Development of Regional Bank Erosion Relationships for the Coastal Plain Hydrophysiographic Region

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ABSTRACT

Many streams in Florida, and in the US in general, are impaired due to excessive sediment loading. Erosion of streambanks is a major source of the sediment loading. The sediments have many negative economic and environmental impacts and restoration of streams to mitigate these impacts is a multi-million-dollar industry in the US. Because of the large number of eroding streambanks, insufficient funds are available to restore all impaired streams. Consequently, funding agencies need a method to prioritize streambanks for restoration. Prioritization of streambanks has to be based on observed and expected future erosion rates but future rates are hard to predict because prediction models must be based on multi-year observations and easily applied. Several methods have been developed to predict streambank erosion but the most popular one is the BANCS method. The BANCS method predicts streambank erosion with regression models for various categories of banks based on the near-bank-stress of the streamflow and the erosion potential of the streambank. Because the BANCS method is an empirical model it has to be calibrated for every physiographic region. The present study collected data at 75 sites in the Florida Panhandle and adjacent areas of southern Alabama and Southwest Georgia over a three-year period to calibrate the BANCS method for the coastal plain of the northern Gulf of Mexico. Data were collected in accordance with the standard BANCS method but additional ancillary information to enhance the model were also gathered. Annual streambank erosion rates ranged from 2 mm to 1.97 m over the two-year study period. None of the sites had a bank erosion potential in the very low category, indicating that most streams in the northern Gulf coastal plain are prone to bank erosion. The standard BANCS model is not a good predictor of streambank erosion in the study area: R^2 values of regression models for various BEHI and NBS categories of banks were very low, relationships were sometimes the inverse of what was expected based on an understanding of physical processes involved, and models were statistically not significant. Dimensionalizing NBS method 5 resulted in the best but still moderately effective model. We developed a more robust statistical approach using a nonlinear model, data for additional hydrological and geomorphological parameters, and assessment of the effectiveness of all possible subsets of predictor variables. This approach resulted in a much better predictive model ($R^2 \approx 0.6$ with five predictor variables).

ACKNOWLEDGMENTS

This project would not have been possible without all the hard work from graduate student Mitchell McMillan from the Department of Earth and Environmental Sciences at the University of West Florida. Mitchell not only carried out most of the fieldwork for this project but also greatly contributed to the intellectual development of the research and to this document. He was instrumental in the successful completion of the project. The PIs are greatly indebted to him. This final report is largely based on his thesis (http://www.mitchell-mcmillan.com/thesis/). Two other graduate research assistants, Michele Goodfellow and David Cambron, also provided invaluable assistance. We thank them for their technical skills and good humor in sometimes demanding work conditions. The support of numerous undergraduate and graduate student volunteers is also acknowledged. There are too many to list but we thank every one of them for their contributions to this project. This project was supported by the U.S. Fish and Wildlife Service's State Wildlife Grants program through the Florida Fish and Wildlife Conservation Commission's Florida's Wildlife Legacy Initiative (project title: Development of Regional Bank Erosion Relationships for the Coastal Plain Hydrophysiographic Region; project number: 13058).

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INTRODUCTION

Streambank erosion is the result of fluvial entrainment, mass wasting, and other process that detach and remove sediment from streambanks, causing the net horizontal retreat of banks over time. Streambank erosion is an important geomorphic process related to meander bend migration (Güneralp et al., 2012) and channel widening (Langendoen and Simon, 2008), as well as an ecological necessity for creating riparian habitats and delivering large woody debris to river channels (Florsheim et al., 2008). Currently, many fluvial systems are adjusting to increasingly intense human impacts. Accelerated streambank erosion is now widely recognized as a geomorphic response to human impacts such as grazing (Kemp et al., 2016), deforestation, boat wakes (Gregory, 2006), urbanization (Vietz et al., 2014), and the demise of milldams (Pizzuto and O'Neal, 2009), while local bank stabilization has occurred through the introduction of exotic invasive species (Gregory, 2006). In the Upper Mississippi Valley, for instance, land use changes of the past 200 years resulted in an order of magnitude increase in overbank sedimentation and a corresponding increase in bank heights (Knox, 2006). The more confined, higher energy flows led to accelerated bank erosion and the eventual formation of new inset floodplains. A similar pattern of accelerated bank erosion and channel widening was documented by Hupp and Simon (1991) as a response to channelization and bed degradation in Western Tennessee ca. 1900, with channel morphology reaching a new dynamic equilibrium an average of 50 years after disturbance. In many areas of the U.S., streambanks are eroding laterally into deposits of anthropogenic alluvium (legacy sediments) produced by upland erosion associated with de-forestation and agriculture (Knox, 2006) or by sedimentation behind milldams (Merritts et al., 2011). Many of these banks have become major sources of sediment and nutrients within their fluvial systems.

According to the EPA's 2000 National Water Quality Inventory (USEPA, 2000), sediment pollution is the second leading cause of impairment to U.S. streams. More than 40% of river miles assessed by the EPA were considered impaired (USEPA, 2009), especially by hydromodifications (including streambank destabilization and modification) and habitat alterations (including streambank erosion). In areas where sediment pollution and eroding stream banks coincide, professionals are apt to cite bank erosion as a suspected source of contamination. Field studies have consistently shown that streambank erosion is a significant source of alluvial sediment (Bull, 1997; Evans et al., 2006; Fox et al., 2007) and nutrient loading (Miller et al., 2014; Sekely et al., 2002). Bank erosion can lead to a number of problems, not only by contributing sediment, but by altering channel dimensions as bank area is lost. Bank stabilization, channel reconfiguration, and floodplain reconnection have become major goals of stream restoration in the U.S., with millions of dollars spent on tens of thousands of such projects annually (Bernhardt et al., 2005). Recently, stream restoration efforts have shifted toward headwater streams, especially in urban and agricultural areas, often with a focus on improving water quality (Wohl et al., 2015). Thus, funds allotted to federal, state and county agencies for soil conservation and stream stabilization are often used to implement techniques aimed at curbing lateral erosion.

Due to the potentially widespread and long-lived impacts of accelerated streambank erosion, and the substantial cost and effort required to mitigate those impacts, practitioners are often tasked with rapidly identifying and prioritizing hazardous or destabilized streambanks by considering their annual erosion rates. However, realistically, it is impossible to secure funding for complete restoration of all eroding channels. What is needed is a predictive field-based method for identifying sites that will incur the most rapid erosion and approximately how much sediment will be contributed to the channel. With such a powerful tool for prioritizing restoration sites, more funding could be funneled to high risk sites, resulting in more comprehensive restoration projects.

In the last 10 years, several studies have been conducted correlating observed rates of bank erosion with field-measured erosion potential factors (Harmel et al. 1999; Rosgen 2001; Jennings and Harman 2001; Van Eps et al. 2004; Sass and Keane 2012). Such studies, when carried out in a single hydrophysiograhic region and with similar stream types, can provide professionals a means for rapidly estimating the sediment contribution of eroding banks in that region.

These studies, as well as the present project, implemented the Bank Assessment for Nonpoint Source Consequences of Sediment (BANCS) approach, which is the most common method for predicting the annual erosion rates of any streambank within a hydrophysiographic region (Rosgen, 2001). The BANCS method involves measuring a Bank Erodibility Hazard Index (BEHI) and near-bank shear stress index (NBS) at several study banks, which are then used as independent variables in an empirical statistical model. The model, which is calibrated with erosion rates measured at each study bank, can then be used to directly predict annual erosion rates throughout a given hydrophysiographic region. Applied over a large area, such as a major watershed, BANCS erosion rate predictions have been combined with soil analyses to estimate the bed load, suspended load, and total annual sediment load resulting from streambank erosion (Van Eps et al., 2004).

The BANCS method has been endorsed by several key players in the stream restoration community, including the EPA (USEPA, 2012), the U.S. Forest Service (Yochum, 2015), and the U.S. Fish and Wildlife Service, which conducts field training covering BANCS as part of Rosgen's broader fluvial geomorphology approach, and has become the method of choice for many private firms. In addition, the method has recently received interest from the scientific community (Bandyopadhyay et al., 2013; Kwan and Swanson, 2014; Sass and Keane, 2012), including a discussion of the details of its application (Rosgen, 2015).

Currently, the BANCS method has been calibrated for several regions throughout the U.S. (Figure 1). It has been applied with success in Yellowstone National Park, the Colorado Front Range (Rosgen, 2001), and Sequoia National Forest (Kwan and Swanson, 2014) but basic modifications to the method were necessary to generate a useful model in Northeast Kansas (Sass and Keane, 2012). The varying quality of results is often attributed to differences in geology, geomorphology (Kwan and Swanson, 2014), bank vegetation cover (Sass and Keane, 2012), location within reaches or meander bends (pool vs. riffle) (Rosgen, 2015), hydroclimate (Harmel et al., 1999; Rosgen, 2015), or Rosgen stream types (Rosgen, 2001). In general, all of the aforementioned studies have emphasized the need to develop a predictive model for a single hydrophysiographic region, which is defined or assumed to be homogeneous. Each hydrophysiographic region presents unique characteristics and challenges which must be met when modeling streambank erosion using the BANCS method.

The results published thus far demonstrate a need for modifications to the BANCS method. The core aspect of the method is an empirical relationship in which NBS predicts annual erosion rates, stratified by qualitative BEHI categories. The situation is complicated by considering the various measurements and techniques that constitute the BEHI (which includes 3 components that rely on visual estimation in the field) as well as the 7 methods that can be used to estimate NBS. Sass and Keane (2012) simply replaced visual estimates of root depth and root density with a woody vegetation score, which added 2.5 or 8.5 points to the BEHI based on the presence or absence of riparian trees. This simple modification reflected the observation that banks with woody vegetation eroded approximately 3 times slower than those with herbaceous vegetation alone, and produced a predictive model appropriate for Northeast Kansas. Van Eps et al. (2004) obtained better results when BEHI, instead of NBS, was used as the predictor variable, with the banks stratified by qualitative NBS ratings. Harmel et al. (1999) and Sass and Keane (2012) have suggested including bulk density as a component of BEHI, but to date, no study has investigated the results of such a modification.

The current study aims to develop regional bank erosion curves for the Northeast Gulf Coastal Plain thereby providing local management experts a valuable tool for the speedy prioritization of enhancement and restoration projects and follow-up monitoring of restoration efforts. The goal of our study was to develop a predictive model for streambank erosion rates by measuring erosion and environmental data throughout the study area but in this report we also consider ways to improve the BANCS method. We build on previous BANCS studies as well as established fluvial geomorphology relationships to incorporate relatively simple changes to the method, and show that these changes offer some improvements. These changes were necessitated by challenges presented by our study area and are likely to be of interest to researchers in other regions. Our work represents the most comprehensive attempt to modify the BANCS method to date, and the first attempt to calibrate it in the Northeast Gulf Coastal Plain. We also present an alternative, robust statistical, approach to streambank erosion prediction that has a better predictive capacity in the study area than the BANCS model.

