Regional Trends in Vertical Adjustment, Bank Erosion and Effectiveness of Erosion-Control Measures: Returning to West Tennessee 40-Years Later

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Abstract

The channels of West Tennessee have undergone systematic adjustments to their geometry, including incision and widening, over much of the 20th century. As a result, bank erosion from these channels has become a significant source of sediment in the region. The principle aims of this study were to evaluate region-wide rates of bank erosion in the context of the effectiveness of potential erosion-control measures to reduce bank erosion along channels of West Tennessee. Regionalization of channel characteristics (extracted from LiDAR at 155 sites), boundary materials (from in situ field measurements at 80 sites) and a 13-year flow series (derived from records at 19 gaging stations) were used as input into the dynamic version of the Bank-Stability and Toe-Erosion Model (BSTEM-Dynamic).

As documented in regionwide work from the 1980s and 1990s and verified here, rates of channel adjustment were far less today than they were in the second half of the 20th century. Along main-stem channels, additional degradation and consequent increases in bank heights are expected to be limited, with many reaches experiencing aggradation and slowly decreasing bank heights.

Modeling runs were initially conducted for "existing" conditions, representing a "baseline" by which to later compare erosion rates under alternative mitigation strategies. In this regional approach, it was important to conduct the numerical analyses using bank-resistance values that represented not only the median value from each basin (50th percentile), but to include a broader range using the 25th and 75th percentiles from each basin. Median erosion rates for the 25th, 50th and 75th percentiles of bank resistance varied from 51.6 to 0.3 and to 0.0 cubic meters per meter of channel per year (m^3/m/y), respectively. Considering peak values (the 99.99th percentile) as a loading rate (in tonnes per meter per year; t/m/y), bank erosion varied from about 3.8 t/m/y for the 75th percentile of bank resistance (stronger materials) to 265 t/m/y at the 25th percentile (weaker materials). Modeled results were interpolated and extrapolated to non-modeled reaches based on basin-specific regression equations (r^2-values ~ 0.80) relating modeled bank-erosion rates to a metric defined as the area-gradient index (AGI) times excess boundary-shear stress at the "bankfull" discharge.

Analysis of the potential for reductions in bank erosion (effectiveness) were limited to three broad measures: vegetation alone, rock at the bank toe and rock along the entire bank surface. Results of this study show that in general terms, the placement of rock or other resistant materials at the bank toe is the most effective means of achieving significant reductions in bank erosion along the stream channels of West Tennessee. In those reaches that produce high rates of erosion, the rock-toe option also represents the most cost-effective means of achieving water-quality improvements with regard to sediment concentrations and fine-sediment loads. Vegetation has also been shown to be not only effective but cost effective as well under particular circumstances where bank heights are not overly high and erosion rates are, therefore, moderate. The AGI metric was also used to map and regionalize the effectiveness of erosion-control measures.

Background and Objectives

The channels of West Tennessee have undergone systematic adjustments to their geometry, including incision and widening, over much of the 20th century (Simon and Hupp, 1986; Simon, 1989; 1994). Vertical incision has ameliorated over time as is typical of systems adjusting to large-scale disturbances, in this case, channelization. Bank erosion from these channels has become a significant source of sediment in the region. The principle aims of this study were to evaluate region-wide rates of bank erosion in the context of the effectiveness of erosion-control measures using techniques grounded in analysis of the driving and resisting forces that control bank-erosion processes. The overall objective was to provide a scientifically based, regional-scale, quantitative evaluation of the applicability of the use of rock and other mitigation alternatives to reduce bank erosion along channels of West Tennessee. To accomplish this, we utilized measurements of the hydraulic and geotechnical resistance of the channel banks at more than 80 sites and developed a 13-year flow series from gaging-station data for analysis of bank-erosion rates and the effectiveness of erosion-control measures. This information was input into the dynamic version of the Bank-Stability and Toe-Erosion Model (BSTEM-Dynamic) (Simon et al., 2000; 2011) using channel-geometry data extracted from LiDAR for 155 sites across the region.

Regionalization of Bank Geometry, Material Properties and Flow

A numerical modeling framework to evaluate regional bank-stability conditions was required to avoid the need to analyze every stream or river kilometer in the region. This was accomplished by selecting specific locations that encompassed the range of characteristics such as bank height, bank angle, channel slope, bank strength etc., in each sub-basin. Determining these data distributions established the framework for selecting locations for numerical experiments using BSTEM to determine the effectiveness of bank-stabilization treatments.

One of the most critical of these data sets were cross-section and channel-slope data that were extracted from publicly available LiDAR (1-m DEM). This was done according to USGS QL2 standards in different parts of the region between 2011 and 2017. Raw data on cross-section geometry and channel slopes were extracted for 502 sites across the region in spreadsheet format, sorted by drainage basin. This data set proved invaluable for evaluating the range of channel geometries across the region and within each of the five major drainage systems. It also served as the foundation for calculating other metrics (such as boundary shear stress) relevant to evaluating channel responses and bank-erosion rates. Ranges were established by sorting the data by drainage basin to help determine the limits that needed to be considered. Distributions for parameters such as bank heights, channel gradients, bank angles, and material resistance or strength, were developed for each basin and/or soil type.

It was decided to use representative locations within each major drainage basin from the actual LiDAR-extracted data. Associated data on bank-material strength and resistance would then be provided according to data distributions from material testing conducted within each of those basins. In total, 155 sites through the region were selected (Table 1). The location of the sites, represented by the extracted LiDAR data are shown along with their site IDs in Figure 1.

Table 1 Spatial distribution of channel-geometry data selected from the 2011-2017 LiDAR data base sorted into the major drainage basins and rivers (Top) and range of values for the 502 extracted sites (Bottom).

