Modeling Bank Migration on the Missouri River with HEC-RAS: A Calibrated HEC-RAS/BSTEM Model

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The US Army Corps of Engineers' Hydrologic Engineering Center began to include mobile bed capabilities with Version 4.0 of the River Analysis System (HEC-RAS) software. These capabilities compute vertical bed changes in response to dynamic sediment mass balance and bed processes. However, many riverine sediment problems involve lateral bank erosion. Lateral toe erosion and bank failure processes require models that simulate feedback between bed and bank processes. The Bank Stability and Toe Erosion Model (BSTEM) developed by the National Sediment Laboratory, United States Department of Agriculture (USDA), Agricultural Research Station (ARS) was included in HEC-RAS version 5.0 and updated in subsequent releases. BSTEM couples iterative, planar bank failure analysis based on a fundamental force balance with a toe scour model that allows feedback between the hydraulic dynamics on the bank toe. These feedbacks can exacerbate failure risk (in the case of toe scour) or decrease failure risk (in the case of toe protection).

The Missouri River eroded aggressively, downstream of Gavins Point dam for about 20 years after dam closure (Skalak et al, 2013). The erosion along this reach included both bed degradation and bank migration. The Hydrologic Engineering Center (HEC) and the Omaha District of the US Army Corps of Engineers (NWO) developed an HEC-RAS model of the Missouri River from Gavins Point Dam (RM 811) to Ponca (RM 751) to simulate historical large-scale bank movement and sediment inputs, and to evaluate alternative design impacts on future bank movement. The study team selected the bank erosion parameters in the USDA-ARS BSTEM module to calibrate bank migration against five surveys spanning August 1986 through August 2011.

Model Setup

The study team calibrated the model against computed longitudinal cumulative Planform Area Change (LCPAC) curves, rather than the longitudinal cumulative volume change (LCVC) curves that HEC-RAS automatically generates and modelers typically used to evaluate sediment transport models. Planform area change (PAC) is the lateral migration of the bank toe multiplied by the control volume streamwise length. This metric is analogous to computations of bank area loss based on differencing surveyed bank lines with GIS. LCPAC curves differ from LCVC curves in that they do not consider the bank height in change calculations. LCPAC curves may be more representative of bank losses than LCVC curves when surveys of the floodplain surface are missing or have reduced accuracy relative to channel surveys, and to isolate the calibration of bank change from uncertainty in bed change calibration. LCPAC curves can be computed from the HEC-RAS BSTEM outputs (and from historic surveys) as the difference in the bank toe location at a cross-section between successive observations multiplied by the cross-section length.

Cross section geometries were compared to aerial photographs to identify potential issues. Three cross sections (1960RM 775.8, 773.76, 768.41) were problematic because channel migration changed the angle between the original cross section and the river, making them diverge from the 1D assumption of orthogonality. These cross sections would severely over-estimate actual bank migration; an example of this issue is shown in **Error! Reference source not found.**. The identified cross sections were therefore excluded from the calibration dataset.

Figure 1. An example of the potential for erroneous bank change calculations due to channel migration. Range line labels refer to 1941 river mile markers. The channel has migrated such that the survey range line in the lower-right corner becomes essentially parallel to the channel. Erosion of the river-left bank occurring below range line 810.2 would be erroneously captured in repeated surveys of range line 808.5.

BSTEM requires several additional soil parameters. Many of these parameters have significant spatial variability and can vary by multiple orders of magnitude along a short river reach. Even with extensive field data collection efforts, bank erosion parameters (e.g. soil erodibility and critical shear stress) have high uncertainty. The study team opted to use a single representative soil type for the model for initial values prior to detailed calibration. This decision was consistent with the Oct 2012 Missouri River Jet Erosion Testing Report, which established that virtually all banks in the modeled reach are composed of sand. The average gradation generated from the dataset was used for the representative bank soil type. The properties of the representative soil type are shown in Table 1. The study team selected two of these soil properties calibration parameters; the representative values for the remaining six parameters were used for all cross sections. Critical shear stress was the primary calibration parameter to account for the uncertainty in the one-dimensional shear stress assumptions. Erodibility was used as a secondary parameter to account for variability in soil characteristics. Both parameters carry a high degree of uncertainty and are difficult to measure in the field, particularly in sandy soils.