The State Wildlife Action Plan (SWAP) identifies improving or maintaining hydrologic conditions, water quality, or physical habitats for the support of Species of Greatest Conservation Need (SGCN) as the primary goal for freshwater systems. High ranking stresses to stream conditions as outlined by the SWAP include “Nutrient loads-urban”, “Nutrient Loads-Agriculture”, “Altered water quality”, “Erosion/Sedimentation” and “Altered Hydrologic Regime”. This project addresses the conservation actions indicated in the SWAP for Calcareous and Softwater streams by providing a user-friendly tool based on numeric criteria allowing for the rapid assessment of threats and prioritization of areas in need of restoration. Both USFWS and UWF personnel will continue to monitor most of the study sites of this project as part of their future professional and educational efforts and thus, this project will continue to serve the purpose of the grant program after its formal completion in 2016.

STUDY AREA

The study area of this project is located in the Northeast portion of the Gulf Coastal Plain (NEGCP) physiographic province and coincides with the Florida Panhandle west of Tallahassee and adjacent parts of Alabama and Georgia. The NEGCP, which lies between the Gulf of Mexico and the Appalachian fall line and roughly between Mobile, AL, and Tallahassee, FL, is characterized by broad fluvial valleys with low topographic relief (Figure 2). The study area coincides with the Northwest Florida Coastal Plain hydrophysiographic region, which is distinguished by precipitation, runoff, soil, and drainage density characteristics, and includes areas in southern Alabama and Southwest Georgia (Metcalf et al., 2009).

Near-surface geology is predominately Miocene–Pleistocene siliciclastics and unconsolidated alluvium, with the Plio-Pleistocene Citronelle formation making up most of the surficial geology of the study area, and Holocene deposits confined mainly to coastal areas and active floodplains (Scott, 2001). Precipitation averages 52–64 in. annually (1300–1600 mm/yr) and the land cover, which was cleared of its native longleaf pine forest cover by 1900, is now largely mixed forest, cropland, and pasture, with major urban centers concentrated along the Gulf Coast (Homer et al., 2015). Riparian corridors are largely wetlands, and a riparian buffer of at least 95 ft. (29 m) has been nominally enforced since 1977 (Clean Water Act). Fluvial drainage networks are dendritic, except in notable areas in Okaloosa County (Schumm et al., 1995), and near the Apalachicola River in Gadsden and Liberty Counties (Abrams et al., 2009; Petroff et al., 2011, 2012), where prominent sapping channels have formed trellis networks due to surficial sediments composed of highly permeable quartz sand, which limits the production of runoff.

In contrast to many previous applications of the BANCS method, which were confined to a single watershed, our study area encompasses several major watersheds. All of the watersheds in the study area ultimately drain into the Gulf of Mexico through the Perdido, Escambia, Blackwater, Chipola, Chocktawhatchee, Appalachicola, or Ochlockonee Rivers

METHODS

Methods for objective 1: Identify 75 study sites with various degrees of bank erosion in priority basins in the study area.

This objective was achieved by considering study sites in available reports and previous studies by the PIs and through new observations. We consulted online and hardcopy maps to identify meanderings streams throughout the study area. We visited a large number (>200) of these streams because their degree of bank erosion could only be determined in the field given the small size of many of the streams. We selected 75 streams so as to have a good geographic distribution and a maximum range of bank erosion rates. Study banks were restricted to wadeable streams. Bank locations were surveyed to a horizontal accuracy of <10m using a Trimble Juno Series 3 GPS receiver and were marked with permanent rebar stakes. Location of the study sites is shown in figure 2.

Methods for objective 2: Determine BEHI, NBS, and actual bank erosion annually at each study site.

For this objective we closely followed methods described in Rosgen (1996, 2001) and USEPA (2012) for the BANCS approach. At the core of the BANCS approach is an empirical model that predicts annual streambank erosion rates with a bank erodibility hazard index (BEHI) and near-bank shear stress index (NBS) as independent variables. Actual bank erosion during the two-year study period was measured at each study bank using repeated vertical profiles and erosion pins (Lawler, 1993). Bank profiles were measured from a plumb stadia rod at a vertical interval of 5 cm - 25 cm, depending on bank height, and also at major slope breaks. Subsequent profiles were measured using the same vertical positions. Each bank was surveyed twice: first during the 2014 water year and again during the 2016 water year, approximately 24 months later. Average annual erosion rate (cm/yr) was calculated by dividing the area between the initial and final profiles by bank height and dividing the result by 2 years. During the initial survey, three erosion pins 6 mm in diameter were also driven flush into each bank to a depth of approx. 91 cm. For comparison, annual erosion rate was also calculated as the average length of erosion pins exposed during the final survey divided by 2 years. Covered pins were recorded and used as negative values in calculations (Couper et al., 2002). All calculations were performed in Matlab.

The BEHI rating system was designed by Rosgen to describe bank erosion potential as one of six risk categories, ranging from very low to extreme. The BEHI rating of a stream bank is determined by the individual scores for five risk factors known to affect bank stability (Table 1). Bank angle was measured in the field with a clinometer (>90° for undercut banks). Root depth ratio, root volume density, and surface protection were estimated visually. Bankfull channel dimensions were determined by surveying a monumented cross-section at each study bank (Lawler, 1993). Bankfull height was estimated in the field using bankfull indicators commonly used in the study area, such as active floodplains, bank-tops, point bars, or consistent depositional surfaces found within the channel ("flats") (Metcalf et al., 2009). If no bankfull indicators were observed in the field, bankfull dimensions were modeled using hydraulic geometry relationships previously developed in the NWFCP,

$$W_{bkf} = 3.17A^{0.39}$$

$$D_{bkf} = 0.50A^{0.25}$$

where W_{bkf} is bankfull width (m), D_{bkf} is bankfull mean depth (m), and A is drainage area (km^2) (Metcalf et al., 2009). Two soil samples for texture analysis were collected at each bank. Sand, silt, and clay fractions were analyzed by the pipette method (procedure 3A1; Soil Survey Staff, 2014).

For each study bank, the five BEHI variables were given a 1-10 score using graphs in Rosgen (2009) and summed. The bank material correction was determined by soil texture class. As per the method, five points were added to the BEHI if the soil texture was loamy sand, 10 points were added to the BEHI if the soil texture was sand, and zero points were added otherwise. Ten points were added to the BEHI of two sites for having stratified banks. The final BEHI values were used to assign each bank a qualitative BEHI level (0–10: Very Low, 10–20: Low, 20–30: Moderate, 30–40: High, 40–45: Very High, >45: Extreme) (Rosgen, 2009).

NBS is an estimate of the fluvial shear stress exerted on the bank toe. Various methods exist to estimate NBS (USEPA, 2012) (Table 1) but all represent a measure for the hydraulic forces affecting a streambank. Rosgen (2001) and USEPA (2012) provide a method to convert the numerical measures for NBS to one of five qualitative ratings ranging from low to extreme stress. In this study, NBS was calculated using two methods (Table 1) and each was used to fit separate prediction models. Radius of curvature was surveyed in the field as the perpendicular distance from two points located on the crest of the study bank approximately one channel width upstream and downstream from the cross-section (Rosgen, 2009). This method differs from other commonly employed methods, which measure the curvature of the inner bank (Hickin, 1978; Nanson and Hickin, 1983) or channel centerline (e.g., Güneralp and Rhoads, 2007). We assume that centerline curvature can be related to outer bank or inner bank curvature by adding or subtracting, respectively, one bankfull half-width. Near-bank maximum depth was measured within 1/3 channel width of the study bank. Bankfull mean depth was calculated by dividing bankfull cross-sectional area by bankfull width. The NBS values resulting from each of the methods were used as independent variables in separate predictive models.

TABLE 1. Variables used to calculate BEHI and NBS.

Name	Description	Measurement range	BEHI range
BEHI			
Bank height ratio	Bank height / bankfull height	1–3.5	1–10
Bank angle	Dominant bank slope	0–120°	1–10
Root depth ratio	Root depth / bank height	1–0	1–10
Weighted root density	Root volume density × root depth ratio	100–0%	1–10
Surface protection	Bank surface area protected	0–100%	1–10
NBS			
BANCS method 2	Radius of curvature / bankfull width	3–1.5	—
BANCS method 5	Near-bank maximum depth / mean depth	1–3	—

Methods for objective 3: Establish predictive statistical models for bank erosion based on BEHI categories and NBS categories.

All regression coefficients and statistics were computed using the R language. For each BEHI level, ordinary least squares regression was used to fit the line

$$\ln Y = aX + b \qquad (3)$$

where Y is annual erosion rate (cm/yr), X is NBS, and a and b are free parameters. The coefficients a and b were found by log-transforming annual erosion rates and fitting a linear model using the lm() function in R. Banks with net deposition (negative Y values) were excluded from this analysis (n = 5). Four prediction models were created using the following combinations of BEHI and NBS as predictor variables: one model with NBS method 2 as the predictor variable and BEHI as the categorical variable; one model with NBS method 5 as the predictor variable and BEHI as the categorical variable; one model using the larger of the two NBS estimates for each site as the predictor variable (as recommended by Rosgen (2009)) and BEHI categories as the categorical variable; and one model with BEHI as the predictor variable (as recommended by Van Eps et al. 2004) and the larger of the two NBS estimates for each site as the categorical variable.

Methods for objective 4: Enhance the predictive power of the statistical models by incorporating additional ancillary data into the models.

To create a better predictive model, compared to the standard model (see objective 3), we tested modifications of the NBS and BEHI and developed a new statistical model with additional ancillary data. The NBS was modified by multiplying it with channel width, which introduces dimensionality to NBS, and the BEHI was modified with a new root density measurement. NBS is expressed as a non-dimensional quantity by the BANCS approach while erosion rates are in dimensional form. Therefore, we calculated dimensionalized versions of both NBS measurements. The dimensioned NBS method 5 (NBS5*) is simply multiplied by channel width,

$$NBS5^* = B\ (Hmax/H)$$

where B is bankfull width, Hmax is maximum near-bank depth, and H is bankfull mean depth. NBS5* accounts for the intrinsic scale of the channel and has units of meters. While NBS method 2 assumes an approximately linear relationship between scaled channel curvature R/B and erosion rate, Hickin and Nanson (1984) and Nanson and Hickin (1983) showed that migration rates often peak at an intermediate value of curvature R/B = 2.5 and drop sharply below this value. We therefore applied the following transformation to scaled curvature:

$$(R/B)^* = \mathrm{erfc}\ (|R/B - (R/B)c|) + 1$$

where erfc denotes the complimentary error function and (R=B)c is the critical curvature value corresponding to the maximum observed erosion rates. The term within the parentheses represents the departure from the critical curvature value. The dimensionalized NBS method 2 (NBS2*), which also has units of meters, is then given by $NBS2^* = B(R/B)^*$.

Previous studies have emphasized the importance of woody vegetation and its associated root networks on streambank erodibility (Allmendinger et al. 2005; Pizzuto 1984; Sass and Keane 2012). We took two approaches to modifying the BEHI to reflect this observation. To improve on the visual root density estimation we carried out a root survey using a modified point intercept method (Allmendinger et al., 2005). In this root point-intercept method, (Rpim) we inserted a thin, 50 cm long, metal rod horizontally into the bank on a regular 20 cm x 20 cm grid that was centered on the survey cross section. The grid extended horizontally 1m in both directions and vertically to 2 m or maximum bank height, whichever was lower. We tallied the percentage of roots hit by the metal rod, which was taken as root density. No rocks were present at our study sites. When tested in soil pits, in which we applied Rpim and then excavated the soil and separated and weighted the dried roots, Rpim successfully estimated below-ground biomass (R^2=0.70 for Rpim [%] vs root mass). Root hit percentage was used to modify BEHI by directly replacing weighted root density and root depth, which are traditionally estimated visually. Because 2 BEHI variables are replaced by a single variable, the indexed value of root percentage was multiplied by 2. Our field experience suggests that the presence of woody vegetation and bedrock exert the dominant controls on streambank erodibility within the study area. We developed a simple erodibility index (SEI) to account for these 2 effects. First, banks were assigned a woody vegetation score of 2.5 or 8.5 based on the presence of significant trees (Sass and Keane 2012). Banks composed of bedrock were given an SEI of 0. SEI values of 0, 2.5, and 8.5 correspond to qualitative descriptors of Very Low, Low, and High.

