dry ravel, ice scour, liquifaction/collapse, positive pore water pressure, both saturated and unsaturated failures and soil piping. Hydraulic and gravitational forces occur within the soil mantle as well as within the water column of the stream itself. The velocity, velocity gradients, boundary shear stress, strong down-welling and up-welling currents in the near-bank region, back-eddy circulation and other flow mechanics also affect rates of erosion. Extensive research has been underway for some time dealing with failure types and mechanics and factor of safety calculations. Recent streambank mechanics and streambank stability analysis prediction has been published by Thorne (1982), Simon and Thorne, (1996), Darby and Thorne (1997), Thorne, (1999) and Simon, et al (1999). These process research studies need to be continued for us to better understand the complexities involved. The complexity of the quantitative consequence of each individual physical processes of erosion, however, has precluded reliable streambank erosion rate prediction.

GENERAL METHOD

This empirically derived, process-integrated-streambank erosion prediction model requires field practitioners to integrate rather than isolate individual streambank erosion processes. Streambank characteristics (susceptibility to detachment/collapse) were identified separate from near-bank velocity gradients and shear stress in the model. Erodibility and near-bank stress relations were established between measured field variables that were sensitive to a wide range of erosional processes. Numerical values were converted from the field measurements to a scaling factor of risk ratings. In addition to the streambank erodibility factors, measured vertical velocity profiles were obtained on numerous sites in order to evaluate velocity gradients and shear stress in the near-bank region. To test these relations, direct measurements of annual erosion rates were obtained using bank pins and bank profiles, compared with the field variables used to develop the indices of bank erosion hazard index (BEHI) and near-bank stress (NBS). Two separate hydro-physiographic regions were selected for independent study: the Lamar Basin in Yellowstone National Park, Montana and the Front Range of Colorado on the USDA Forest Service, Arapaho and /Roosevelt and Pike/San Isabel National Forests. These studies were carried out in 1987 and 1988 with the assistance of Park Service and USDA Forest Service personnel. Prior to snowmelt and stormflow runoff, erosion study sites were established for a wide range of BEHI and NBS ratings, then re-surveyed the following year. Relations were empirically derived between BEHI, NBS and measured annual streambank erosion rates. An analysis of variance was performed on each of the two regional, independent data sets to obtain levels of significance and coefficients of determination of predicted versus actual annual bank erosion rate. The model was tested in other regions for validation and subsequent potential applications by field practitioners.

MODEL DEVELOPMENT

Stream Bank Characteristics. Key streambank characteristics were identified that would be sensitive to the various processes of erosion in order to develop the BEHI rating. These streambank variables included: bank height ratio (stream bank height/maximum bankfull depth), ratio of rooting depth/bank height, rooting density, per cent surface area of bank protected, bank angle, number and location of various soil composition layers or lenses in the bank, and bank material composition. An expert system was used to transfer field observations of potential erodibility to relative ratings (Figure 1). Field experience from direct observations of streambank instability was used to document streambank conditions associated with active erosion and various modes of failures. The field measured variables assembled as predictors of erodibility (BEHI) were converted to a risk rating of 1-10 (10 being the highest level of risk). The risk ratings from 1 to 10 indicate corresponding adjective values of risk of very low, low, moderate, high, very high, and extreme potential erodibility (Figure 1). The total points obtained as converted from the measured bank variables to risk ratings are shown in Table 1. These relationships were established based on a catalog of field observations as opposed to a factor of safety analysis as described by Thorne (1999) and Simon, et.al. (1999). Since these factor of safety analyses were not related to measured erosion, the process-integration approach was used as an alternative to provide a linkage for the field practitioner to estimate annual bank erosion rate.

Near-bank velocity gradient and shear stress distribution. At selected measured stream bank erosion study sites, vertical velocity profiles, corresponding velocity isovels and velocity gradients were obtained. Velocity isovels are shown in Leopold et al (1964) and Rosgen (1996). The stream width was divided into thirds to apportion the shear stress in the near-bank (one third width) region compared to bankfull shear stress of the entire channel. Calculations of both velocity gradient and near-bank shear stress (ratio of near-bank shear stress/bankfull shear stress) were obtained. These measured velocity gradients and near bank stress values were then converted to a risk rating system from very low to extreme stress (Table 2).