Table 1. Representative bank soil parameters.

Parameter	Value
Saturated unit weight	$117.8 \frac{\mathrm{lbf}}{\mathrm{ft}^3}$
Friction angle	28.3°
Cohesion	$8354 \frac{lbf}{ft^2} (*)$
ϕ^b	15°
Critical Shear Stress	$0.0106 \frac{lbf}{ft^2}$
Erodibility	$8.96 \times 10^{-5} \frac{ft^3}{lbf \cdot s}$
Saturated hydraulic conductivity	$300 \frac{ft}{day} (*)$
Reservoir width	$1\, ft (*)$

(*) This parameter was assigned a synthetic value to prevent bank failure plane computation.

Calibration

The calibration approach adjusted the global erodibility parameter first and then changed local critical shear stresses at each cross-section bank to generate a strong calibration for the 1960-1986 survey period. Both erodibility and critical shear stresses were the adjusted to improve bank migration results for all 5 survey periods. The calibration results are included in 2 (calibration for total combined bank change) and 3 (calibration of left and right bank change separately). These are LCPAC calibrations that compare the cumulative planform area change from the model and the repeated cross sections from upstream to downstream.

A strong calibration was achieved for both banks for all five survey periods. For some cross sections in the lower third of the model reach, calibrating the later surveys required some over-prediction of bank area change in the 1960-1986 period. In general, error between modeled and simulated toe migration were within 25-50%. This is consistent with the expected uncertainty of sediment transport models. Errors in simulated bank migration are magnified by control volume lengths; larger control volumes have a disproportionately large effect on the LCPAC curves relative to the actual error in toe migration. The calibrated critical shear stresses and erodibility mostly varied from 0.0025 to 0.16 lb/ft^2 and 0.0003 to 0.0009 ft^3/lbf/s respectively.