Because of the weak and moderate predictive capacity of the standard and modified BANCS models respectively, we also applied a more robust statistical approach to better predict streambank erosion in the region. Because factors affecting stream bank erosion are nonlinear and interact with each other we selected a nonlinear statistical model for this (Nanson and Hickin 1983, Smyth 2002). The model is of the form $Y=\alpha x_1^{\beta 1} x_2^{\beta 2} \ldots x_n^{\beta n}$ in which $x_1 \ldots x_n$ are the various predictive input variables. Based on a comprehensive literature search we identified 18 input variables that are assumed to be related to streambank erosion rates: NBS, BEHI, bank height, bankfull width, near-bank depth excess, boundary shear stress, drainage area, channel cross-sectional area, bank slope, stream power, curvature, bulk density of bank soil, clay fraction of bank soil, weighted biomass density, root density, bank shear strength, bank vegetation cover, and antecedent precipitation (Table 2). Akaike's Information Criterion (AIC), corrected for small n, was used to select the optimal models, i.e. the models with the highest predictive power relative to the number of predictor variables (Akaike 1974). The AIC procedure is an all-subsets regression in which all possible models are ranked according to their AIC. Unlike the often-used R^2 indicator for goodness-of-fit, which always increases with additional model terms, AIC ranks models based on a complexity-fit tradeoff (lower is better). Subsequently, five-fold cross-validation of the models was performed to simulate out-of-sample prediction. Cross validation simulates out-of-sample prediction by withholding some observations from model fitting, then predicting those observations using the fitted model. Repeating this procedure allows different combinations of observations to constitute the folds. We repeated the five-fold cross-validation five times, and used the average mean square prediction error from all cross-validation tests to rank the models. All statistical analyses were performed in the R software environment.

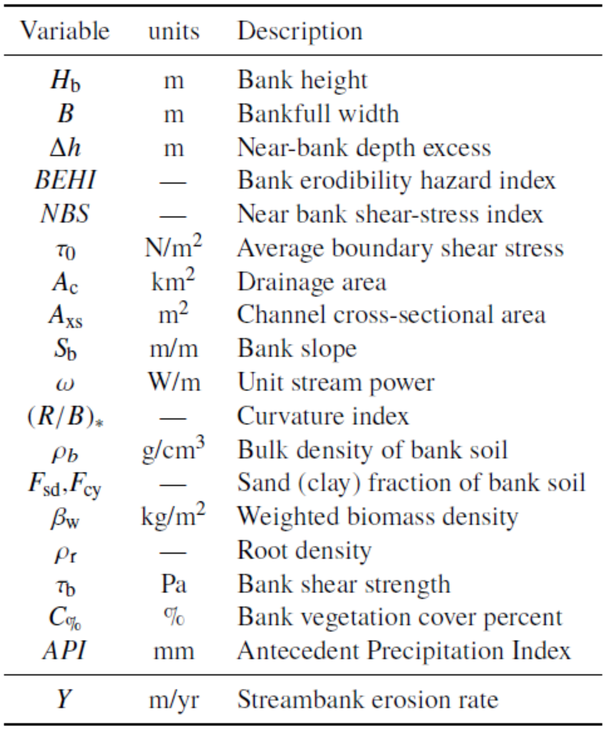
Methods for objective 5: Generate a ranked list of study site stream-bank erosion potential to facilitate restoration.

After successful completion of the above objectives, a ranked list of study sites was obtained by sorting the sites based on their observed average annual erosion rate during the project period.

Methods for objective 6: Disseminate data and results through technical reports, peer reviewed publication(s) and presentations.

The results of this study are being disseminated through the present technical report, peer reviewed publications and professional presentations.

TABLE 2. Variables used in statistical analyses.



Variable	units	Description
H_b	m	Bank height
B	m	Bankfull width
Δh	m	Near-bank depth excess
$BEHI$	—	Bank erodibility hazard index
NBS	—	Near bank shear-stress index
τ_0	N/m^2	Average boundary shear stress
A_c	km^2	Drainage area
A_{xs}	m^2	Channel cross-sectional area
S_b	m/m	Bank slope
ω	W/m	Unit stream power
$(R/B)_*$	—	Curvature index
ρ_b	g/cm^3	Bulk density of bank soil
F_{sd}, F_{cy}	—	Sand (clay) fraction of bank soil
β_w	kg/m^2	Weighted biomass density
ρ_r	—	Root density
τ_b	Pa	Bank shear strength
$C_{\%}$	%	Bank vegetation cover percent
API	mm	Antecedent Precipitation Index
Y	m/yr	Streambank erosion rate

RESULTS

Erosion Rates

Ignoring sites with net deposition, erosion rates averaged over the entire study period ranged from 0.002m/yr to 1.97m/yr, with a mean of 0.117m/yr and a standard deviation of 0.297m/yr. Although erosion rates were lower on average compared to other BANCS studies, they expressed higher variability. Calculations resulted in negative erosion rates for five banks (Table 3, appendix). Two of these received significant amounts of deposition (PR01 and SM01); the other three experienced very little erosion or deposition. Two of the sites with negative erosion rates experienced significant erosion of the inner bank (GM01 and MO01).

Banks mostly fell into the Moderate BEHI category (*n* = 41), followed by Low (14), High (12), Extreme (3), Very High (2) and Very Low (2) (Table 3). Almost all of the banks (65 or 88%) had root depths of 100% of bank height, while weighted root density estimates averaged 44%. This combination of high root depths and low to moderate root densities had a moderating effect on BEHI values. Excluding streambanks with negative erosion rates, there is only one bank with a Very Low BEHI rating (PW01). Because this bank is composed of bedrock, it is not grouped with the banks rated Low, but is plotted separately.

The two NBS methods gave largely different qualitative estimates of near-bank shear stress, a result that is expected considering their different measurements (Rosgen 2009). The two methods agreed on the qualitative descriptor for 11 banks. Method 2 gave higher estimates of near-bank shear stress on average, a direct result of the highly sinuous meandering channels in the study area.

Standard BANCS Model

Figure 3 plots the results of calibrating the BANCS model using both NBS methods. Several BEHI categories have negative trends, the opposed of what is expected. The highest positive correlation is for banks with High BEHI ($R^2 = 0.36$) using NBS method 5. Sites with extreme BEHI plotted against NBS method 2 have a very high R^2 but there are only three sites in that category. None of correlations plotted in Figure 3 are significant ($p > 0.1$).

Rosgen (2009) suggested using the largest NBS value obtained when multiple NBS methods are employed. Figure 4 shows that this gives similarly weak results. There does appear to be a strong correlation between NBS and erosion rate for banks classified as Very High BEHI, but this relationship is not significant ($p > 0.1$). Some researchers have produced predictive models using BEHI as the independent variable and NBS categories to group the data points (Van Eps et al. 2004). Figure 4 also shows the results of grouping banks in this way. The correlation between BEHI and erosion rate for banks with Extreme NBS values ($R2 = 0.48$, $p < 0.001$) emerges as the only statically significant relationship. The other NBS categories show large amounts of scatter. Nevertheless, this scheme produces results that are closest to being useful predictions of erosion rate.

NBS Modifications

The dimensioned NBS method 5 (NBS5*) showed a significant correlation to erosion rates ($R^2 = 0.31$, $p < 0.001$) (Figure 5). Grouping data points by BEHI shows significant correlations for Low ($R^2 = 0.33$, $p = 0.037$) and Moderate ($R^2 = 0.29$, $p < 0.001$) BEHI. The dimensioned NBS method 2 (NBS2*) also showed a strong significant correlation to erosion rates ($R^2 = 0.33$, $p < 0.001$) (Figure 6). Grouping data points by BEHI shows significant correlations for Moderate (R^2

= 0.30, $p < 0.001$) and Very High ($R^2 = 0.99$, $p < 0.048$) BEHI, but there are only 3 data points classified as Very High.

BEHI Modifications

Replacing the BEHI visual estimates of root depth and root density with the root percentage obtained from the root survey changed the qualitative BEHI descriptor for 11 sites. Figure 7 plots the results of incorporating the root survey technique into the standard BANCS method for the 53 sites at which the survey was carried out. The lack of root survey data for 21 of the original data points complicates direct comparison with the graphical models obtained using the standard BEHI, but it is clear that the incorporation of the root density survey into the BEHI did not greatly improve the predictive models. A potential reason is the indexation that is part of the BANCS approach and which decreases any improvement the more objective Rpim measure may offer. A graphical model using the modified BEHI as the predictor variable with the larger NBS estimate as the categorical variable was also produced, but showed similarly weak results and is not printed here.

The SEI score, which represents the presence or absence of woody vegetation and bedrock, was incorporated into graphical models using NBS5* and NBS2* as predictor variables. The vast majority of streambanks fell into the Low category, while one bank (PW01) was classified as Very Low and 3 banks (sites HH01, SM01, BW05) were classified as High. Figure 8 shows that this simple erodibility index captures much of the basic variability in bank erodibility, but there is still significant scatter in the graphs. Only the correlation for Low SEI is insignificant in both graphs, and the correlations are not made any stronger by SEI classification.

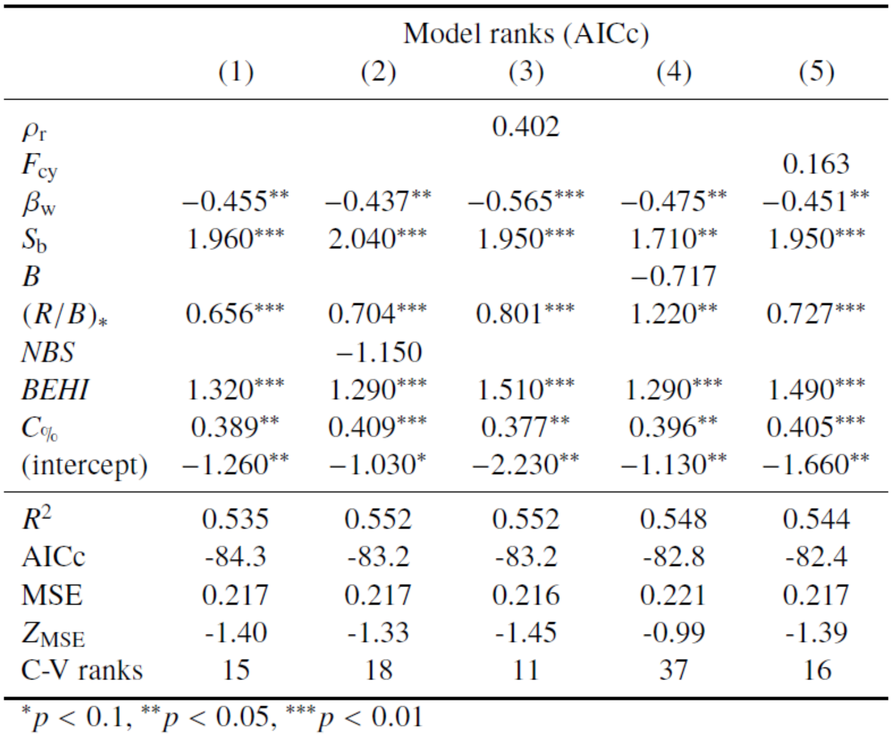
Statistical Approach

The top five models from the AIC selection process and their statistical parameters are shown in Table 4. Symbols are in Table 2. The fitted equation for the best model (lowest AIC) is given by:

$$Y = 10^{-1.26}\ \beta_{\omega}^{-0.46}\ Sb^{1.96}\ (R/B)^{0.66}\ BEHI^{1.33}\ C_{\%}^{0.39}$$

in which β_{ω} is the weighted biomass, Sb is the bank slope, (R/B) is the curvature index, and C% is the bank vegetation cover index. This model explained the majority of the variance ($R^2 =$ 0:538, $p < 0.001$) and each term is statistically significant ($p < 0.05$). All of the top AIC models contained the β_{ω}, Sb, (R/B), BEHI, and $C_{\%}$ terms (Table 4). The signs of the exponents are physically realistic, with the possible exception of the positive relationship between vegetation cover ($C_{\%}$) and erosion rate. Figure 9 plots a measure of the importance of each covariate as the sum of the likelihoods for every model in which the covariate appears. This indicates that five of the covariates form a consistently strong prediction of streambank erosion rates and that additional terms are probably not warranted.