Basin	River	# Sites	River mile range		# Sites	
		Main stem	Lower	Upper	Tributary	Total
Obion	North Fork	7	5.2	51.3	6	13
	Middle Fork	6	2.2	35.3	8	14
	Rutherford Fork	7	1.7	48.5	2	9
	South Fork[1]	4	68.5	100.7	11	15
	Obion	4	25.5	59.1	0	4
Forked Deer	North Fork	5	9.7	45.2	11	16
	Middle Fork	6	5.0	57.3	9	15
	South Fork	7	8.5	71.8	14	21
Hatchie	Hatchie	6	5.5	186.2	12	18
Loosahatchie	Loosahatchie	6	7.9	59.5	7	13
Wolf	Wolf[2]	9	10.0	76.8	8	17
TOTAL		67			88	155

1 from mouth of Obion River

2 includes North Fork

Basin	River	# Sites	Maximum bank height			Channel gradient			Bank angle		
			min	max	median	min	max	median	min	max	median
			(m)			(m/m)			(degrees)		
Obion	North Fork	30	0.6	7.3	3.9	0.00032	0.00351	0.00088	12.1	57.3	42.5
	Middle Fork	31	1.3	4.6	3.2	0.00025	0.00385	0.00112	27.0	61.8	41.0
	Rutherford Fork	18	2.0	6.5	4.3	0.00040	0.00670	0.00100	26.0	56.0	40.6
	South Fork	56	1.4	6.5	3.8	0.00022	0.00620	0.00132	8.7	52.7	38.5
	Obion	4	7.3	14.3	10.2	0.00014	0.00018	0.00015	32.7	67.8	39.5
Forked Deer	North Fork	41	2.2	7.4	4.0	0.00010	0.00855	0.00098	8.7	52.1	33.9
	Middle Fork	52	0.3	6.9	3.4	0.00030	0.00875	0.00177	7.0	52.7	33.9
	South Fork	100	0.3	6.8	2.7	0.00024	0.01555	0.00211	5.2	57.8	33.9
Hatchie	Hatchie	75	1.6	6.8	3.8	0.00005	0.00910	0.00050	8.0	65.0	37.0
Loosahatchie	Loosahatchie	56	1.3	11.8	5.5	0.00004	0.00774	0.00109	10.0	63.0	38.0
Wolf	Wolf	39	0.7	6.9	3.3	0.00024	0.00490	0.00185	6.0	58.0	31.0

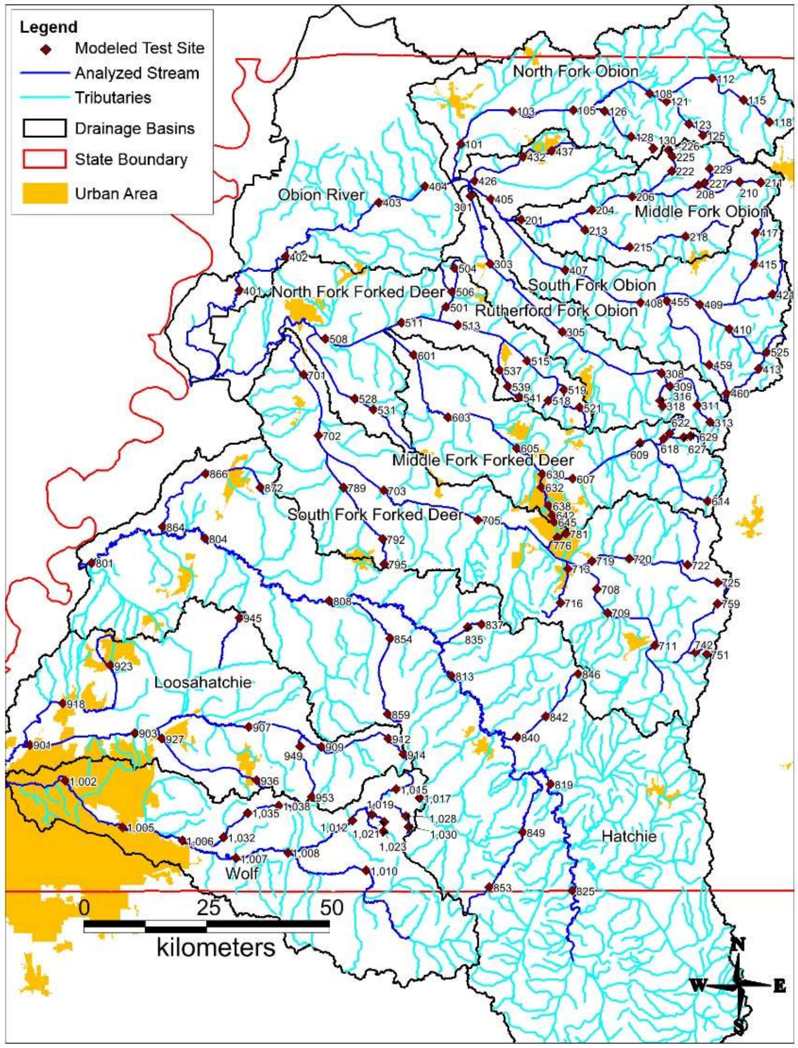


Figure 1. Map of West Tennessee showing the major drainage systems and sites selected for numerical modeling.

The evaluation of bank erosion is founded on an analysis of the hydraulic and geotechnical forces operating on the banks (driving forces) relative to the forces that resist fluvial erosion and mass failure (resisting forces). A total of 87 borehole shear tests were conducted to determine bank-material shear strength; 83 submerged-jet tests were conducted to quantify critical shear stress as a measure of the resistance to hydraulic (flow) forces. Locations are listed in Table 2 and shown in Figure 2. These field data were then used to establish the ranges of bank-material properties for each major drainage basin (ie. Hatchie, North Fork Forked Deer, Middle Fork Obion, etc.). Results were then used as inputs into BSTEM-Dynamic for numerical modeling of bank erosion and the effectiveness of bank protection for all sites within the specific basin. As expected, results showed generally erodible bank materials, particularly within the Hatchie and Loosahatchie River Basins. In contrast, banks of the Middle Fork Forked Deer showed relatively more resistant materials. The inter-quartile ranges of the most important bank-resistance data for hydraulic erosion (critical shear stress) and mass failure (effective cohesion) are shown in Figure 3.

Table 2 Spatial distribution of field-test locations by major drainage basin and rivers in West Tennessee.

Basin	River & tributaries	Number of tests	
		BST	Jet
Hatchie	Hatchie	12	15
Loosahatchie	Loosahatchie	16	17
Forked Deer	Middle Fork	10	6
	North Fork	8	8
	South Fork	6	6
Obion	Middle Fork	6	6
	North Fork	6	6
	Rutherford Fork	6	5
	South Fork/Main stem	13	10
Wolf	Wolf	4	4