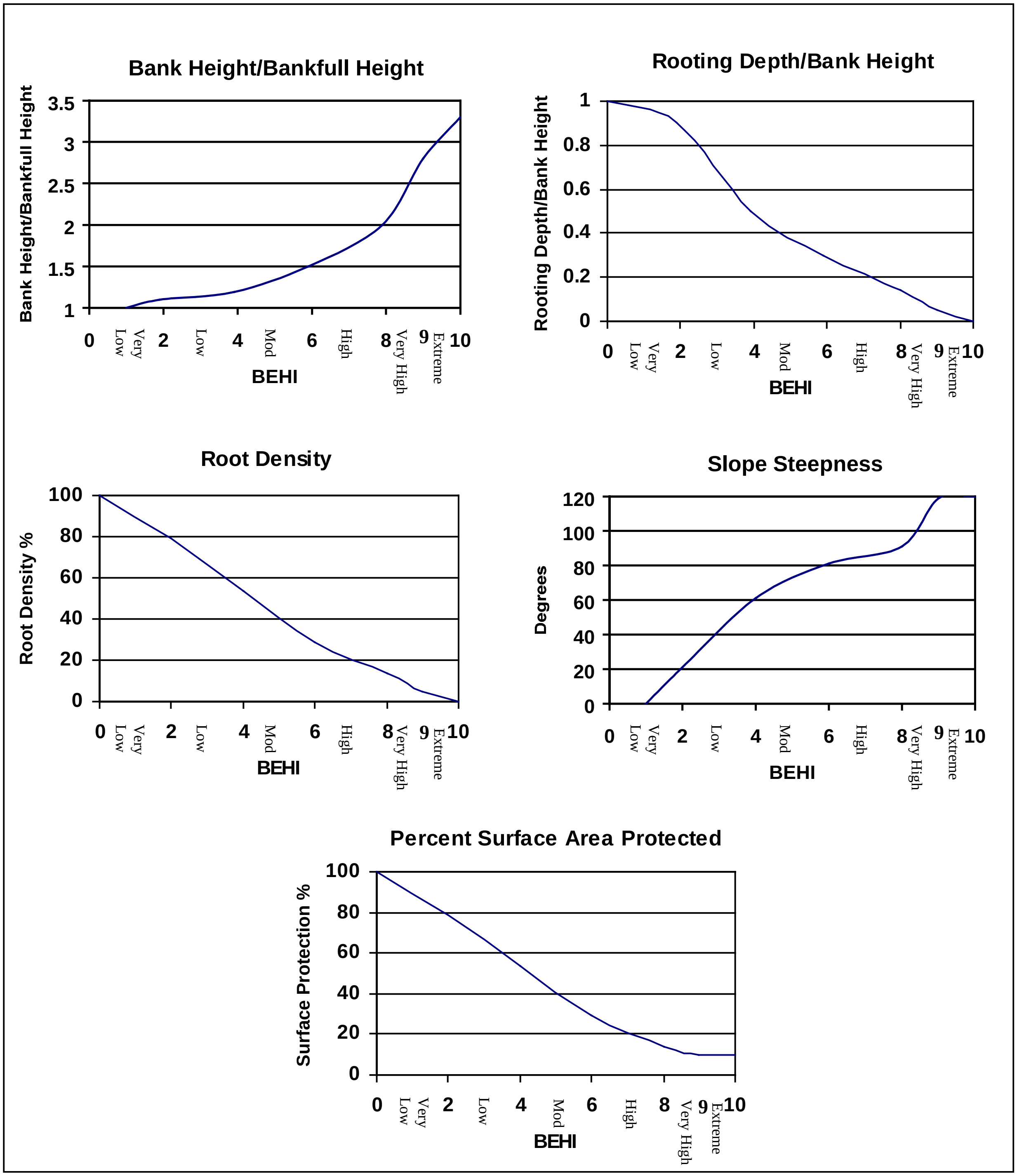


Figure 1. Example of streambank erodibilility variables in relation to the Bank Erosion Hazard Index (BEHI)

