A PHYSICALLY-BASED CHANNEL-MODELING FRAMEWORK INTEGRATING HEC-RAS SEDIMENT TRANSPORT CAPABILITIES AND THE USDA-ARS BANK-STABILITY AND TOE-EROSION MODEL (BSTEM)

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Abstract: One-dimensional sediment-transport models historically simulate vertical channel adjustment, raising or lowering cross-section node elevations to simulate erosion or deposition. This approach does not account for bank erosion processes including toe scour and mass failure. In many systems lateral channel adjustments can be as important – or more important – than vertical bed changes. There is also important feedback between incision, deposition, toe scour, and bank-failure processes. Each process can depend on the others. Additionally, bank-derived sediments can affect downstream processes and impact downstream projects, depositing in flood damage reduction channels, silting natural or engineered spawning substrates, or filling downstream reservoirs. Therefore, to account for these processes and feedback between them, the USDA-ARS Bank Stability and Toe Erosion Model (BSTEM) has been integrated with the sediment transport methods in HEC-RAS 5.0.

BSTEM is a physically based bank-erosion model that accounts for hydraulic, toe erosion and bank-failure processes in homogeneous or layered banks. It computes toe-erosion by subdividing flow segments in the near bank zone to compute a vertical distribution of boundary shear stresses and calculates a critical failure plane through layered bank sediments, failing the bank and adjusting the cross section when driving forces exceed resisting forces.

Because of their complementary features, river modelers often run HEC-RAS and BSTEM iteratively, in tandem, simulating toe scour and bank failure with BSTEM and computing water surface elevations, simulating bed change and routing bed and bank-derived sediment with HEC-RAS. To provide a more efficient, integrated modeling framework and continuous simulation of potential bed and bank-erosion loadings, HEC-RAS and BSTEM have been coupled, automating the feedbacks between hydraulic, bed, toe, and bank processes. BSTEM uses HEC-RAS hydraulics to determine water surface elevations and to compute the vertical distribution of shear stresses along the bank surface, and evaluates if cross section deposition or erosion simulated by HEC-RAS sediment transport exacerbates or improves bank stability. If BSTEM computes failure, HEC-RAS updates the cross section to reflect the new bank geometry and adds the sediment mass of the failed layers (by particle-size class) to the transport model, routing it downstream. This paper will describe the model integration, and present an example application and model validation.

Keywords: Sediment modeling, Bank Failure, Toe Erosion, HEC-RAS, BSTEM

INTRODUCTION

The USDA ARS – Bank Stability and Toe Erosion Model (BSTEM) simulates two major stream bank erosion processes:

1. Bank Failure: A geotechnical model that evaluates bank stability by computing failure planes through the bank to determine if the driving forces exceed the resisting forces, and selecting the 'critical failure plane,' with the lowest factor of safety.

2. Toe Scour: A lateral erosion model that computes a shear distribution between the water surface and bank toe and simulates lateral hydraulic scour in this zone.

HEC-RAS sediment transport simulates a third processes:

3. Channel Erosion or Deposition: Vertical adjustment of the channel portion of the cross section in response to erosion or deposition.

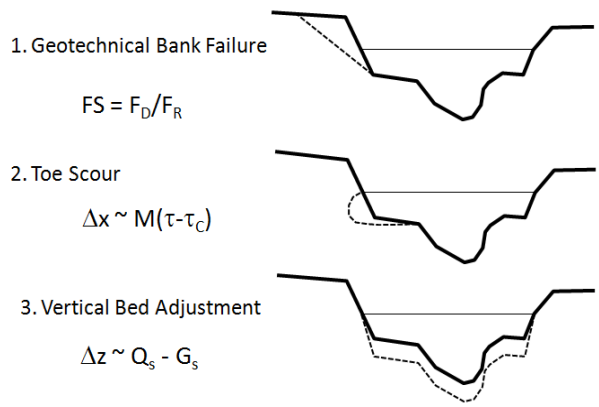

Figure 1 The three processes coupled in the integration of the USDA-ARS BSTEM model and HEC-RAS, including bank and toe-erosion processes from BSTEM and vertical adjustment (and sediment routing) from HEC-RAS, where FS=factor of safety, F_D=driving forces, F_R=resisting forces, Δx=lateral bank change, M=erodibility, τ=shear stress, τ_c=critical shear stress, Δz=vertical bed change, Q_s=sediment supply, and G_s=sediment capacity.

However, these three processes interact. Vertical change can stabilize toes or steepen banks, accelerating or preventing bank failures. Bank scour and failure add sediment to the stream, affecting sediment continuity and downstream deposition or erosion while decreasing available shear stress for a given discharge. To simulate these processes simultaneously, and to capture the interactions and feedbacks between them, USDA-ARS BSTEM algorithms were incorporated into the HEC-RAS sediment-transport algorithms.