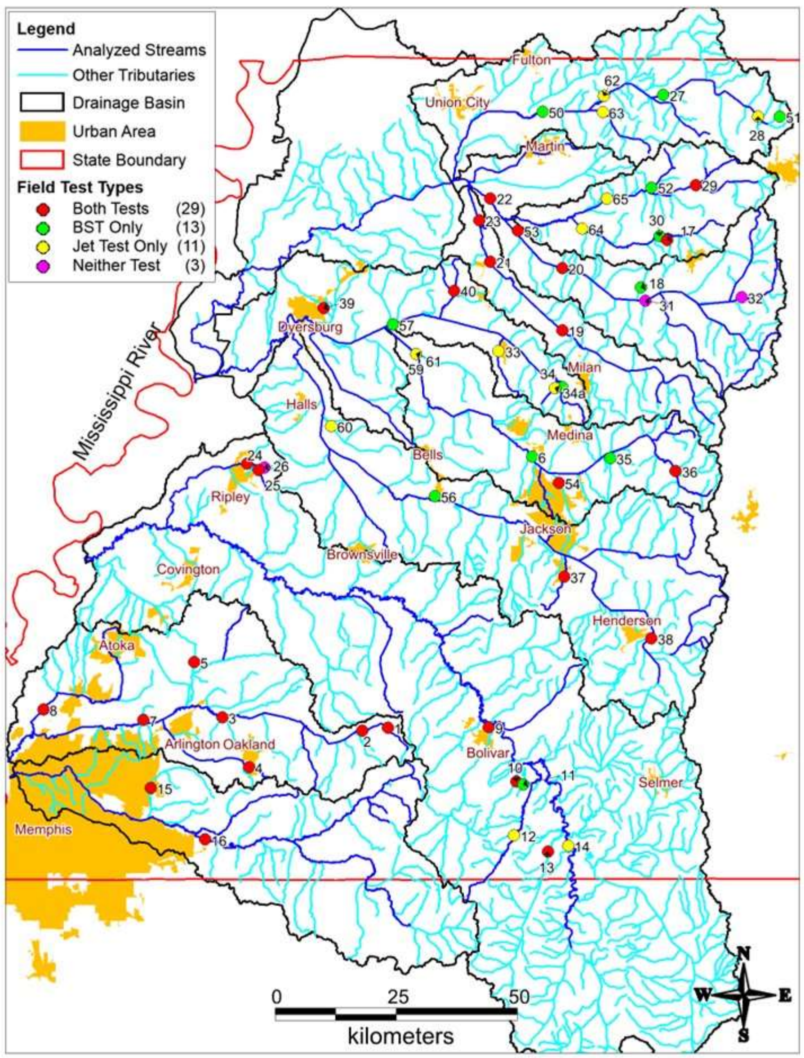
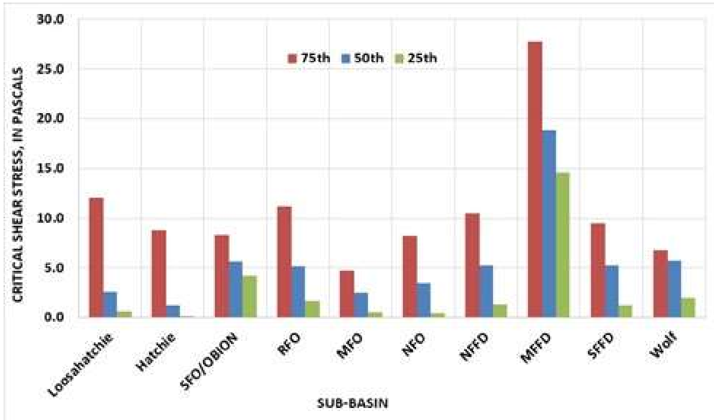
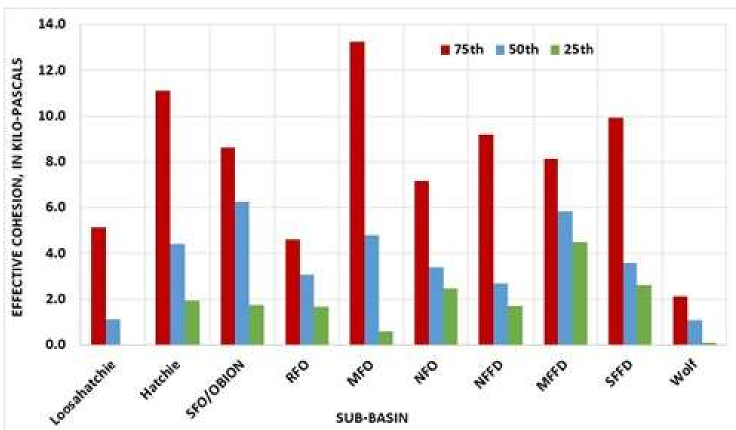


Figure 2 Map of locations of field-data collection of bank materials used to determine distributions of hydraulic and geotechnical resistance.



Basin	Percentile			# Tests
	75th	50th	25th	
Loosahatchie	12.0	2.63	0.641	17
Hatchie	8.81	1.23	0.154	15
SFO/OBION	8.26	5.63	4.22	10
RFO	11.2	5.19	1.65	5
MFO	4.76	2.53	0.55	6
NFO	8.18	3.48	0.49	6
NFFD	10.5	5.22	1.28	8
MFFD	27.8	18.9	14.56	6
SFFD	9.5	5.21	1.26	6
Wolf	6.7	5.71	2.00	5



Basin	Parameter	Percentile			#Tests
		75th	50th	25th	
Loosahatchie	c'	5.13	1.10	0.00	16
	ϕ'	36.9	35.8	31.9	
Hatchie	c'	11.1	4.42	1.93	12
	ϕ'	35.1	30.5	28.7	
SFO/OBION	c'	8.61	6.26	1.72	13
	ϕ'	33.7	32.7	29.7	
RFO	c'	4.57	3.05	1.67	6
	ϕ'	35.3	34.8	33.8	
MFO	c'	13.2	4.76	0.55	6
	ϕ'	36.5	35.0	34.3	
NFO	c'	7.15	3.40	2.43	6
	ϕ'	35.8	32.5	31.4	
NFFD	c'	9.18	2.67	1.70	8
	ϕ'	36.4	34.7	30.5	
MFFD	c'	8.14	5.83	4.49	10
	ϕ'	36.8	33.4	28.5	
SFFD	c'	9.92	3.57	2.59	6
	ϕ'	32.9	31.9	31.0	
WOLF	c'	2.11	1.07	0.10	4
	ϕ'	38.0	37.3	35.6	

Figure 3 Median values and inter-quartile range (25th and 75th percentiles) of critical shear stress (in Pascals) for the 10 drainage systems studied (Top) and effective cohesion (c') (Bottom). Effective friction angle (ϕ' is also shown).

Numerical Modeling of Erosion Rates and Effectiveness of Alternative Treatments using BSTEM-Dynamic

Numerical modeling of bank stability and erosion form the crux of the analytic investigation into the applicability, effectiveness and cost-effectiveness of rock and other bank-stabilization measures in West Tennessee. Here we utilize scaled values of flow with measured data on bank resistance to simulate bank-erosion rates across the region under "existing" and mitigated conditions. Differences between these rates for a given set of bank and channel conditions represent the effectiveness of different treatment options.