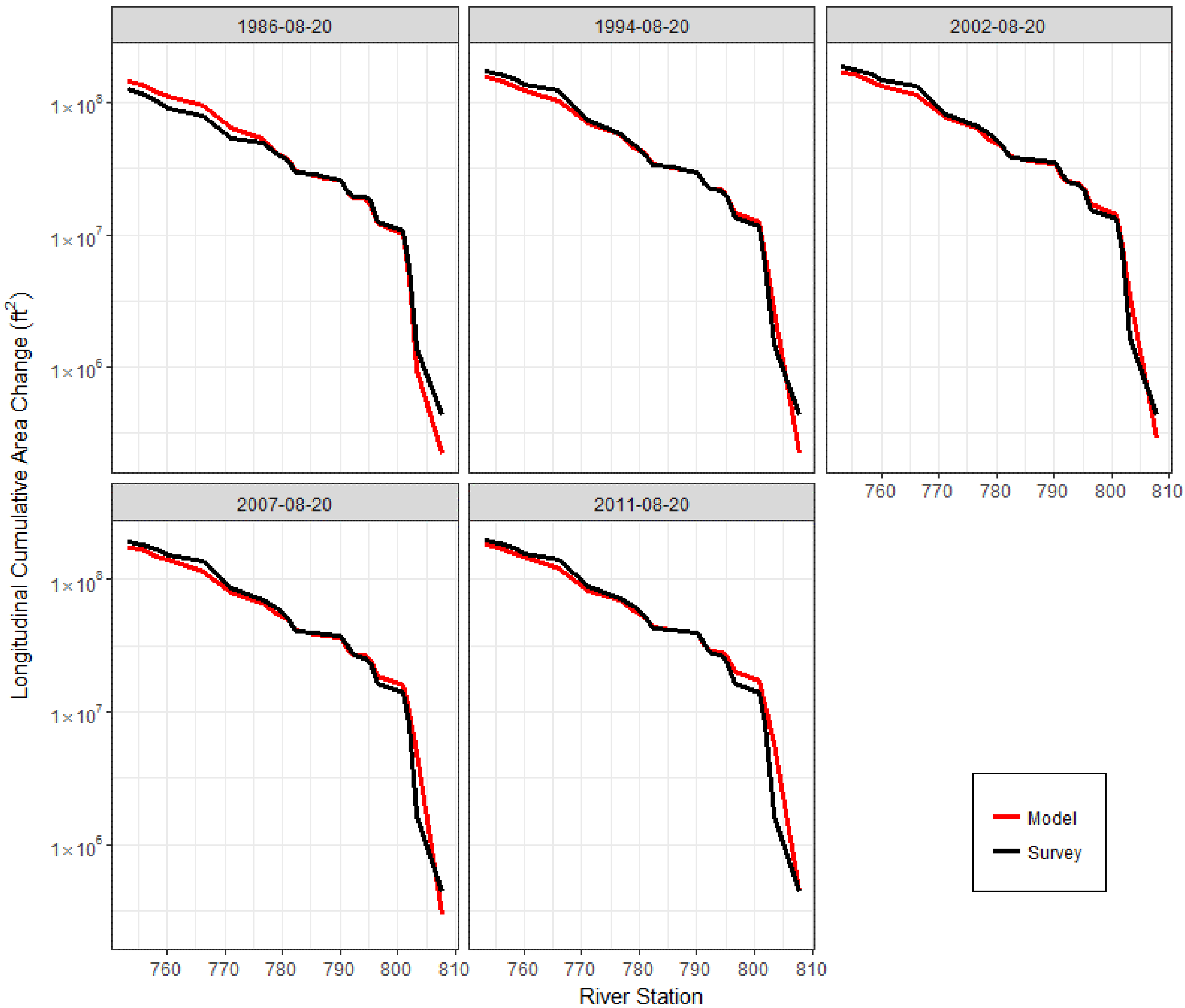


Figure 2. LCPAC calibration results.