Table 4. Model statistics of the five top AIC models. Average mean squared error (MSE) from cross-validation (C-V), normalized MSE (Z_{MSE}), and C-V ranks are reported for each model.



	Model ranks (AICc)				
	(1)	(2)	(3)	(4)	(5)
ρ_r			0.402		
F_{cy}					0.163
β_w	-0.455^{**}	-0.437^{**}	-0.565^{***}	-0.475^{**}	-0.451^{**}
S_b	1.960^{***}	2.040^{***}	1.950^{***}	1.710^{**}	1.950^{***}
B				-0.717	
$(R/B)_*$	0.656^{***}	0.704^{***}	0.801^{***}	1.220^{**}	0.727^{***}
NBS		-1.150			
$BEHI$	1.320^{***}	1.290^{***}	1.510^{***}	1.290^{***}	1.490^{***}
$C_{\%}$	0.389^{**}	0.409^{***}	0.377^{**}	0.396^{**}	0.405^{***}
(intercept)	-1.260^{**}	-1.030^{*}	-2.230^{**}	-1.130^{**}	-1.660^{**}
R^2	0.535	0.552	0.552	0.548	0.544
AICc	-84.3	-83.2	-83.2	-82.8	-82.4
MSE	0.217	0.217	0.216	0.221	0.217
Z_{MSE}	-1.40	-1.33	-1.45	-0.99	-1.39
C-V ranks	15	18	11	37	16

$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

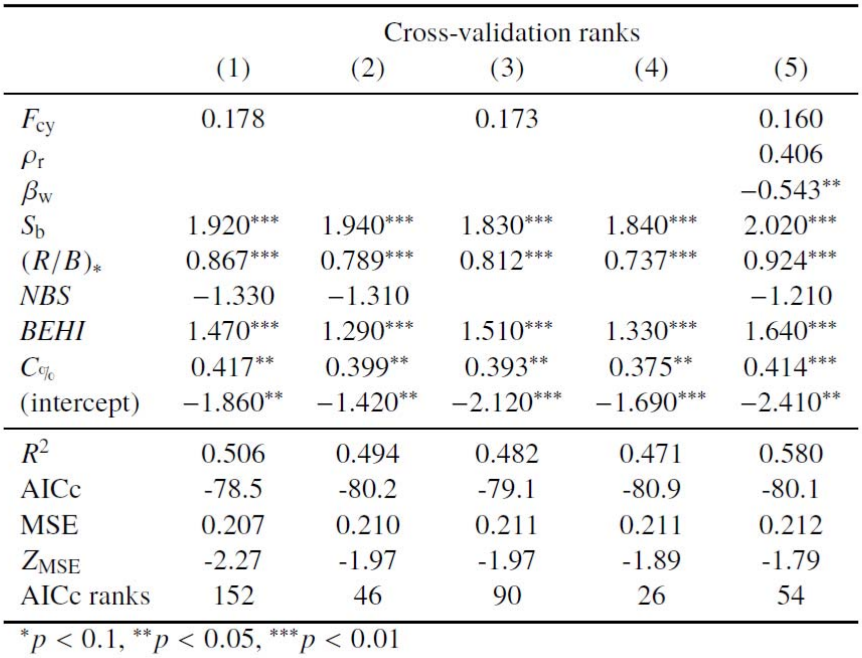
The model that minimized prediction error across the 5 cross-validation tests is given by the equation:

$$Y = 10^{-1.86} F_{cy}^{0.178} S_b^{1.92} (R/B)^{0.87} BEHI^{1.47} C_{\%}^{0.42}$$

This model is very similar to best equation based on the AIC but contains F_{cy} , the clay fraction of the bank sediments, in place of β_ω.

The five rounds of 5-fold cross-validation resulted in a different set of five models than the top five models from AIC (Table 5). The C-V process resulted in models containing the same covariates as the AIC models but in different combinations. Whereas weighted biomass was included in all five top AIC models, it only appears in one of the top five cross-validated models (model 5). The R^2 values were relatively consistent across the AIC models, but they are more variable for the cross-validated models and lower in general.

Table 5. Model statistics of the five best cross-validation models. Akaike's Information Criterion (AIC), average mean square error (MSE), normalized MSE (Z_{MSE}), and AIC ranks are reported for each model.



	Cross-validation ranks				
	(1)	(2)	(3)	(4)	(5)
F_{cy}	0.178		0.173		0.160
ρ_r					0.406
β_w					-0.543^{**}
S_b	1.920^{***}	1.940^{***}	1.830^{***}	1.840^{***}	2.020^{***}
$(R/B)_*$	0.867^{***}	0.789^{***}	0.812^{***}	0.737^{***}	0.924^{***}
NBS	−1.330	−1.310			−1.210
BEHI	1.470^{***}	1.290^{***}	1.510^{***}	1.330^{***}	1.640^{***}
$C_{\%}$	0.417^{**}	0.399^{**}	0.393^{**}	0.375^{**}	0.414^{***}
(intercept)	-1.860^{**}	-1.420^{**}	-2.120^{***}	-1.690^{***}	-2.410^{**}
R^2	0.506	0.494	0.482	0.471	0.580
AICc	-78.5	-80.2	-79.1	-80.9	-80.1
MSE	0.207	0.210	0.211	0.211	0.212
Z_{MSE}	-2.27	-1.97	-1.97	-1.89	-1.79
AICc ranks	152	46	90	26	54

$^*p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

The top models from the statistical approach have R^2 values of about 0.6 and are statistically significant. Because of the natural variability in streambank erosion and controlling factors it is likely that a longer-term study would produce models with an even better predictive power. The suite of models reported here allows insight into bank erodibility in the study area.

Ranking of Sites

The ranking of study sites based on observed bank erosion rates is given in Table 6, appendix B.

Dissemination of Results

The first of our peer-reviewed publications has been submitted to Catena, a high quality international geomorphology journal. The second peer-reviewed publication is 98% complete and is currently passing final review by the co-authors before submission. It will be submitted to the Journal of the American Water Resources Association, which seems to be the main outlet for studies that employ the BANCS model. McMillan is also preparing a peer-reviewed publication on an automated geospatial method to predict streambank erosion and is using the data collected in this project to evaluate his model. That manuscript is about 75% complete at the time of this writing. Project results have been presented, among other venues, at the national meeting of the American Water Resources Association, at the Rocky Mountain Stream Restoration Conference where the developer of the BANCS model was a prominent attendee and provided us with valuable feedback, at the Ecostream 2016 conference in Asheville, North Carolina, which was the ideal venue to present our research results because it was attended by stream restoration professionals from coastal areas throughout the Southeast, and at the annual conference of the Geological Society of America where we presented to colleagues from academia. Details of publications and presentations are as follows:

Publications

- McMillan, M., Liebens, J. and Bagui S. A statistical model for streambank erosion in the Northern Gulf of Mexico coastal plain. In review, Catena.
- McMillan, M., Liebens, J. and Metcalf, C. Evaluating Rosgen’s BANCS framework in the northern Gulf of Mexico coastal plain. In preparation, 98% complete, to be submitted to the Journal of the American Water Resources Association.
- McMillan, M. and Hu, Z. A process-based, spatially distributed model for forested streambank erosion. In preparation, 75% complete.

Presentations

- “A practical streambank erosion model for the coastal plain of the northern Gulf of Mexico.” (Poster, Liebens first author). Annual Meeting of the Geological Society of America. September 2016, Denver, CO.

- "Streambank erosion model for the northern Gulf of Mexico coastal plain." (Oral presentation, Liebens first author). EcoStream 2016: From Ridgeline to Thalweg. August 2016, Asheville, NC.
- "Predicting streambank erosion rates in the US Gulf coastal plain: BEHI and beyond." (Oral presentation, McMillan first author). Rocky Mountain Stream Restoration Conference. July 2016, Breckenridge, CO.
- "Streambank erosion estimated using new field methods." (Poster, McMillan first author). UWF Student Research Symposium. April 2016, Pensacola, FL.
- "Coupling a hydrodynamic model and geospatial data to predict streambank erosion rates." (Poster, McMillan first author). Florida Statewide Graduate Student Research Symposium. March 2016, Gainesville, FL.
- "Predicting streambank erosion rates in the US Gulf Coastal Plain." (Poster, McMillan first author). 70th Annual Meeting of the Southeastern Division of the Association of American Geographers. November 2015, Pensacola, FL.
- "Streambank erosion modeling: Improving field methods." (Oral presentation, McMillan first author) American Water Resources Association - 2015 Annual Water Resources Conference. November 2015, Denver, CO.
- "Predicting streambank erosion on the northern Gulf of Mexico coastal plain: Pitfalls and solutions." (Oral presentation, Liebens first author). 40th Annual NAEP Conference, National Association of Environmental Professionals. April 2015, Honolulu, HI.