Developing a Flow Series to Model Bank Erosion

This task involved developing a flow series to model each of the 155 sites that could be used as input along with site-specific channel geometry and basin distributions of bank-material resistance. Following analysis of the available flow data, 19 gaging stations were selected for use, and these provided a coverage from 1/1/2000 to 12/31/2012. An example of the 13-year flow series from one station in each of the 5 major drainage systems is shown in Figure 3. Notable peaks occurred late November to early December 2001, early May 2010, and late April to early May 2011.

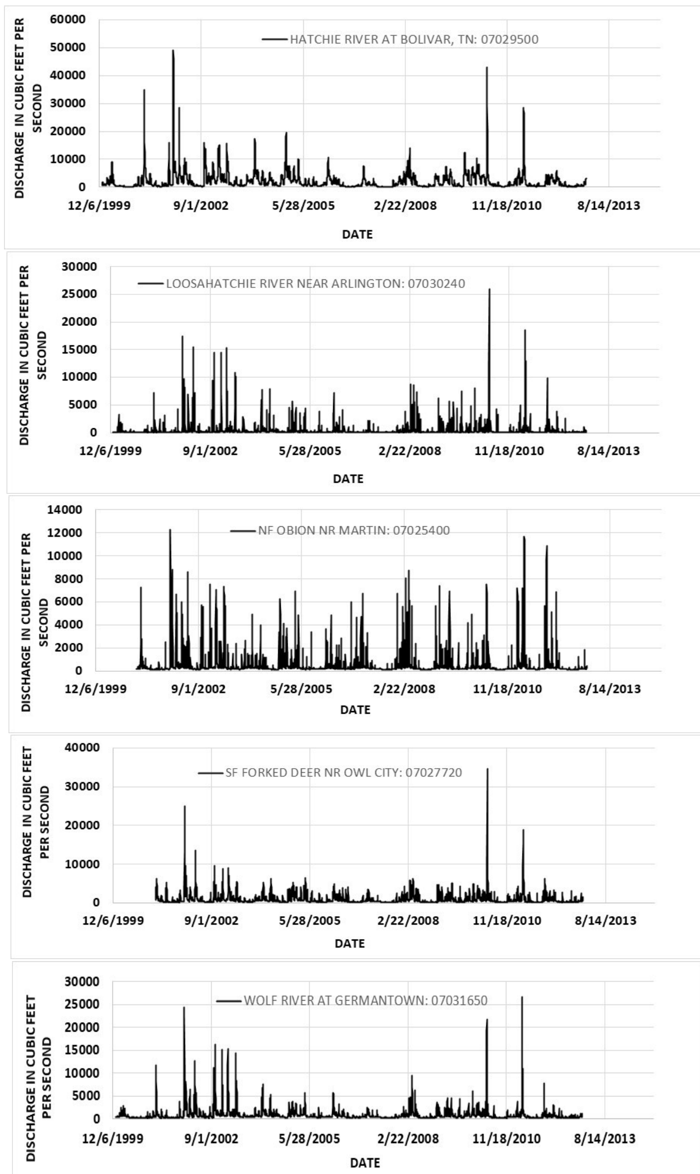


Figure 3 Examples of mean-daily flows for 2000-2012 for 5 gaging stations in West Tennessee, one from each of the five major drainage systems in the region. Data from these gages and 14 others were used to develop flow series for all 155 modeled sites.

Using the flow, geometry and bank-resistance data described above, numerical modeling of bank-erosion rates for the 2000-2012 period was conducted with BSTEM-Dynamic to represent "existing" conditions without any protection. Results of this modeling established a data base of average-annual erosion rates for the 155 sites and their respective drainage basins. It was also important to conduct these numerical analyses using bank-resistance values that represented not only the median value from each basin, but a broader measure of values representing the central tendency of these distributions (25th and 75th percentiles, representing the inter-quartile range). This is because physical testing of the bank materials was not conducted at the 155 modeled sites but at other sites throughout the sub-basins, thereby providing somewhat of a sensitivity analysis based on bank resistance.

For the 13-year modeling period, bank-erosion (in meters cubed per meter; m^3/m) ranged from zero to 2,025 for 25th percentile bank resistance, to 240 for median bank resistance, and to 29.1 for 75th percentile bank resistance. Median values were 51.6, 0.3 and 0.0 $m^3/m/y$ for the same three resistance conditions. In general, differences in total erosion reflect the role of bank resistance and show order of magnitude differences due to differences in critical shear stress and effective cohesion. It is perhaps more instructive to consider the bank-erosion data as a loading rate that is in tonnes per peter per year (t/m/y). In this case and assuming no bank vegetation, values that are exceeded only 0.01% of the time (99.99th percentile) vary from about 3.8 t/m/y for the 75th percentile of bank resistance to 265 t/m/y at the 25th percentile. Median values decrease from 6.7 t/m/y for the weaker 25th percentile values to 0.04 t/m/y for the median resistances, to 0.0 for the stronger, 75th percentile values. The variation for the inter-quartile range of resistances are shown in Figure 4.

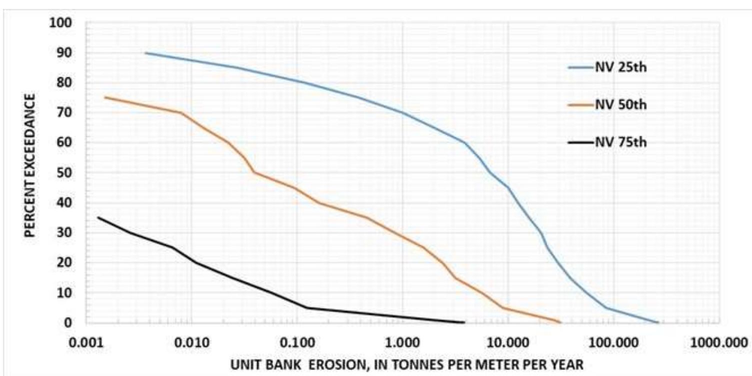


Figure 4 Distribution of modeled unit bank-erosion rates (in t/m/y) showing erosion differences due to bank resistance. Note: NV25th, NV50th and NV75th refer to the 25th, 50th, and 75th percentiles of bank-resistance (without vegetation) assigned to each site (based on basin-specific distributions), respectively.