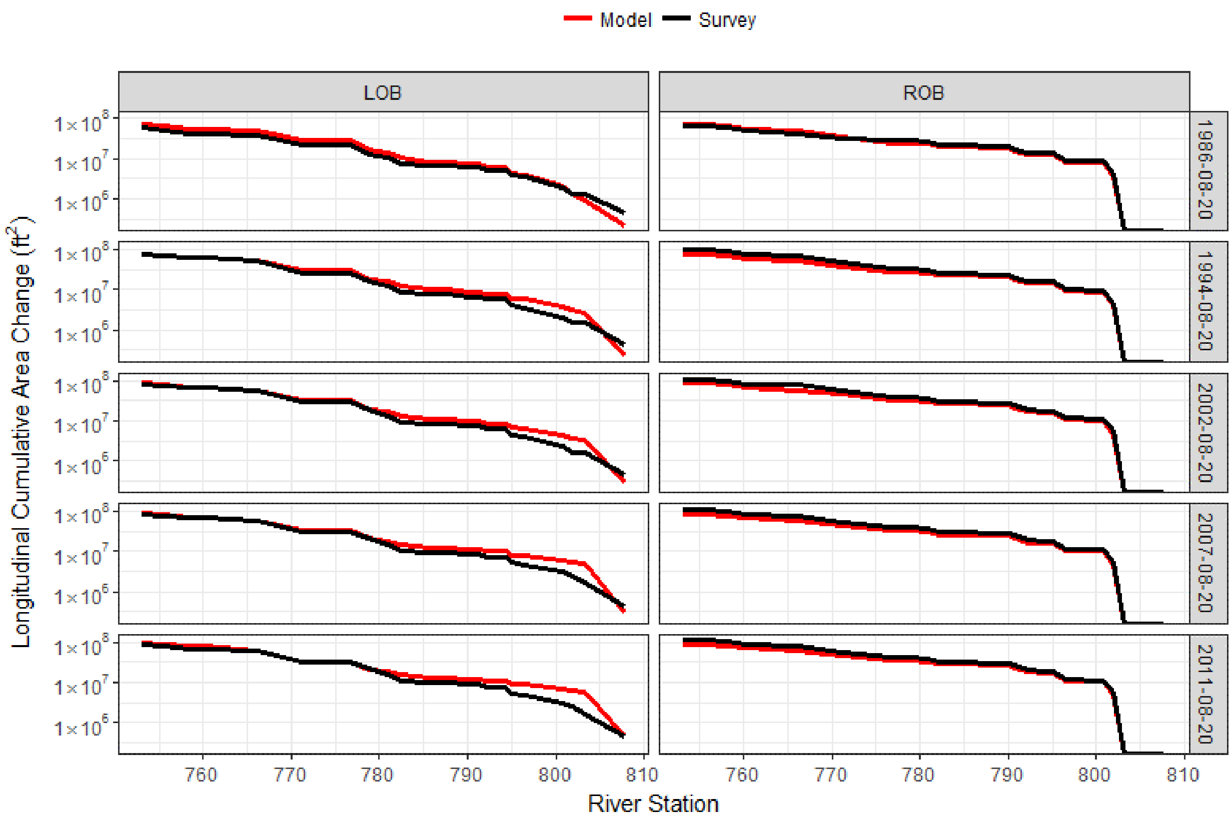


Figure 3. LCPAC calibration results for left and right banks independently.

Modeling Challenges and Lessons Learned

The modeling team encountered several challenges applying the HEC-RAS/BSTEM model on this spatial and temporal scale. These challenges and lessons learned are worth reporting to support future work with this tool.

First, developing an HEC-RAS/BSTEM model requires more careful cross section definition than models that only simulate hydraulics or, even, vertical bed change. Both channel and floodplain geometry contribute to the total volume of computed bank erosion. Therefore, bank erosion analysis requires accurate surveys of both the channel and the floodplain in order to develop accurate estimates of historical bank erosion. The Gavins Reach HEC-RAS/BSTEM model geometry was based on a survey completed in 1960 and compared with five repeat surveys, completed in 1986, 1994, 2002, 2007, and 2011. Some cross sections were not mapped to the same extents in all surveys; for example, the 2007 survey was restricted to the channel and overbank regions were not surveyed. In order to ensure consistency in computations based on the calibration data, missing data for individual cross sections were replaced with data from prior surveys where appropriate.

Second, the BSTEM algorithm is sensitive to the number of cross-section points between the bank toe and top of bank, and to the location of the toe relative to the bank height and adjacent node elevations. The study team found that simplifying BSTEM cross sections by (1) removing nodes between the bank toe and top of bank and (2) ensuring that the bank toe node was located near the channel bed improved model performance and stability. In some cases, small secondary channels were removed to improve model performance. The study team had to correct for these changes for when comparing simulated bank erosion to historical surveys. These geometry modifications to improve model performance changed the original survey data at several locations. Because of these differences, some of the modeled cross sections could not be compared to the surveyed bank volume change and were excluded from the analysis.

Third, HEC-RAS computes bed change and bank migration volume independently. However, parsing lateral bank migration from bed change contributions to the total sediment volume change at a 1D cross section can pose challenges. This is illustrated in the cross section schematic shown in Figure 4. Sediment eroded near the bank toe reflects both bank erosion and bed erosion, but precisely the model cannot identify these contributions precisely. This uncertainty in processes operating at the bank toe must be considered when assessing model performance and validation from calculations of sediment volume. This computational distinction motivated the decision to use LCPAC curves to evaluate the model results. Planform volume analysis avoids issues with floodplain survey accuracy and discriminating between bed and bank change at the toe regions while still capturing the dominant patterns in bank change. The study team computed plan form volume change from the HEC-RAS, HDF5 output using R, but HEC is developing more robust model analysis tools that automate these analyses.