Table 1. Streambank characteristics used to develop Bank erosion Hazard Index (BEHI)

Adjective Hazard or risk rating categories		Bank Height/ Bankfull Ht	Root Depth/ Bank Height	Root Density %	Bank Angle (Degrees)	Surface Protection%	Totals
VERY LOW	Value	1.0-1.1	1.0-0.9	100-80	0-20	100-80	
	Index	1.0-1.9	1.0-1.9	1.0-1.9	1.0-1.9	1.0-1.9	5-9.5
LOW	Value	1.11-1.19	0.89-0.5	79-55	21-60	79-55	
	Index	2.0-3.9	2.0-3.9	2.0-3.9	2.0-3.9	2.0-3.9	10-19.5
MODERATE	Value	1.2-1.5	0.49-0.3	54-30	61-80	54-30	
	Index	4.0-5.9	4.0-5.9	4.0-5.9	4.0-5.9	4.0-5.9	20-29.5
HIGH	Value	1.6-2.0	0.29-0.15	29-15	81-90	29-15	
	Index	6.0-7.9	6.0-7.9	6.0-7.9	6.0-7.9	6.0-7.9	30-39.5
VERY HIGH	Value	2.1-2.8	0.14-0.05	14-5.0	91-119	14-10	
	Index	8.0-9.0	8.0-9.0	8.0-9.0	8.0-9.0	8.0-9.0	40-45
EXTREME	Value	>2.8	<0.05	<5	>119	<10	
	Index	10	10	10	10	10	46-50

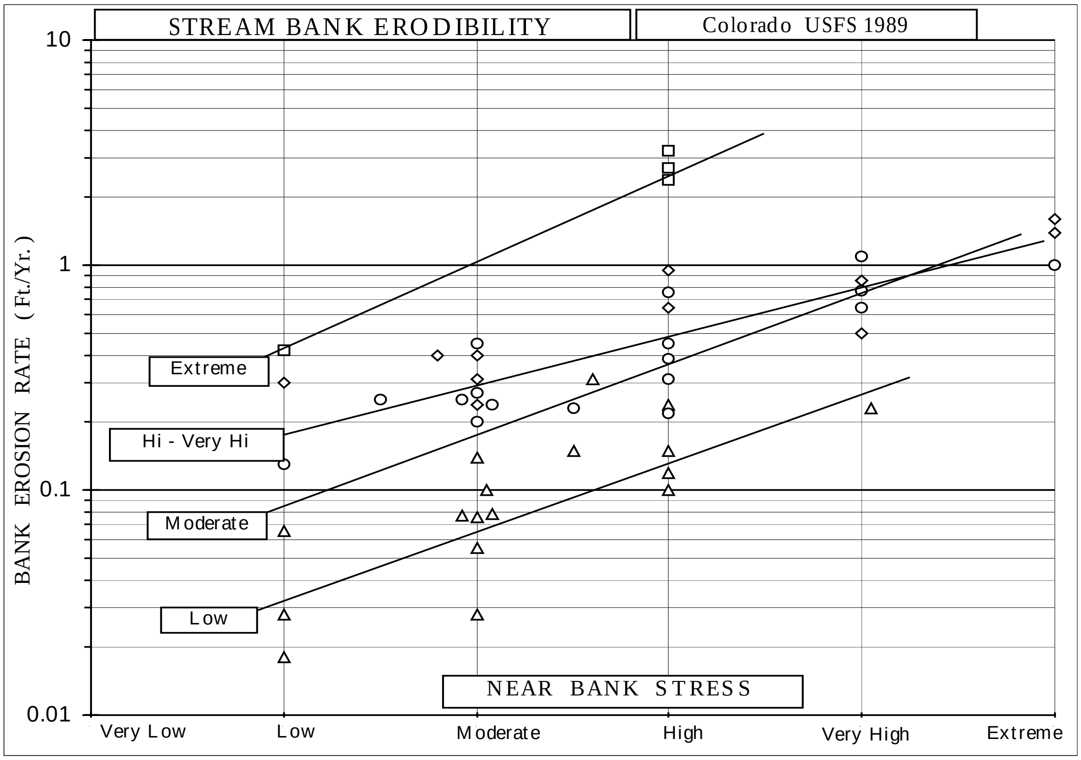
For adjustments in points for specific nature of bank materials and stratification, the following is used:
Bank Materials: Bedrock (very low), Boulders (low), cobble (subtract 10 points unless gravel/sand>50%, then no adjustment), gravel (add 5-10 points depending on % sand), sand (add 10 points), silt/clay (no adjustment).
Stratification: Add 5-10 points depending on the number and position of layers.