CONCLUSIONS

The BANCS framework has been used to develop predictive models for streambank erosion rates in hydrophysiographic regions across the U.S. with varying success. We tried to calibrate the BANCS model for the northern Gulf of Mexico coastal plain. Separate BANCS models incorporating two measurements of near-bank shear stress, one model combining the two NBS measures, and another model based on BEHI as the predictor variable were fitted to streambank erosion data measured over the 2014–2016 water years. None of these models resulted in significant correlations to streambank erosion rates, indicating that most of the sources of variation remained unmodeled. Annual streambank erosion rates were highly variable during the

2-year study and ranged from ≈ 2 mm/yr to ≈ 2 m/yr. At one location, the streambank retreated 10 times faster during water year 2015 than during 2014 due to a combination of factors including lack of riparian forest cover, bend geometry, and possible desiccation and weakening of the bank soil preceding an extreme precipitation event. Other streambanks switched from erosion during low flows to deposition during high discharge events, possibly as a result of lower channel roughness during high discharges. Although a strong predictive model for the study area is unlikely to be developed without modeling within-channel hydrodynamic processes, a simple modification to NBS method 5 is proposed. NBS method 5 is a dimensionless scour factor, but it is used as an independent variable in models predicting streambank erosion rates, a dimensioned quantity. Therefore, we multiplied NBS method 5 by bankfull width and showed that this quantity was a stronger predictor of erosion rates than the standard BANCS parameter. Although stratifying banks by BEHI did not improve this prediction, in the future, other relationships accounting for the dominant processes of streambank erodibility in the study area could be developed to further refine the model. One alternative approach, statistical model selection using the information-theory based AIC and cross-validation, resulted in stronger predictive models. The top models from these techniques comprise streambank properties that are familiar to the stream restoration community and are relatively easy to measure in the field and thus, after further corroboration, offer an alternative to the BANCS method for the coastal plain of the northern Gulf of Mexico. The PIs will continue to monitor the sites established in this project and will periodically rerun the statistical models developed by this project to enhance the predictive power based on longer data sets.

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APPENDIX A: FIGURES

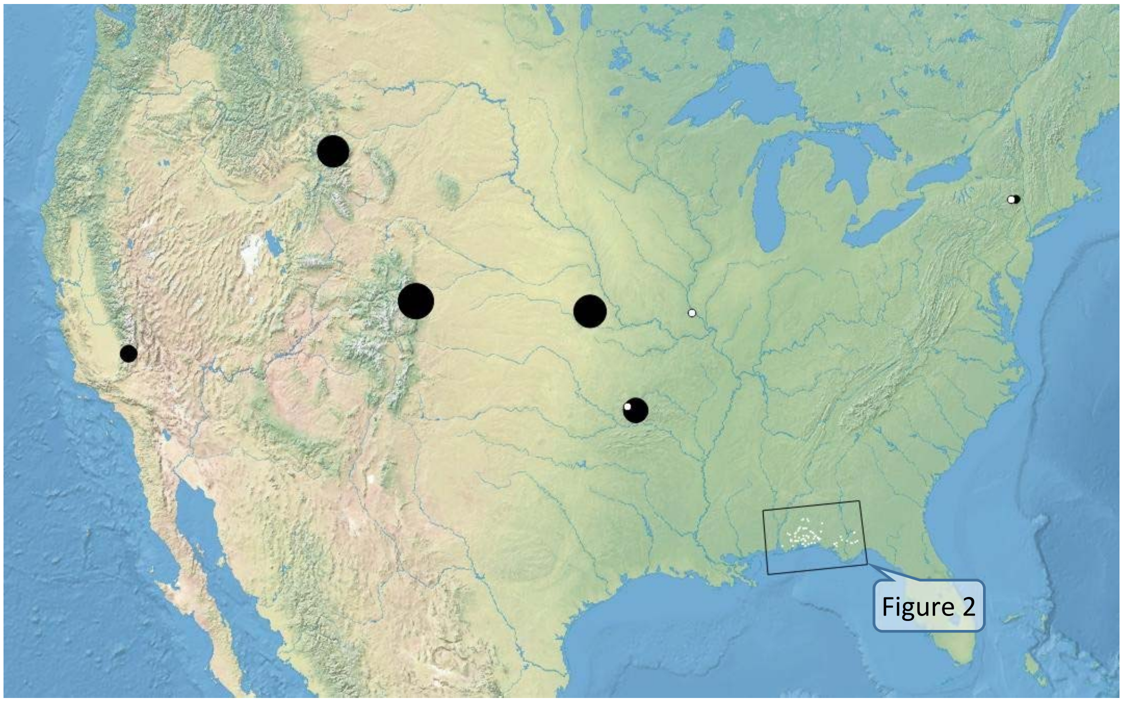


Figure 1. Map showing previous applications of Rosgen's BANCS method. The method has been applied throughout the U.S. Our study area (Figure 2) is boxed. Natural Earth basemap (http://www.naturalearthdata.com).

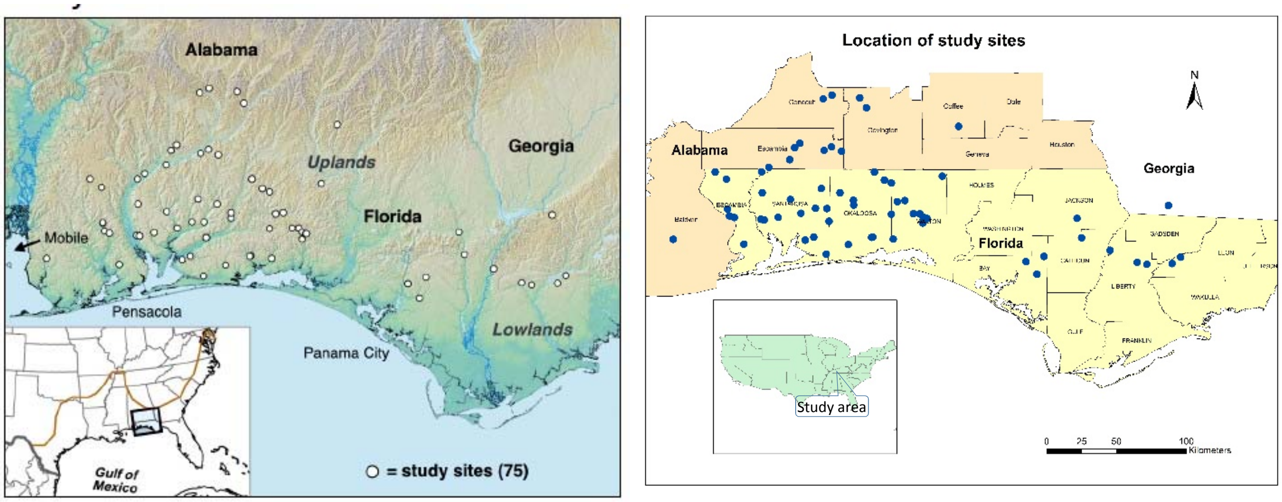


Figure 2. Maps of study area showing location of 75 study sites.

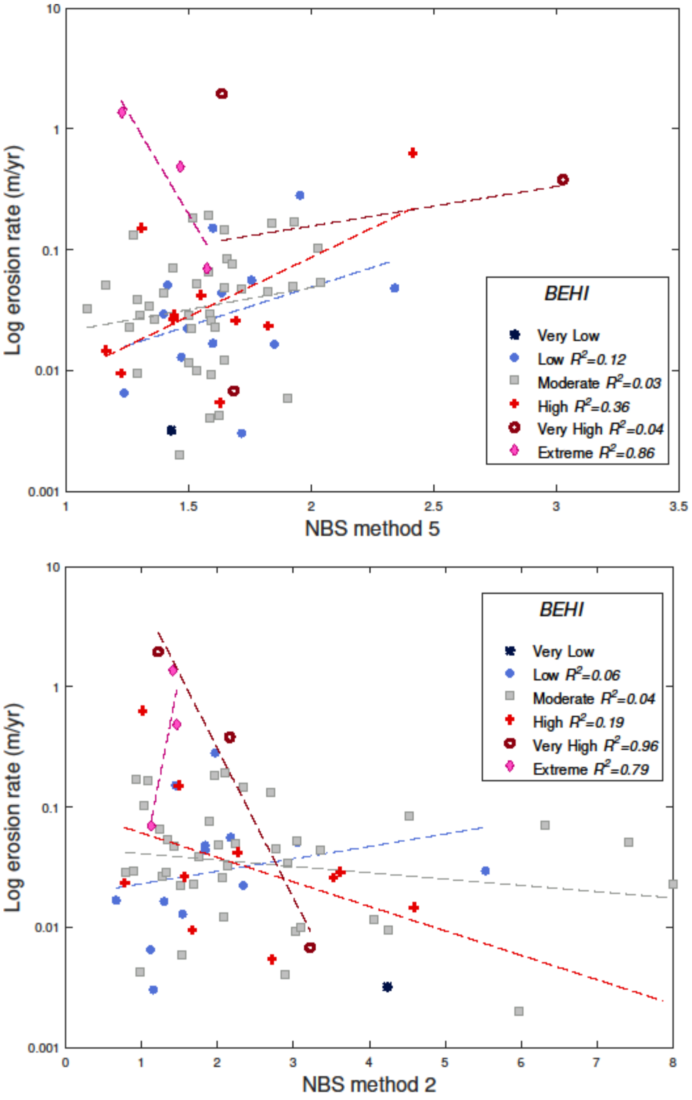


Figure 3. Standard BANCS model for study area. Dashed lines indicate lack of statistical significance (α=5%).

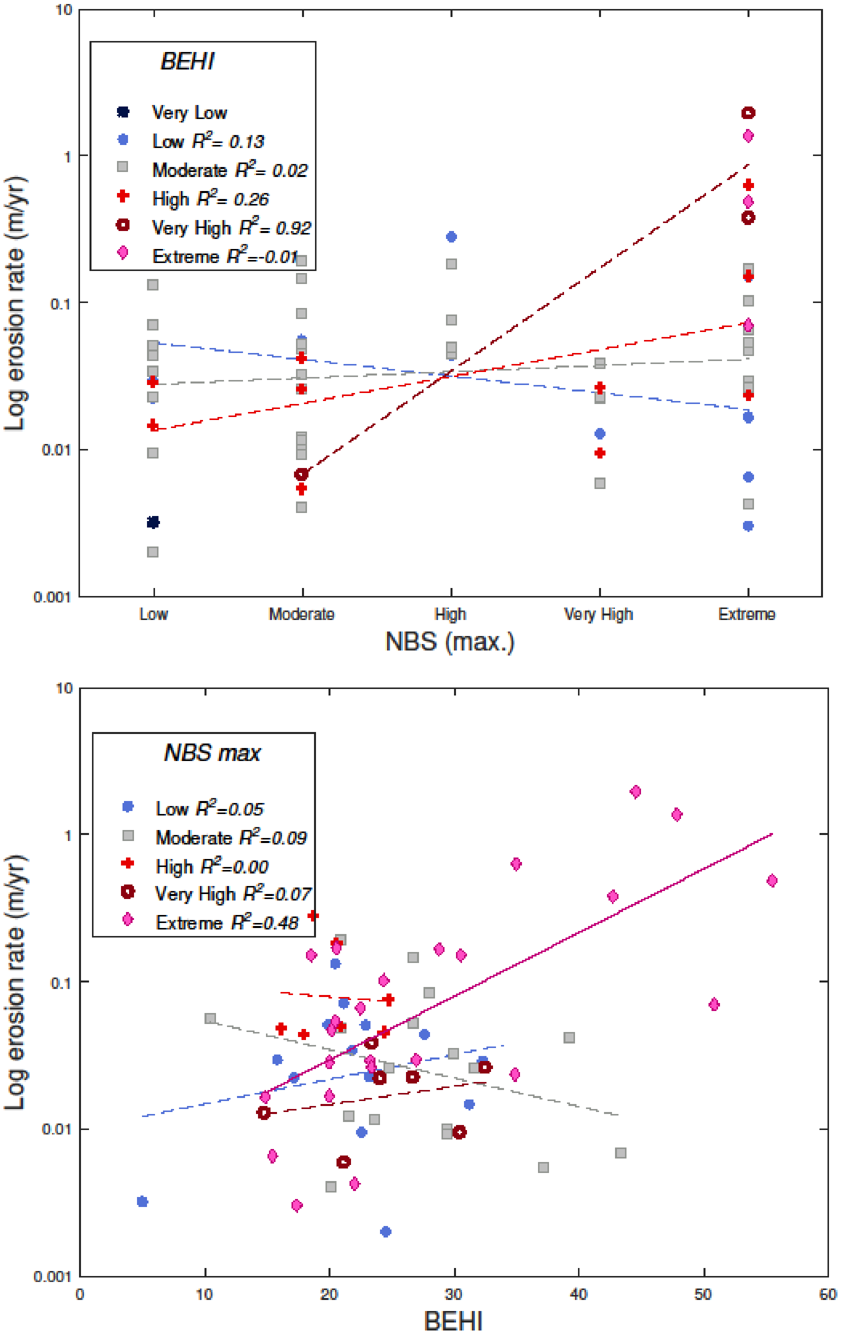


Figure 4. Use of highest NBS value in standard BANCS approach (top) or modified approach as per Sass and Keane (2004) (bottom). Solid line indicates statistical significance (α=5%).