As with the results for all sites considered collectively, differences in bank-erosion rates for the three bank-resistance conditions show important differences by sub-basin (Figure 5). Most of the increases in median erosion rates seen in Figure 5, (due to weaker [25th percentile] bank resistance) is about two orders of magnitude, with the exception of the three highest eroding basins (Loosahatchie, Hatchie and North Fork Obion) which already have relatively high erosion rates for the 50th percentile bank resistance. In these three cases, however, the increases are still 737%, 2,300% and 3,300% respectively, again highlighting the crucial importance of bank strength in controlling erosion rates.

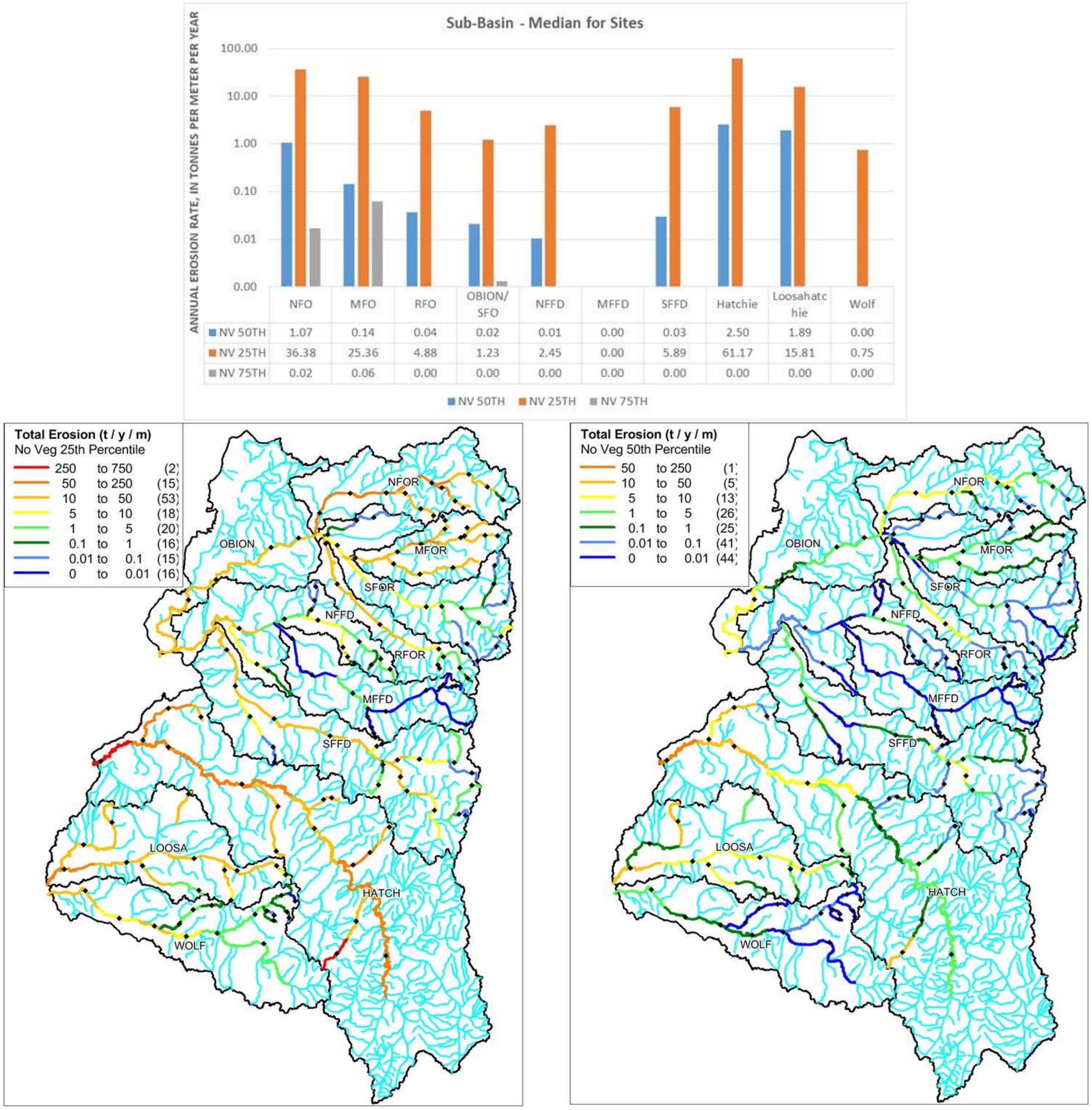


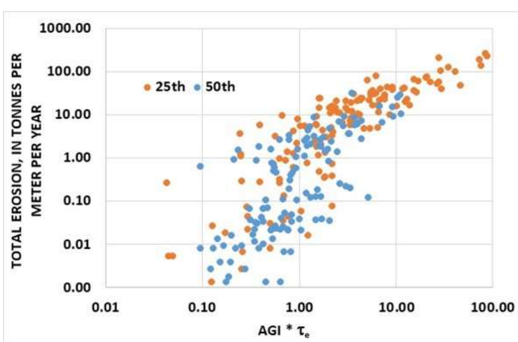
Figure 5 Comparison of annual rates of bank erosion (in t/m/y) for the three quartile measures of bank resistance in the studied sub-basins for the "existing" non-vegetated condition (Top), spatial distribution for 25th percentile resistance (Bottom Left) and Median bank resistance (Bottom Right).

Development of Physically-Based Metric to Spatially Extrapolate Modeled Results

To provide greater detail and extend the spatial integration of bank-erosion rates to the other non-modeled sites that were extracted from the LiDAR database, an empirical relation between modeled erosion rates and physically-based metrics characterizing the sites had to be developed. A series of relations were subsequently tested that in part utilized a measure of total stream power known as the area-gradient index (AGI). This metric is defined as the product of drainage area and bed slope (or gradient) and is a convenient substitute for total stream power because bankfull discharge is closely related to drainage-basin area. To provide a further physical basis on a site-by-site basis, we multiply the AGI by the excess shear stress ($\tau_e = \tau_o / \tau_c$) at bankfull discharge to obtain AGI * τ_e and regress with the modeled bank-erosion rates. To calculate AGI * τ_e from the database of erosion rates for both the 25th and 50th percentile bank-resistance values, the following steps were followed:

1. Take the drainage area of the specific site;
2. Calculate average boundary-shear stress at the bankfull discharge from γ d S, where
   a. Bankfull depth (*d*) is calculated as the height between the estimated thalweg elevation and the elevation of the lower bank (first overflow surface); and
   b. Bed slope (*S*) is given for each site from the LiDAR-extracted data.
3. Assign the critical shear stress (τ_c) according to the relevant 25th or 50th percentile resistance-value for the appropriate sub-basin for the site (τ_c-25th; τ_c-50th);
4. Calculate excess shear stress (τ_e) for the weaker 25th percentile-resistance materials and the median-resistance materials to obtain τ_e-25th and τ_e-50th.