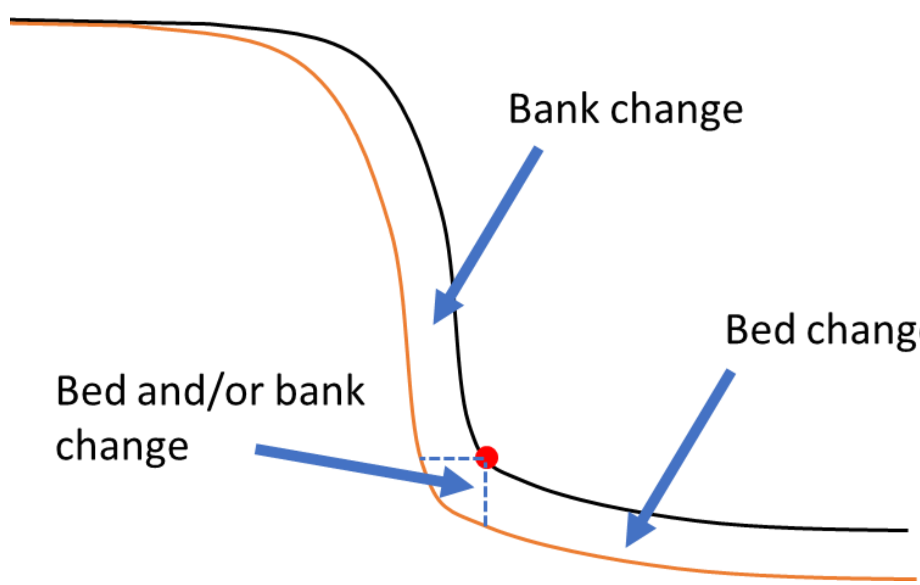


Figure 4. A schematic of cross-section change as computed from survey data. Cross section change in the vicinity of the bank toe can be attributed to bed change, bank change, or some combination of the two.

A fourth challenge arises from simplifications inherent in the cross section-based representation of channels in one-dimensional models. Because bed and bank change computed at cross sections are interpolated upstream and downstream, modeled patterns of cross-section change are significantly simplified and computed bank migration may differ significantly from bank delineations based on aerial or satellite imagery. A schematic of planform area computation at a single cross-section is shown in Figure 5.