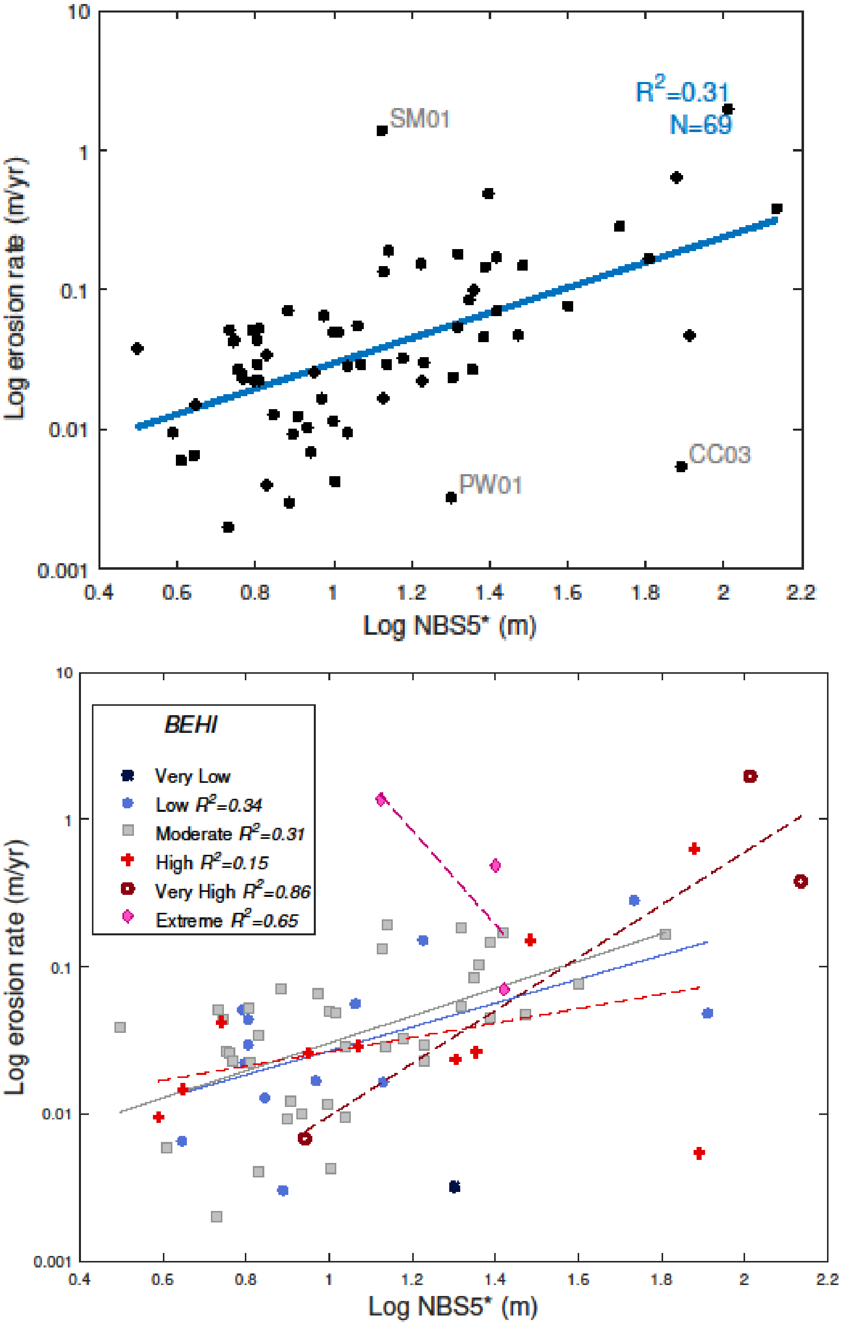


Figure 5. Relationships between modified NBS method 5 and erosion rate (top) and BEHI categories (bottom). Solid lines indicate statistical significance (α=5%).

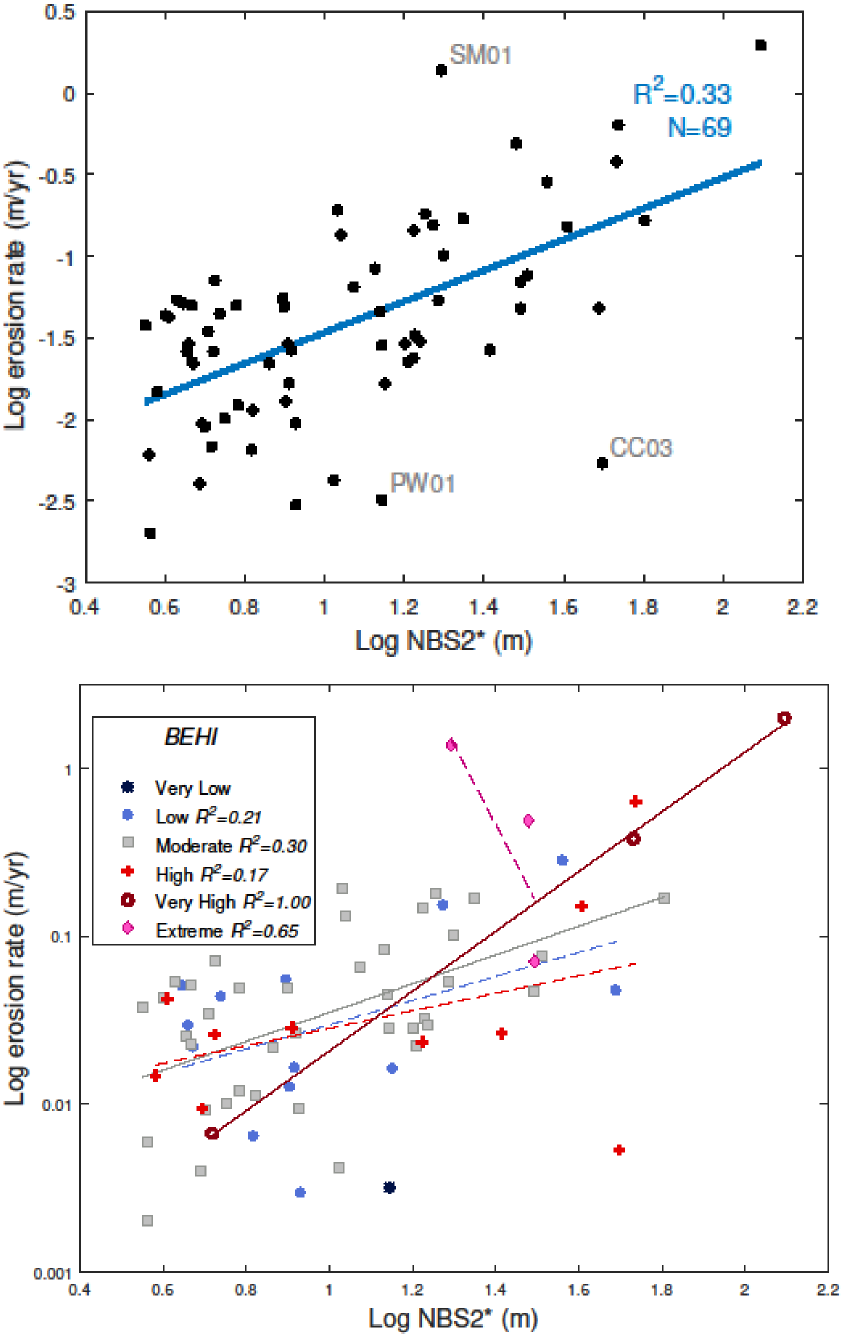


Figure 6. Relationships between modified NBS method 2 and erosion rate (top) and BEHI categories (bottom). Solid lines indicate statistical significance (α=5%).