Results of this analysis showed that roughly 80% of the variance in bank-erosion rates could be explained on a region-wide basis in terms of the metric AGI * τ_e, providing a means to potentially interpolate and extrapolate values to non-modeled reaches of the channel network. Combining the 25th and 50th percentile resistance data provides for a continuum of erosion rates based on differences in excess shear stress while maintaining the consistency of a constant AGI. In a sense then this metric combines two parameters, with one representing available force (AGI) and the other, relative resistance (τ_e). To provide improved applicability and detail for the specific basins, similar relations were developed for each of the major drainage systems (Table 3) and used to extrapolate erosion rates to non-modeled reaches (Figure 7).



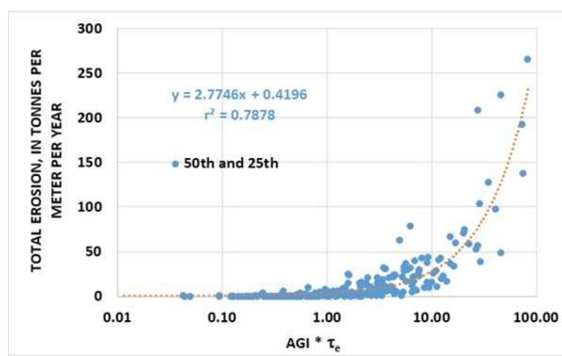


Figure 6 Relation between AGI * τ_e and total bank erosion (in t/y/m) in log-log space and separated into the 25th and 50th percentile excess-shear and erosion values (Left), and in semi-log space for all data combined (Right).

Table 3 Summary of linear-regression equations relating modeled bank-erosion rates to the AGI * τ_e metric for each of the major drainage systems in West Tennessee.

River system	Equation (x is AGI * τ_e)	Constraint*		r^2	AGI* τ_e	
	Total Erosion (t/m/y)	AGI*taue <	Value (t/m/y)		Max	Min
Obion	y = 3.07176x + 0.20848			0.813	28.9	0.04
Forked Deer	y = 3.80538x - 1.06718	0.33	0.188	0.803	7.72	0.01
Loosahatchie	y = 1.27731x + 4.01558			0.776	46.3	0.54
Hatchie	y = 2.83450x + 7.19445			0.771	83.7	0.63
Wolf	y = 1.71442x - 0.70202	0.41	0.055	0.708	8.62	0.02

*Constant erosion estimate below this constraint value

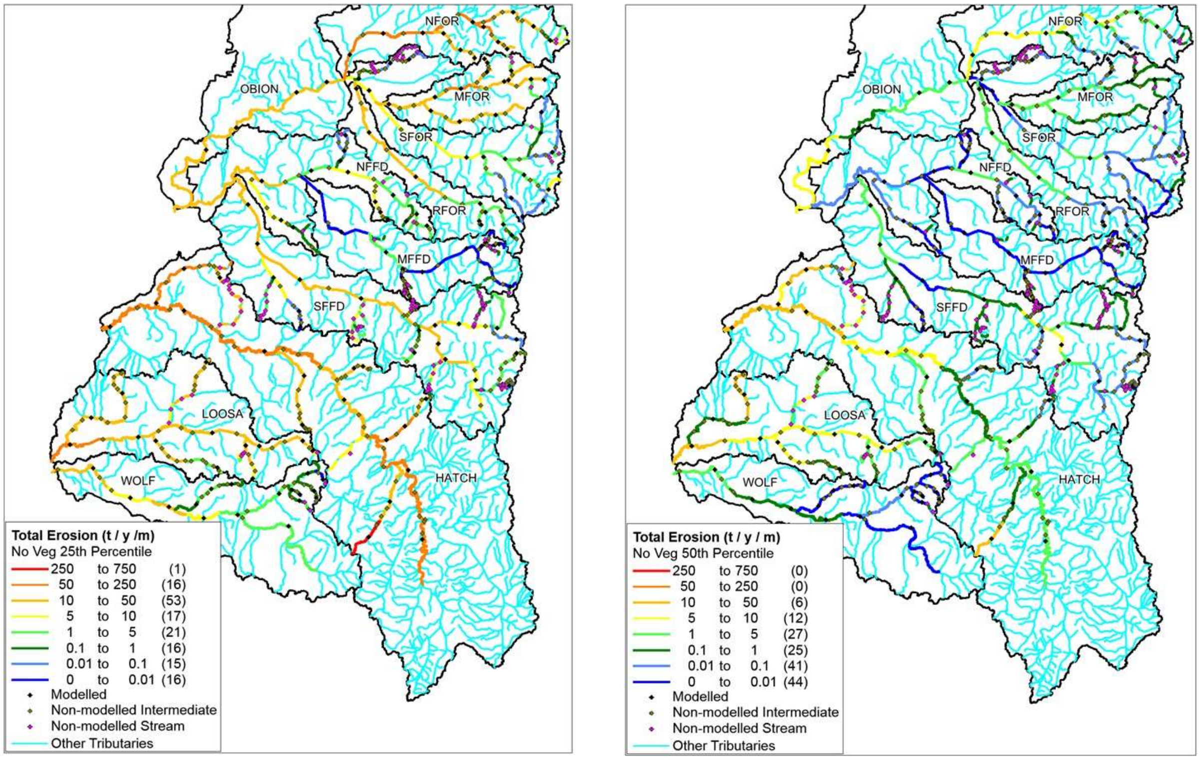


Figure 7 Spatial distribution of average-annual bank-erosion rates (in t/m/y) extended to non-modeled reaches using predictions based on basin-specific AGI * τ_e relationships and assuming 25th percentile (Left) and 50th percentile (Right) bank resistance for the 347 non-modeled sites.

Modeling Results for Alternative-Mitigation Measures

Three types of alternative measures were modeled with BSTEM-Dynamic to determine the amount of erosion under these mitigation scenarios and the magnitude of erosion-rate reductions that could potentially be achieved. As previously stated, these included the use of:

- Riparian vegetation (V) to provide increased bank strength (3.9 kPa) through root reinforcement over the upper 1.0 m of the bank as well as increased hydraulic roughness (n, from 0.025 to 0.035) which serves to reduce the effective hydraulic shear operating on the bank surfaces;
- Placement of 500 mm rock at the bank toe (RT; defined here as 1/3 of the bank height), thereby increasing the critical shear stress and thereby the hydraulic stress required to initiate bank scour and undercutting; and
- Placement of rock along the entire bank surface (RA) based on same rationale as for RT, but providing additional resistance to the upper 2/3 of the bank surface.