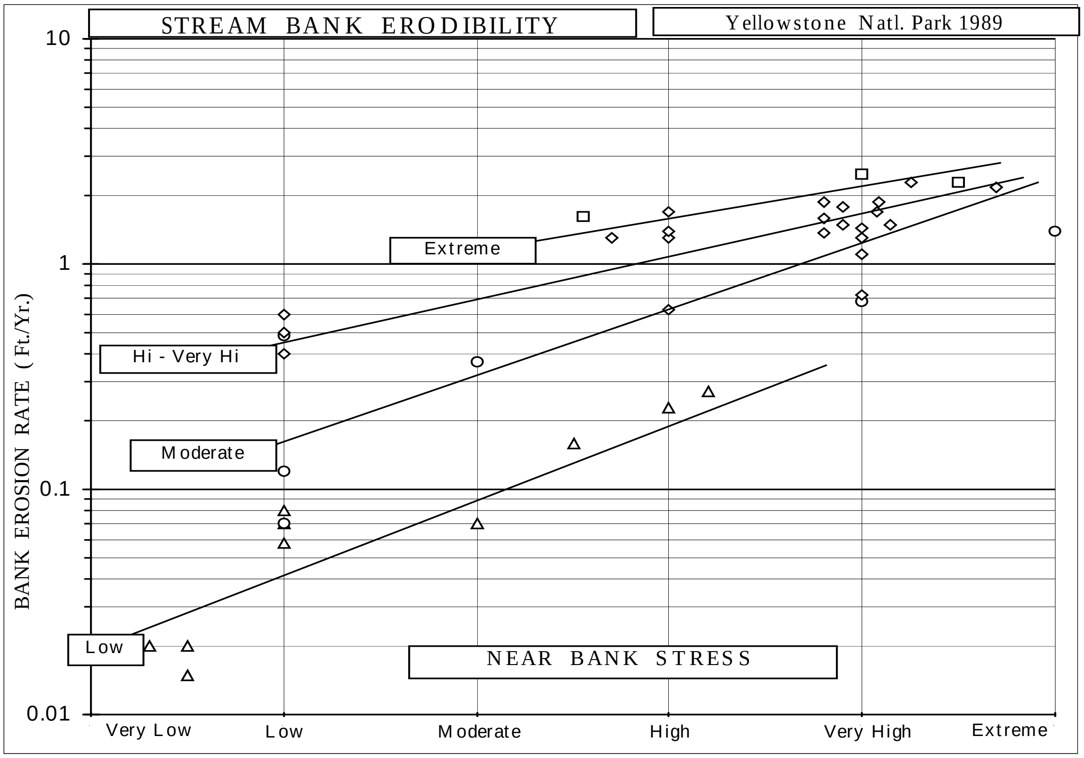
Table 2. Velocity gradient and near-bank stress indices

Bank Erosion Risk Rating	**Velocity gradient**	**Near-bank stress/shear stress**
Very low	Less than 0.5	Less than 0.8
Low	0.5 -1.0	0.8 -1.05
Moderate	1.1 -1.6	1.06 -1.14
High	1.61 - 2.0	1.15 - 1.19
Very High	2.1 -2.4	1.20 -1.60
Extreme	Greater than 2.4	Greater than 1.60