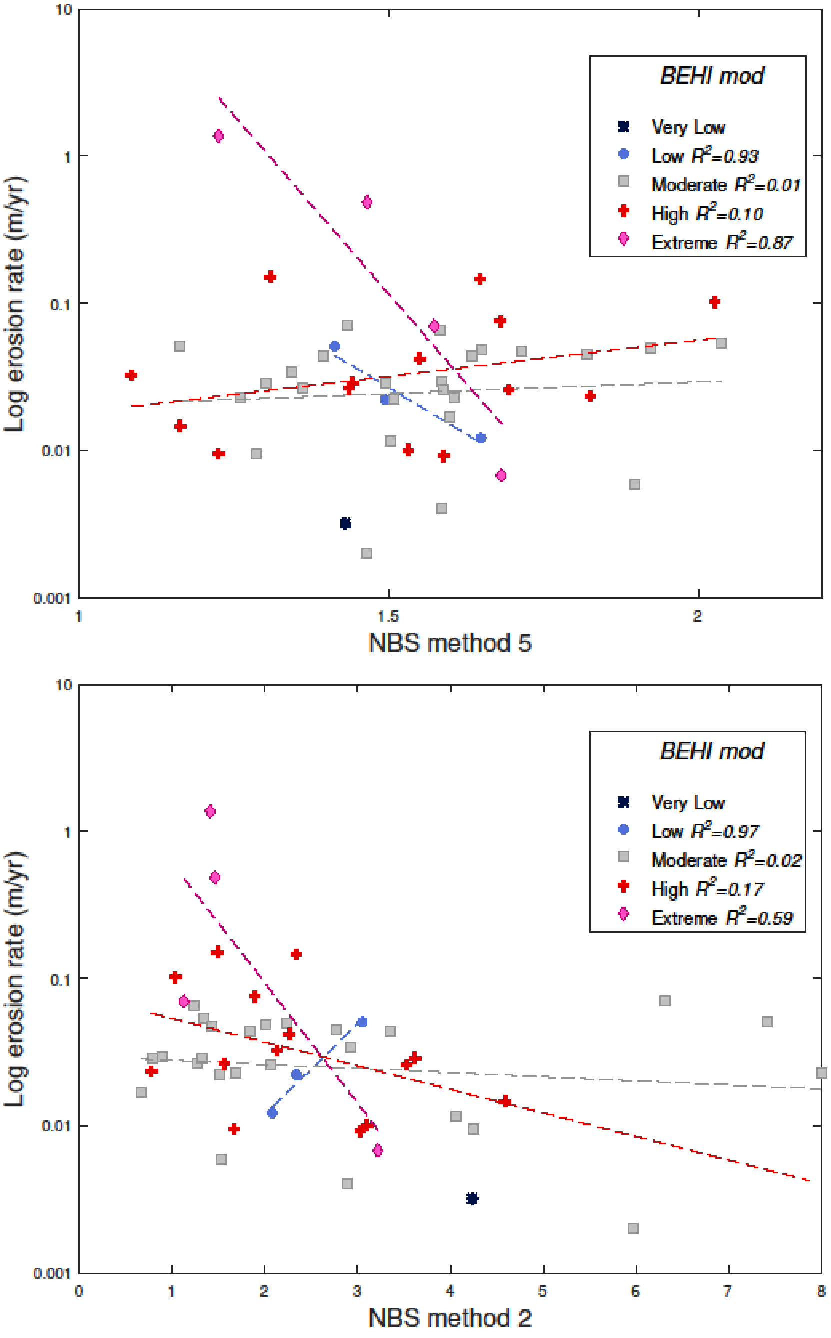
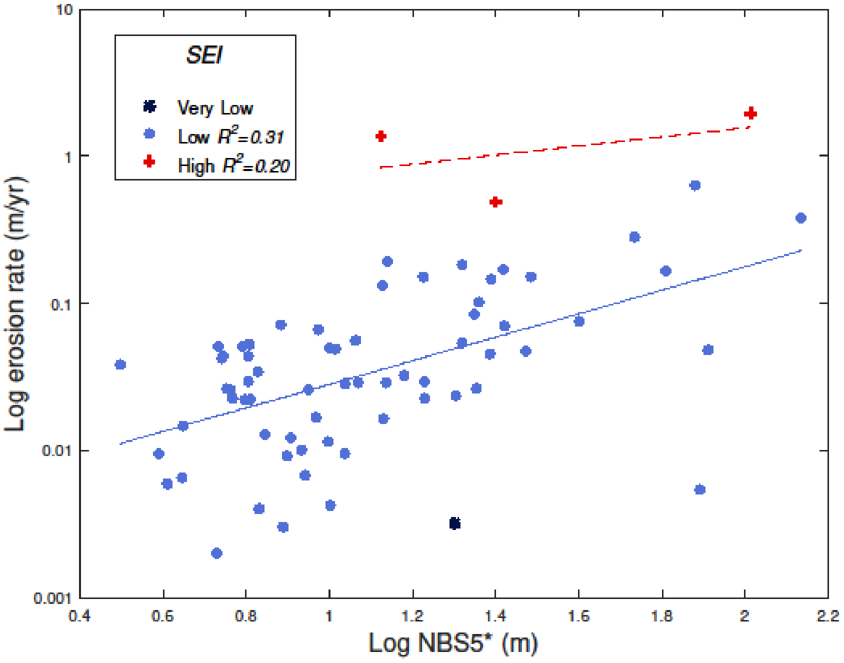


Figure 7. Relationships using modified BEHI with NBS method 5 (top) and NBS method 2 (bottom). Dashed lines indicate absence of statistical significance (α=5%).



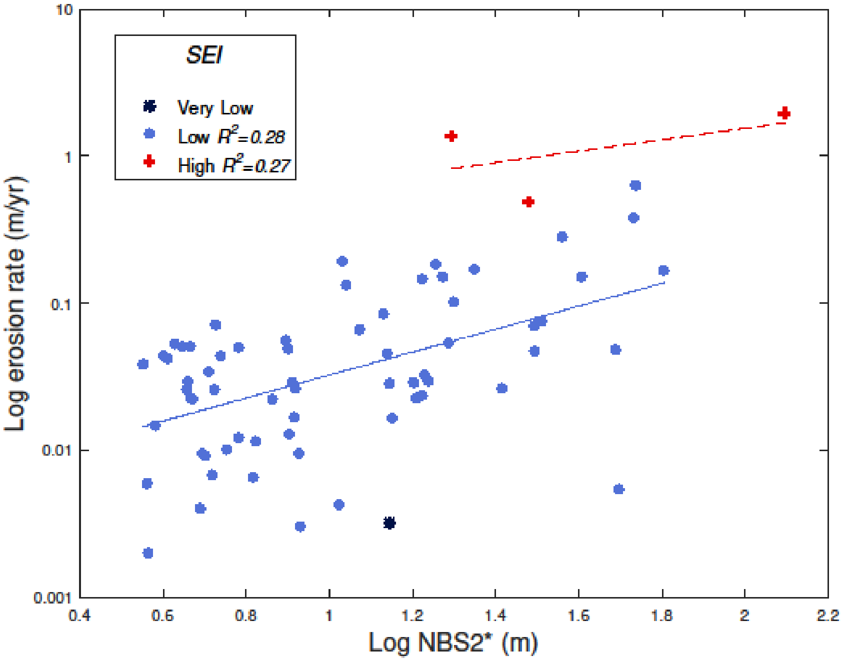


Figure 8. Results of grouping data by the simple erodibility index (SEI) proposed in this paper. Top: Using NBS5* as the predictor variable. Bottom: Using NBS2* as the predictor variable. Solid lines indicate statistical significance (α=5%).

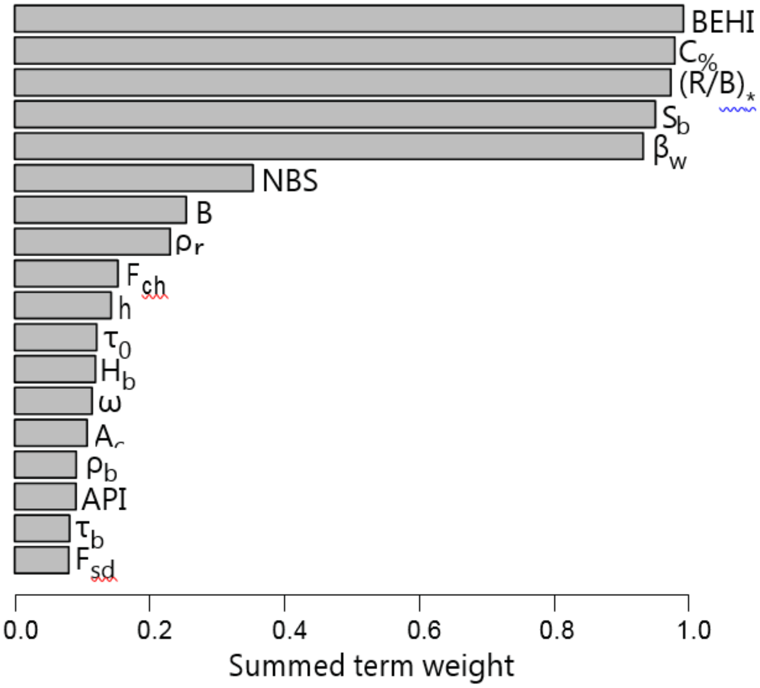


Figure 9. Results of AIC model selection. Relative importance of model terms represented as the sum of the likelihood (AIC weight) of all models containing each term. See Table 2 for an explanation of symbols.

APPENDIX B: FIELD DATA

TABLE 3. Field data.

Site	**Stream**	**Latitude**	**Longitude**	**Erosion rate**	**NBS_5**	**NBS_2**	**NBS_5_name**	**NBS_2_name**	**BEHI**	**BEHI_name**
BW02Y1	Alligator Creek	30.744550	-86.881220	1.01	1.53	3.10	Moderate	Very low	29.46	Moderate
BW03Y1	Panther Creek	30.844502	-86.722937	4.72	1.72	1.43	Moderate	Extreme	20.15	Moderate
BW04Y1	Sweetwater Creek	30.872404	-86.844191	2.65	1.44	1.57	Low	Very high	32.46	High
PR02Y1	Brushy Creek	30.978667	-87.527432	0.95	1.29	4.25	Low	Very low	22.58	Moderate
TC01Y1	Ten mile Creek	30.673760	-87.232410	0.20	1.46	5.96	Low	Very low	24.50	Moderate
PR01Y1	Eleven mile Creek	30.513516	-87.342185	-7.35	1.64	2.73	Moderate	Low	26.49	Moderate
PR03Y1	Pine Barren Creek	30.932319	-87.455314	1.22	1.65	2.08	Moderate	Moderate	21.50	Moderate
CW01Y1	Manning Creek	30.801956	-87.043020	2.58	1.69	3.53	Moderate	Very low	31.58	High
PC01Y1	Reader Creek	30.686413	-87.121704	0.40	1.59	2.88	Moderate	Low	20.22	Moderate
SC01Y1	Seven mile Creek	30.669430	-87.213000	2.57	1.59	2.07	Moderate	Moderate	24.80	Moderate
SC02Y1	Seven mile Creek	30.669770	-87.212100	2.21	1.49	2.35	Low	Low	17.20	Low
AL01Y1	Alligator Creek	30.695912	-87.436087	3.41	1.34	2.92	Low	Low	21.84	Moderate
PE01Y1	Penasula Creek	30.685462	-87.403535	5.08	1.41	3.05	Low	Very low	19.93	Low
JM01Y1	Julian Mill Creek	30.661137	-86.793913	5.06	1.16	-7.41	Low	Very low	22.89	Moderate
JM02Y1	Julian Mill Creek	30.661097	-86.793961	2.27	1.26	7.99	Low	Very low	23.17	Moderate

Site	**Stream**	**Latitude**	**Longitude**	**Erosion rate**	**NBS_5**	**NBS_2**	**NBS_5_name**	**NBS_2_name**	**BEHI**	**BEHI_name**
JM03Y1	Julian Mill Creek	30.660862	-86.793565	4.24	1.55	2.26	Moderate	Low	39.21	High
BG01Y1	Big Creek	30.978574	-86.501166	5.39	2.04	1.35	High	Extreme	20.47	Moderate
BG02Y1	Big Creek	30.978381	-86.501346	10.11	2.03	1.04	High	Extreme	24.29	Moderate
CH01Y1	Hollis Branch	30.554689	-85.166704	2.21	1.51	1.52	Moderate	Very high	24.02	Moderate
OR01Y1	Blue Creek	30.383531	-84.746141	0.67	1.68	3.22	Moderate	Very low	43.27	Very high
FR01Y1	Freeman Creek	30.388290	-84.584118	4.40	1.64	1.84	Moderate	High	17.95	Low
PK01Y1	Polk Creek	30.429566	-84.528511	2.33	1.83	0.78	High	Extreme	34.86	High
TG01Y1	Telogia Trib.	30.396003	-84.808777	0.95	1.23	1.67	Low	Very high	30.43	High
CC01Y1	Cedar Creek	31.135319	-87.014974	15.10	1.31	1.48	Low	Extreme	30.49	High
CC02Y1	Cedar Creek	31.135747	-87.015774	7.55	1.68	1.89	Moderate	High	24.76	Moderate
MC01Y1	Mill Creek	30.765591	-86.635146	0.91	1.59	3.02	Moderate	Very low	29.48	Moderate
MH01Y1	Mendenhall Creek	31.118842	-86.825614	-1.02	1.16	7.87	Low	Very low	32.91	High
CC03Y1	Cedar Creek	31.164760	-86.981510	0.54	1.63	2.72	Moderate	Low	37.10	High
TR01Y1	Travis Creek	31.058158	-87.047165	2.88	1.30	0.79	Low	Extreme	23.31	Moderate
OT01Y1	Old Town Creek	31.450660	-86.832440	14.54	1.65	2.34	Moderate	Low	26.64	Moderate
PW01Y1	Piney Woods Creek	31.474670	-86.774450	0.32	1.43	4.23	Low	Very low	5.00	Very low
BC01Y1	Buck Creek	31.456740	-86.595970	2.88	1.44	3.62	Low	Very low	32.27	High
BC02Y1	Buck Creek	31.392980	-86.553140	3.24	1.09	2.13	Low	Moderate	29.96	Moderate
BB01Y1	Bishop Branch	30.708510	-86.210180	1.48	1.16	4.58	Low	Very low	31.18	High
BB02Y1	Bishop Branch	30.708590	-86.208750	4.34	1.40	3.36	Low	Very low	27.58	Moderate
CM01Y1	Cosson Mill Creek	30.688360	-86.187210	6.55	1.58	1.24	Moderate	Extreme	22.52	Moderate
SM01Y1	Sconniers Mill Creek	30.679060	-86.162880	138.34	1.23	1.42	Low	Extreme	47.86	Extreme