In addition, the following setup rules specific to input requirements for BSTEM-Dynamic were put in place:

- Top of the bank toe was set to 20% of the total bank height;
- Depth of the top layer (Layer 1) was set to 1.0 m to accept the root-reinforcement value of 3.9 kPa for the V condition;
- Layer 5 to be the lowest 20% of the bank height to accept the lower n-value for the V case;

- Height/thickness of Layer 4 to be the difference in the heights of the 20% and 33% heights for the RT runs; and
- Last topographic point for bank geometry to be located at ½ of the bottom width from the base of the bank toe.

Because erosion using 75th percentile bank-resistance values was generally very low under "existing conditions", BSTEM-Dynamic simulations of the three mitigation measures were conducted only for the conditions of 25th and 50th percentile bank resistance. Region-wide differences in bank-erosion rates for all tested scenarios can be summarized conveniently by frequency distributions of total erosion ($m^3/m/y$), unit bank-erosion rates (in t/m/y) (Figure 8). Three distinct patterns stand out:

- There are relatively small improvements (erosion reductions) between the non-vegetated, "existing" case and the vegetated case;
- There are large, significant improvements (reductions in erosion) for the two scenarios that employed rock; rock at the toe (RT) and rock along the entire bank face (RA); and
- For the highest erosion rates (lowest exceedance values) there is little difference between the two rock options (RT and RA).

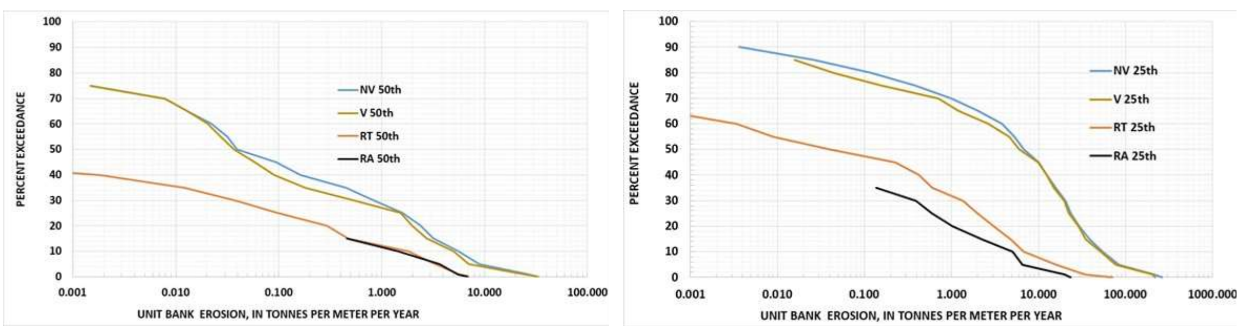


Figure 8 Comparisons of distributions of unit-bank erosion rates (in t/m/y) for the "existing" non-vegetated condition and the three modeled mitigation options: vegetated (V), rock toe (RT) and rock all (RA) for 50th percentile values of bank resistance (Left) and 25th percentile (Right).

Results of this study show that in general terms, the placement of rock or other resistant materials at the bank toe is the most effective means of achieving significant reductions in bank erosion along the stream channels of West Tennessee (Figure 9). This is made possible in part by the fact that continued incision and deepening of the main-stem channels as a response to channel modifications has apparently run its course Simon et al (2020). In those reaches that produce high rates of erosion, the rock-toe option also represents the most cost-effective means of achieving water-quality improvements with regard to sediment concentrations and fine loads. Although the placement of rock along the entire bank surface can show slightly greater reductions in erosion, the significantly greater costs and potentially negative environmental consequences preclude its serious consideration as a viable technique. Vegetation has also been shown to be not only somewhat effective but cost effective as well under particular circumstances where bank heights are not overly high and erosion rates are, therefore, moderate.

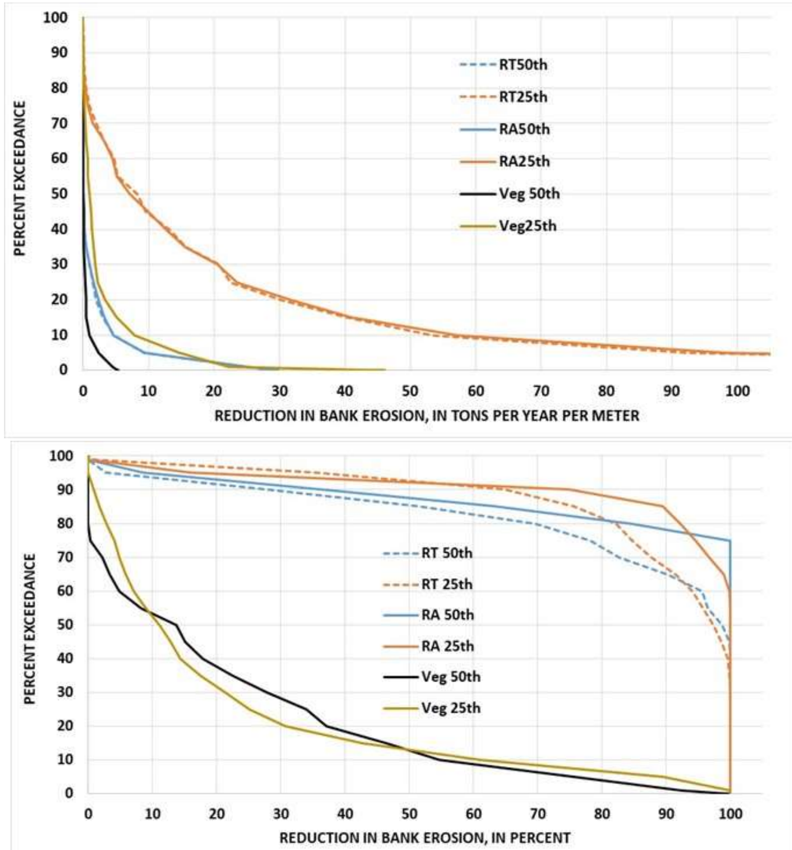


Figure 9 Reductions in unit-bank erosion rates in t/m/) (Top) in percent (Bottom) relative to the comparable non-vegetated “existing” for the three modeled mitigation options: vegetated (V), rock toe (RT) and rock all (RA) for 50th and 25th percentile values of bank resistance.