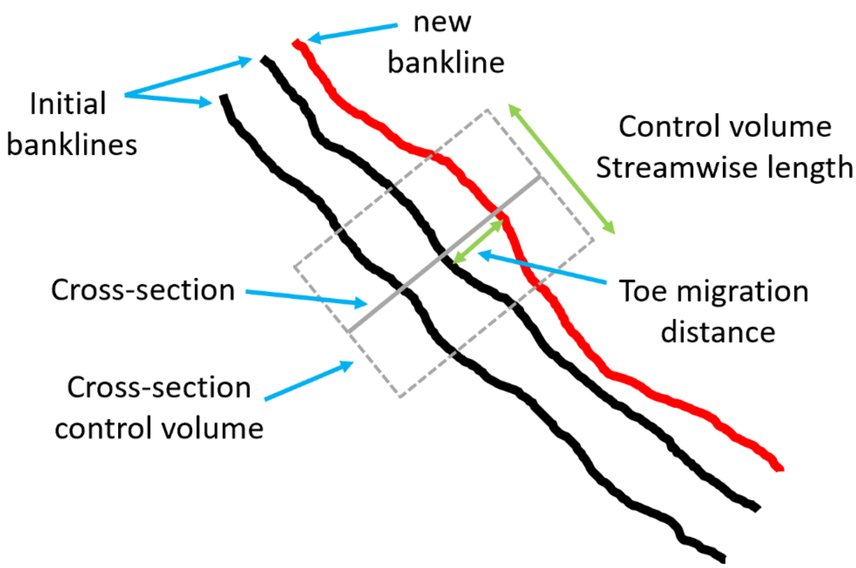
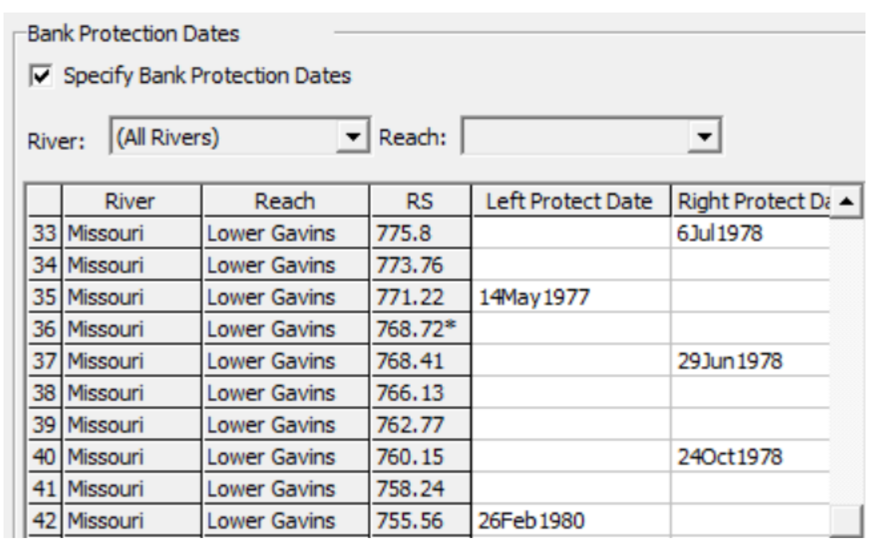


Figure 5. Schematic of bank planform area change computation.

Finally, bank protection complicates long term bank erosion simulations like the one documented above. If agencies or individuals stabilize banks successfully – within a calibration period - a well parameterized model will over-predict bank migration or a modeler might artificially select parameters to match the cumulative erosion assuming the bank eroded over the whole simulation. Both approaches make the model inappropriate for future projections. Therefore, HEC added a bank protection feature to the HEC-RAS/BSTEM module in versions 5.0.3 and later. HEC-RAS can account for bank stabilization by disabling the bank erosion model for any simulation time after a user-specified protection date (Figure 6). Because bank protection was common in the 1970's and 1980's along this reach, the calibration presented in Figure 2 and Figure 3 would not be possible without accounting for it. And without accounting for bank protection, the model would not be useful for projection.



	River	Reach	RS	Left Protect Date	Right Protect Da
33	Missouri	Lower Gavins	775.8		6Jul1978
34	Missouri	Lower Gavins	773.76		
35	Missouri	Lower Gavins	771.22	14May1977	
36	Missouri	Lower Gavins	768.72*		
37	Missouri	Lower Gavins	768.41		29Jun1978
38	Missouri	Lower Gavins	766.13		
39	Missouri	Lower Gavins	762.77		
40	Missouri	Lower Gavins	760.15		24Oct1978
41	Missouri	Lower Gavins	758.24		
42	Missouri	Lower Gavins	755.56	26Feb1980	

Figure 6: Bank protection tool added to HEC-RAS version 5.0.3 and later.

Conclusion

The USDA-ARS Bank Stability and Toe Erosion Model (BSTEM) incorporated in HEC-RAS simulated bank migration on the Missouri River, downstream of Gavins Point dam. The calibration required critical shear stresses that spanned three orders of magnitude to reproduce longitudinal volume change (per cross section and for each individual bank) over five calibration periods spanning 71 years. The calibrated erodibilities spanned less than two orders of magnitude, with the majority of cross sections requiring an erodibility slightly smaller than the value determined from laboratory analysis.

References

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