RESULTS

Yellowstone Park, Montana and Front Range Colorado Data. The methods and results presented here to predict annual streambank erosion rate represent an approach different and more quantitative than previous studies. The rate of erosion was measured in distance of bank recession per year. The measured annual, lateral erosion rate for 49 separate sites are plotted for the Front Range Colorado and for 40 sites in the Lamar River Basin Montana, Figure 2 and Figure 3, respectively. An analysis of variance (SAS Users Guide, 1989) was used to assess the relationship between bank erosion hazard index (BEHI) and Near-Bank Stress (NBS) in the prediction of erosion rate There are significant differences in two or more of the means (p=.0001) in both cases for both parameters, thus both BEHI and NBS are highly significant predictors of bank erosion rate. Mean BEHI values for the highest and lowest NBS indices (X axis) were used to locate and plot the four BEHI models for their corresponding erosion rate as shown in Figures 2 and 3. The models plotted in Figure 2 and 3 represent the means derived from analysis of variance and are used to graphically predict bank erosion rate from field level data compilations. "Site" was a significant parameter in the analysis indicating the Montana and Colorado data sets could not be aggregated. Coefficients of determination, or r^2 values were 0.92 and 0.84 for the Colorado and Yellowstone data, respectively. Since the Colorado and Montana data could not be aggregated, it is necessary to empirically develop these relations unique for a given geology. For example, loess soils of the Mid-Western United States would yield much higher erosion rates for the same BEHI and NBS ratings than the curves presented in Figure 2 and Figure 3. Thus, it would require field practitioners to establish the local curves in a similar fashion as was initially completed in Montana and Colorado.


STREAM BANK ERODIBILITY
Colorado USFS 1989
BANK EROSION RATE (Ft./Yr.)
10
1
0.1
0.01
Extreme
Hi - Very Hi
Moderate
Low
NEAR BANK STRESS
Very Low
Low
Moderate
High
Very High
Extreme


STREAM BANK ERODIBILITY
Yellowstone Natl. Park 1989
BANK EROSION RATE (Ft./Yr.)
10
1
0.1
0.01
Extreme
Hi - Very Hi
Moderate
Low
NEAR BANK STRESS
Very Low
Low
Moderate
High
Very High
Extreme

Subsequent Research. The initial results prompted continued research of model prediction to measured annual streambank erosion rates. Research was conducted in North Carolina by the combined efforts of North Carolina State University and personnel of the USDA Natural Resources Conservation Service, (Harmon and Jessup, personal communication, 1999). The results of these studies are shown in Table 3. The data from North Carolina plots quite close to the Colorado data set (Figure 2). This may be due to the similar alluvial composite bank type of their study sites with the Colorado sites.

Table 3. Streambank study results on Mitchell River, North Carolina (Harmon and Jessup, 1999).

Bank Erodibility Hazard (BEHI)	Near-Bank Stress (NBS)	Predicted Streambank Erosion (Colorado curve) m/yr	ft/yr	Observed Streambank Erosion m/yr	ft/yr
Moderate	High	0.12	0.38	0.09	0.30
Moderate	Extreme	0.45	1.5	0.21	0.70
High	Extreme	0.76	2.5	0.85	2.8
Extreme	Extreme	4.27	14.0	3.35	11.0

Research on the Illinois River in Oklahoma (Harmel, et al 1999) found that streambank erosion rate increased as the bank erosion hazard increased. The near-bank stress combined with the streambank erosion prediction indices relationship, however showed a poor correlation. In this study, cross-sectional area ratios were used rather than either near-bank shear stress or velocity gradient. Our studies have shown that either velocity gradients or shear stress ratios predict much better than the cross-sectional area ratio, thus users should not apply the latter for near-bank stress. As a result of the effort by Harmel, et al (1999), we may want to partition this application by soil type. Their poor correlation may be also due to fact that the flows generating the measured erosion rate were four times the bankfull stage. The data presented for the Colorado and Montana data sets are associated with flows at or near the bankfull discharge. Complexities of streambank mechanics and hydraulics during such floods, may create such differential rates of erosion making predictions very difficult.