Site	**Stream**	**Latitude**	**Longitude**	**Erosion rate**	**NBS_5**	**NBS_2**	**NBS_5_name**	**NBS_2_name**	**BEHI**	**BEHI_name**
SM02Y1	Sconniers Mill Creek	30.678533	-86.162370	-19.31	1.42	2.25	Low	Low	33.91	High
MD01Y1	McDavid Creek	30.739350	-87.448050	2.82	1.50	1.32	Low	Extreme	20.03	Moderate
MD02Y1	McDavid Creek	30.739660	-87.447660	1.15	1.50	4.06	Moderate	Very low	23.69	Moderate
GC01Y1	Gum Creek	30.797022	-86.637482	7.08	1.43	6.32	Low	Very low	21.12	Moderate
PD01Y1	Pond Creek	30.907610	-86.391650	4.53	1.82	2.77	High	Low	24.31	Moderate
GM01Y1	Grab Mill Creek	31.141284	-86.777910	-0.14	1.33	0.88	Low	Extreme	24.06	Moderate
HH01Y1	Horsehead Creek	30.926960	-86.437310	49.10	1.47	1.46	Low	Extreme	55.54	Extreme
HH02Y1	Horsehead Creek	30.926600	-86.437100	7.03	1.57	1.13	Moderate	Extreme	50.88	Extreme
LC01Y1	Larson Creek	30.787430	-86.353740	0.60	1.90	1.53	High	Very high	21.18	Moderate
CN01Y1	Chestnut Creek	30.951963	-86.064336	2.95	1.58	0.90	Moderate	Extreme	26.98	Moderate
CN02Y1	Chestnut Creek	30.952074	-86.064531	2.25	1.61	1.68	Moderate	Very high	26.68	Moderate
MO01Y1	Moore Creek	30.845313	-87.224780	-1.13	1.27	8.71	Low	Very low	5.00	Very low
LM01Y1	Little Moccasin Creek	30.400940	-85.524660	2.65	1.36	1.26	Low	Extreme	23.42	Moderate
MN01Y1	Moccasin Creek	30.400713	-85.524974	4.93	1.65	2.02	Moderate	Moderate	20.94	Moderate
WC01Y1	Willacoochee Creek	30.762320	-84.607268	1.66	1.60	0.67	Moderate	Extreme	19.96	Low
WC02Y1	Willacoochee Creek	30.762501	-84.607279	4.95	1.92	2.24	High	Low	20.83	Moderate
AB01C1	Anderson Branch	30.559730	-86.512080	0.30	1.72	1.15	Moderate	Extreme	17.40	Low
BE01C1	Bear Head Creek	31.112440	-86.713170	NaN	NaN	NaN	<undefined>	<undefined>	NaN	<undefined>

Site	**Stream**	**Latitude**	**Longitude**	**Erosion rate**	**NBS_5**	**NBS_2**	**NBS_5_name**	**NBS_2_name**	**BEHI**	**BEHI_name**
BH01C1	Bullhide Creek	30.709657	-86.250117	5.32	1.53	3.04	Moderate	Very low	26.70	Moderate
BR01C1	Bear Creek	30.434478	-85.408453	1.65	1.85	1.30	High	Extreme	14.90	Low
BR02C1	Bear Creek	30.320080	-85.454610	18.21	1.51	1.97	Moderate	High	20.60	Moderate
BW01Y1	Ates Creek	30.743460	-86.807430	NaN	1.73	NaN	Moderate	<undefined>	17.73	Low
CL01C1	Big Coldwater Creek	30.712811	-86.975103	4.77	2.34	1.84	High	High	16.10	Low
CR01C1	Chipola River Reach 15	30.679630	-85.195870	37.80	3.03	2.16	Extreme	Moderate	42.70	Very high
ER01C1	Big Escambia River	30.980230	-87.229160	62.97	2.41	1.01	High	Extreme	35.00	High
FS01C1	Fish River	30.544460	-87.797817	8.41	1.65	4.52	Moderate	Very low	28.00	Moderate
GU01C1	Gum Creek	30.706508	-86.392356	0.42	1.62	0.99	Moderate	Extreme	22.00	Moderate
HK01C1	Hicks Creek	30.539847	-86.947131	2.94	1.40	5.53	Low	Very low	15.80	Low
JU01C1	Juniper Creek	30.557144	-86.519978	13.30	1.27	2.71	Low	Low	20.50	Moderate
LD01C1	Little Double Bridges	31.273000	-85.959190	15.27	1.60	1.45	Moderate	Extreme	18.50	Low
LE01C1	Little Escambia River	31.008930	-87.181170	28.18	1.96	1.97	High	High	18.70	Low
LR01C1	Little Rocky Creek	30.545917	-86.380189	19.25	1.58	2.10	Moderate	Moderate	21.00	Moderate
LS01C1	Little Sweetwater Creek	30.473472	-84.982536	1.27	1.47	1.54	Low	Very high	14.80	Low
MR01C1	Moore Creek	30.558478	-86.891994	0.65	1.24	1.11	Low	Extreme	15.40	Low
PN01C1	Panther Creek	30.449350	-86.812017	5.53	1.76	2.18	Moderate	Moderate	10.40	Low
SR01C1	Shoal River	30.794836	-86.304844	16.69	1.84	1.09	High	Extreme	28.80	Moderate

Site	**Stream**	**Latitude**	**Longitude**	**Erosion rate**	**NBS_5**	**NBS_2**	**NBS_5_name**	**NBS_2_name**	**BEHI**	**BEHI_name**
TL01C1	Tallaperla Creek	30.649718	-86.189824	3.82	1.29	1.76	Low	Very high	23.40	Moderate
TU01C1	Turtle Creek	30.510760	-86.669870	16.88	1.93	0.92	High	Extreme	20.60	Moderate
BW05C1	Blackwater River	30.723497	-86.798926	197.21	1.63	1.23	Moderate	Extreme	44.60	Very high

TABLE 6. Streambank ranking according the observed average annual erosion rate [cm/yr].

Site ID*	Stream name	Bank	Average annual erosion rate [cm/yr]
BW05C1	Blackwater River	Right	197.21
SM01Y1	Sconniers Mill Creek	Right	138.34
ER01C1	Big Escambia River	Left	62.97
HH01Y1	Horsehead Creek	Right	49.10
CR01C1	Chipola River Reach 15	Left	37.80
LE01C1	Little Escambia River	Left	28.18
LR01C1	Little Rocky Creek	Left	19.25
BR02C1	Bear Creek	Left	18.21
TU01C1	Turtle Creek	Left	16.88
SR01C1	Shoal River	Left	16.69
LD01C1	Little Double Bridges	Left	15.27
CC01Y1	Cedar Creek	Right	15.10
OT01Y1	Old Town Creek	Right	14.54
JU01C1	Juniper Creek	Left	13.30
BG02Y1	Big Creek	Left	10.11
FS01C1	Fish River	Right	8.41
CC02Y1	Cedar Creek	Right	7.55
GC01Y1	Gum Creek	Right	7.08
HH02Y1	Horsehead Creek	Left	7.03
CM01Y1	Cosson Mill Creek	Left	6.55
PN01C1	Panther Creek	Left	5.53
BG01Y1	Big Creek	Right	5.39
BH01C1	Bullhide Creek	Left	5.32
PE01Y1	Penasula Creek	Left	5.08
JM01Y1	Julian Mill Creek	Left	5.06
WC02Y1	Willacoochee Creek	Left	4.95
MN01Y1	Moccasin Creek	Left	4.93
CL01C1	Big Coldwater Creek	Left	4.77
BW03Y1	Panther Creek	Left	4.72
PD01Y1	Pond Creek	Left	4.53
FR01Y1	Freeman Creek	Right	4.40
BB02Y1	Bishop Branch	Left	4.34
JM03Y1	Julian Mill Creek	Left	4.24
TL01C1	Tallaperla Creek	Left	3.82
AL01Y1	Alligator Creek	Right	3.41

Site ID*	Stream name	Bank	Average annual erosion rate [cm]
BC02Y1	Buck Creek	Left	3.24
CN01Y1	Chestnut Creek	Right	2.95
HK01C1	Hicks Creek	Left	2.94
TR01Y1	Travis Creek	Right	2.88
BC01Y1	Buck Creek	Left	2.88
MD01Y1	McDavid Creek	Right	2.82
BW04Y1	Sweetwater Creek	Right	2.65
LM01Y1	Little Moccasin Creek	Left	2.65
CW01Y1	Manning Creek	Right	2.58
SC01Y1	Seven Mile Creek	Right	2.57
PK01Y1	Polk Creek	Left	2.33
JM02Y1	Julian Mill Creek	Right	2.27
CN02Y1	Chestnut Creek	Left	2.25
CH01Y1	Hollis Branch	Right	2.21
SC02Y1	Seven Mile Creek	Right	2.21
WC01Y1	Willacoochee Creek	Right	1.66
BR01C1	Bear Creek	Left	1.65
BB01Y1	Bishop Branch	Right	1.48
LS01C1	Little Sweetwater Creek	Left	1.27
PR03Y1	Pine Barren Creek	Left	1.22
MD02Y1	McDavid Creek	Left	1.15
BW02Y1	Alligator Creek	Right	1.01
TG01Y1	Telogia Trib.	Left	0.95
PR02Y1	Brushy Creek	Left	0.95
MC01Y1	Mill Creek	Right	0.91
OR01Y1	Blue Creek	Right	0.67
MR01C1	Moore Creek	Left	0.65
LC01Y1	Larson Creek	Right	0.60
CC03Y1	Cedar Creek	Right	0.54
GU01C1	Gum Creek	Left	0.42
PC01Y1	Reader Creek	Right	0.40
PW01Y1	Piney Woods Creek	Right	0.32
AB01C1	Anderson Branch	Left	0.30
TC01Y1	Ten Mile Creek	Right	0.20
GM01Y1	Grab Mill Creek	Left	-0.14
MH01Y1	Mendenhall Creek	Right	-1.02
MO01Y1	Moore Creek	Right	-1.13

Site ID*	Stream name	Bank	Average annual erosion rate [cm]
PR01Y1	Eleven Mile Creek	Left	-7.35
SM02Y1	Sconniers Mill Creek	Left	-19.31
BE01C1	Bear Head Creek	Left	site damaged
BW01Y1	Ates Creek	Right	site damaged

* See table 3 for coordinates.