Applying the erosion-reduction results (existing erosion – mitigated erosion [in t/m/y]) to the AGI * τ_e metric, and mapping the results provides a spatial view of potential reductions in bank erosion across the region. This was conducted for both the 25th and 50th percentile bank-resistance conditions and can be seen in Figure 10. The numbers in parentheses represent the number of modeled sites that fall within each erosion-reduction class. Note that there appear to be some similarities in these spatial distributions, notwithstanding the gross differences in erosion-control effectiveness reported above. This is particularly true in those reaches with relatively low erosion rates. Still, because these maps reflect 50th percentile resistance conditions, they provide a reasonable picture of average reductions in sediment delivery from the channel banks that could be expected.

When viewing erosion reduction under 25th percentile (weaker) bank-resistance conditions, differences in the spatial distribution of effectiveness are starker, with drastic shifts in the classes plotted for individual reaches (Figure 10). Of the 155 sites modeled, planting of vegetation produced reductions > 5 t/m/y at 15 sites (~10%) compared to 77 sites (~50%) for the RT alternative. These maps represent what conditions would be like at the more sensitive sites (owing to the weaker materials) where existing erosion rates would be generally higher. It is along these reaches (or at sites) with weaker materials and perhaps with greater bank heights and angles that have higher erosion rates and hence, where there is greater opportunity for significant reductions.

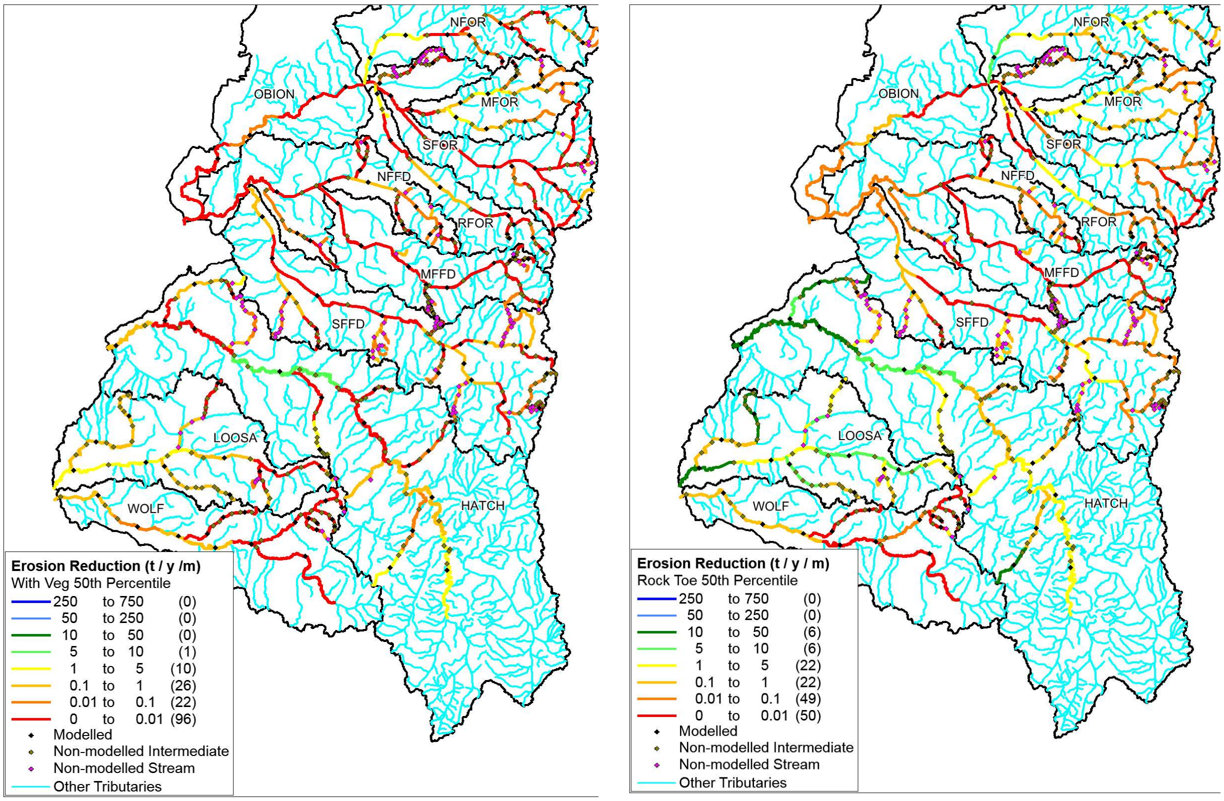


Figure 10 Comparison of the spatial distribution of the average-annual reduction in bank erosion (in t/m/y) using vegetation (Left) versus rock at the bank toe (Right) for median-resistance conditions.

Summary

The channels of West Tennessee have undergone systematic adjustments to their geometry, including incision and widening, over much of the 20th century. As a result, bank erosion from these channels has become a significant source of sediment in the region. The principle aims of this study were to evaluate region-wide rates of bank erosion in the context of the effectiveness of potential erosion-control measures using techniques grounded in analysis of the driving and resisting forces that control bank-erosion processes. The overall objective was to provide a scientifically based, regional-scale, quantitative evaluation of the applicability of the use of rock and other mitigation alternatives to reduce bank erosion along channels of West Tennessee. To accomplish this, we utilized measurements of the hydraulic and geotechnical resistance of the channel banks at more than 80 sites and developed a 13-year flow series from gaging-station data for analysis of bank-erosion rates. This information was input into the dynamic version of the Bank-Stability and Toe-Erosion Model (BSTEM-Dynamic) using channel-geometry data extracted from LiDAR for 155 sites across the region. In addition, previously documented channel-adjustment trends along the mainstem channels were revised to determine where and to what extent, aggradation and degradation processes were still active.

Analysis of the potential for reductions in bank erosion (effectiveness) were limited to three broad measures: vegetation alone, rock at the bank toe and rock along the entire bank surface. Results of this study show that in general terms, the placement of rock or other resistant materials at the bank toe is the most effective means of achieving significant reductions in bank erosion along the stream channels of West Tennessee. In those reaches that produce high rates of erosion, the rock-toe option also represents the most cost-effective means of achieving water-quality improvements with regard to sediment concentrations and fine-sediment loads. Vegetation has also been shown to be not only somewhat effective, but cost effective as well under particular circumstances where bank heights are not overly high and erosion rates are, therefore, moderate.

The overly general measures were used because they could easily be applied to the general channel-geometry and sub-basin distributions of the hydraulic and geotechnical resistance of the banks. In reality, however, application of erosion-control measures is likely to contain combinations of these practices as well additional techniques. With regard to combining some of these measures, vegetative planting would almost always be considered on the mid to upper bank surfaces if rock or other resistant materials (such as large wood) were to be placed at the bank toe. The same goes for the flattening of bank slopes, where vegetation would generally be a part of any design of that type.

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