Streambank erosion studies were conducted in 1998 and 1999 on a C4 stream type reach on the Weminuche River in Southwestern Colorado that had been subjected to poor grazing practices. Predicted values compared to measured values of streambank erosion for various BEHI and NBS ratings using the relations in Figure 2 are shown in Table 4 and summarized in Figure 4. Horizontal placed bank pins and elevation rod readings were taken from the toe pin to profile the bank before and after runoff. Cross-sections are also obtained to determine vertical and horizontal stability changes concurrent with the streambank erosion study. The C4 stream type is associated with a terraced alluvial valley with streambanks composed of a composite mixture of fine alluvium, sand, gravel and cobble. The riparian type is a willow/grass type, with reaches converted to a grass/forb riparian plant community. The research on the Weminuche shows encouraging results that field data collected at low flow utilizing this process-integration model can provide comparable results to measured values.

Selection of representative curves to be used for erosion rate prediction for corresponding BEHI and NBS is based on the river type and materials characteristic of the empirically derived data. For example, the Weminuche River resembles the meandering alluvial stream types in Colorado, thus, Figure 2 was used. However, the studies on the East Fork San Juan River, a D4 (braided channel) mostly resembles the braided river of the Lamar River and tributaries, thus, the relation in Figure 3 was used to predict and compare erosion rate on this D4 stream type.

Table 4. Predicted values versus measured streambank erosion rates for reaches of the Weminuche River, Southwestern Colorado.

Cross-section location	Bank Erosion Hazard Index (BEHI)	Near-Bank Stress (NBS)	Predicted erosion rate m/yr.- (ft./yr.)	Measured erosion rate m/yr.- (ft./yr.)
25 + 62	Very High	Extreme	0.457 - (1.5)	0.481 - (1.58)
27 + 15	Very High	Very high	0.268 - (0.80)	0.335 - (1.1)
40 + 26.5	Very high	Moderate	0.055 - (0.18)	0.064 - (0.21)
41 + 00	Extreme	Moderate	0.335 - (1.1)	0.427 - (1.4)
44 + 25	Low	Very High	0.079 - (0.26)	0.091 - (0.3)

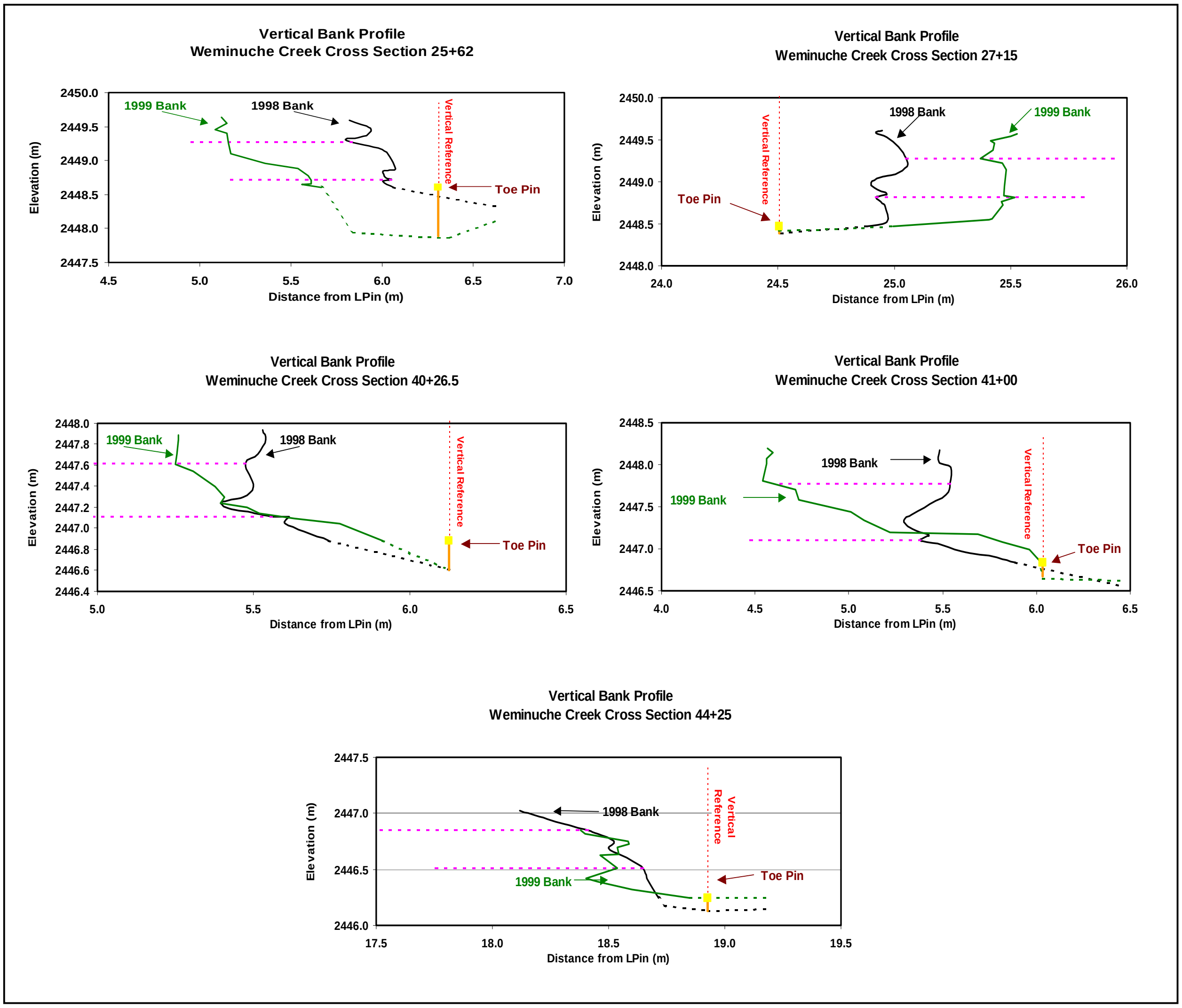


Figure 4. Streambank profiles on the Weminuche River Study – Colorado, showing streambank erosion rate for several locations during one runoff season, (1998-1999). Streamflows included a bankfull event.

A streambank erosion study from 1999-2000 on the braided (D4 stream type), East Fork of the San Juan River in Southwestern Colorado showed close agreement to the relations in Montana (Figure 3) due to the similarity of the braided (D4) stream type and relatively coarse river alluvium. The prediction and subsequent annual measurements were made by advanced level students of the Wildland Hydrology Research Institute and Educational Center for River Studies in Pagosa Springs, Colorado. The results are shown in Table 5.

Table 5. Predicted versus actual measured streambank erosion rates for braided reach of East Fork San Juan River.

Bank Erosion Hazard Index (BEHI)	Near-Bank Stress (NBS)	Predicted Streambank Erosion (Yellowstone)		Measured Streambank Erosion	
		M/year	Ft./year	M/year	Ft./year
Extreme	Extreme	0.85	2.8	0.73	2.40
Extreme	High	0.55	1.8	0.59	1.95
Moderate	High	0.19	0.62	0.22	0.73
Low	High	0.06	0.20	0.06	0.20
High	Low	0.14	0.45	0.12	0.40
High	Low	0.14	0.45	0.14	0.47

APPLICATIONS

A particular need in watershed management is to determine the volume, size and source of sediment. Once a relationship between BEHI and NBS is established with corresponding measured bank erosion rates, inventories of bank conditions along extensive reaches of rivers can be obtained. Potential lateral erosion rates corresponding to BEHI and NBS ratings, multiplied times bank height, times the length of similar conditions can produce volumes/year of sediment introduced to the stream from streambank erosion processes. The size of introduced sediment is also important for predicting channel response. This tool is also useful to provide a rapid inventory to assist in channel stability evaluation, assess priorities for restoration and provide information for riparian habitat management recommendations. Clean sediment TMDL's can also benefit from a quantitative assessment of potential sediment supply from streambank erosion, leading to mitigative measures to reduce accelerated sediment supply from this source.

The potential reduction in streambank erosion can be shown using effectiveness monitoring by designing restoration methods that decrease BEHI and NBS ratings and their corresponding annual erosion rate. Such monitoring as carried out in Southwestern Colorado on Turkey Creek and the Weminuche River respectively involved an upstream/downstream comparison of measured bank retreat rates. Erosion rates showed a reduction from 0.128 m/yr, and 0.55 m/yr. to virtually zero following post-restoration runoff. Natural stable alluvial streams with both BEHI and NBS ratings of very low have negligible rates of erosion. Reductions in tons of sediment/year can provide verification of the effectiveness of reducing sediment supply from restoration efforts in order to satisfy restoration objectives as well as meeting TMDL's established by individual states to comply with the Clean Water Act requirements.

Streambank erosion studies were conducted by the author on Wolf Creek in Southwestern Colorado to determine the results of spraying willows on a C4 stream type (a gravel bed, meandering, low gradient alluvial channel with a well developed floodplain. Accelerated streambank erosion occurred due to a conversion from willow/grass to grass/forb composition and stream channel instability followed, converting a C4 stream type to a D4 stream type (gravel bed, braided channel). The BEHI and NBS ratings on the C4 stream type immediately above the sprayed areas were low/low, respectively. Using Figure 2, the predicted streambank erosion rate of .0091 meters/year (.03 feet/year) was compared to the measured values of .0061 meters/year (.02 ft./year). The sprayed reach immediately downstream that initially was the same C4 stream type had BEHI and NBS ratings of very high/extreme, respectively. The predicted rate of erosion was 0.457 meters/year (1.5 feet/year) compared to the measured rate of 0.597 meters/year (1.96 feet/year). The model closely predicted a nearly three orders of magnitude increase in erosion rate as a consequence of spraying willows that converted the riparian type to a grass/forb plant community. During major floods on this reach 18.3 meters (60 feet) of erosion occurred during a three-year period in the sprayed reach compared to 0.012 meters (.04 feet) in the undisturbed C4 stream reach. The excessive land loss that increased sedimentation could have been prevented if the organization responsible for the spraying would have been able to predict the adverse consequence of streambank erosion, associated channel instability and eventual change in stream type from meandering (C4) to braided (D4).

An application that separated natural geologic erosion rates from anthropogenic helped provide quantitative prediction of the consequence of riparian vegetation change. For example, in the winter range of the Lamar valley in Yellowstone National Park, riparian vegetation composition was changed from a willow/alder/grass community to a grass/forb community due to severe browsing utilization in the winter range by elk and buffalo (Kay, 1990). Streambank erosion rates were measured on a reference reach or "control" upstream of the winter range on the same river, on the same stream type, the same bank stratigraphy and for similar streamflows in the same runoff season. The comparison of the upstream reach (good riparian vegetation condition of willows) compared to downstream reach (poor riparian condition of grass/forbs) indicated an erosion rate increase over geologic by three orders of magnitude. The extent of this accelerated streambank erosion affected many miles of stream and associated stream channel instability in the winter range of the Lamar valley (Rosgen, 1993). As shown in other studies, a conversion of riparian plant community from a predominantly cottonwood/willow to grass/forb on C4 stream types results in several orders of magnitude increase in annual streambank erosion rate. Floods particularly do extensive damage as these streams become "set up" for failure. Conversion of stream type due to the accelerated streambank erosion initiated an evolutionary shift from a C4 (meandering) to D4 (braided) stream type that presently exists within the winter range of the Lamar River and many of its tributaries. These same stream type conversions observed on the

Lamar River have been observed on many other heavily grazed riparian communities, including the East Fork San Juan River, Weminuche River, and Wolf Creek, Colorado.

CONCLUSIONS

The use of this process-integration approach to predict annual streambank erosion associated with normal high flow, shows excellent promise for management. Stratification by geologic and soil types should be accomplished to establish a family of curves for various geologic and hydro-physiographic provinces. Once a quantitative relationship is obtained, mapping changes in the BEHI and NBS ratings can be used to estimate consequence of change in locations beyond where the measured bank erosion data is obtained. Since streambank erosion measurements are very time consuming, extrapolation of these relations can extend the application and effectiveness of river assessments.

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