METHODOLOGY

Exhaustive presentation of the processes, equations and algorithms that compose USDA-ARS BSTEM and HEC-RAS sediment transport are outside of the scope of this paper. A separate document accompanies the HEC-RAS 5.0 (USACE, 2015), documenting the methodology in detail. However, it is important to summarize the model approach to the three main processes:

1. Bank Failure Methods

The USDA-ARS Bank Stability and Toe Erosion Model (BSTEM) computes the critical linear failure plane through layered bank materials. It uses either the method of slices (Langendoen and Simon, 2008) or the horizontal layer method (Simon et al., 2000) to compute a factor of safety for multiple failure planes, starting at several elevations along the bank and extending through the bank at multiple angles. At each time step specified, a "bracket and Brent" optimization algorithm (Teukolsky et al., 2007) converges on the critical failure-plane angle at each bank intersection point within a few iterations and

selects the failure plane with the lowest factor of safety as the 'critical failure plane'. If BSTEM computes a factor of safety less than 1.0, HEC-RAS fails the bank, introducing the failure block mass into the sediment routing model as a sediment source. HEC-RAS also updates the cross section to compute future hydraulics based on the new, wider, cross-section geometry. The geotechnical model can compute failure planes through homogeneous banks or 'soil layers,' stratified materials with distinct vertical variation in soil properties. The method of slices can also compute tension cracks, which decrease failure plane length, usually removing more resisting forces than driving forces, decreasing the factor of safety and increasing bank-failure frequency.

The geotechnical algorithms are very sensitive to pore-water pressure. Positive and negative pore-water pressures are computed from groundwater elevation and the relation between hydrostatic pressures in the bank and the confining hydrostatic forces from the water in the channel. Groundwater elevation can be specified in HEC-RAS or computed dynamically, in response to rising and falling water-surface elevations in the channel, with a simple 'bank reservoir' groundwater model.

2. Toe Scour Methods

The BSTEM toe erosion model (Simon et al., 2011) moved specified cross section nodes normal to the bank surface. HEC-RAS moves nodes laterally to keep nodes from eroding below the bed elevation. The toe scour methods use cohesive equations if ≥20% (an adjustable threshold) of the layer is silt and clay and cohesionless methods if the fine content is lower than the threshold. Cohesive scour uses a simple excess shear equation emphasizing site specific soil parameters (critical shear stress and erodibility [k in cm^3/N-s or ft^3/lbf-s]). However, neither laboratory nor field methods reliably measure cohesionless erodibilities, so the cohesionless methods apply transport functions. Applying bed transport equations to well graded (poorly sorted) bank sediment (especially with substantial silt or clay content, but not enough to trigger the cohesive equations) can pose sorting problems and often over predicts scour. Bed sorting algorithms and theory (Gibson and Piper, 2007) are not directly applicable. The development team is experimenting with alternate bank sorting methodologies to model these processes.

Both cohesive and cohesionless toe scour methods compute lateral adjustment based on local bank shear at each cross section node. HEC-RAS is a one-dimensional model, which computes a single, cross section average bed shear for each time step. Bank shear stress is maximum at the bed, decreasing up the bank towards the water surface, so applying the average bed shear to all bank nodes overpredicts scour. BSTEM accounts for this, computing shear at each inundated bank node with a radial shear distribution, based on the ratio of the hydraulic radius of the local radial flow zone to the hydraulic radius of the bank (Simon et al., 2011).

Unlike stand alone, USDA-ARS versions of BSTEM (Simon et al., 2011), toe scour algorithms in HEC-RAS cannot currently simulate overhanging banks. If a node scours past the node above it, which is common since shear stress is higher at deeper nodes or material is more erodible, HEC-RAS shears the bank vertically, scouring the higher node to match station of the node below it. This is a technical limitation (HEC-RAS requires monotonically increasing cross section stations) but translates into the physical assumption that cantilever failure will make overhanging banks vertical.

3. Bed Change Methods

HEC-RAS added sediment transport calculations in version 4.0, (Gibson et al., 2006), applying sediment transport functions, bed mixing algorithms, and temporal limiters to compute a sediment balance at each control volume, then adjusting wetted cross section nodes vertically, raising them in response to erosion and dropping them in response to deposition. These capabilities leveraged the full suite of steady flow hydraulic analysis in those earlier versions of HEC-RAS (e.g. ineffective flow areas, inline structures,

flow dependent roughness, etc…) and HEC-RAS 5.0 integrates sediment transport capabilities with unsteady flow (Gibson and Boyd, 2014, Shelley et al. 2015) and powerful features associated with that modeling environment (e.g. lateral structures, flow splits, operational rules).

MODEL INTEGRATION

HEC-RAS 5.0 includes the USDA-ARS Bank Stability and Toe Erosion Model (BSTEM) interface as an optional third tab in the sediment editor (Figure 2). The model requires users to designate the 'bank' portion of the cross section, the nodes that can scour laterally and the zone where failures can start, between the bank 'toe' and 'edge' stations. It also requires a ground water elevation which will either remain static for the entire simulation or initializes the dynamic groundwater model. Finally, BSTEM requires soil properties for each bank layer.

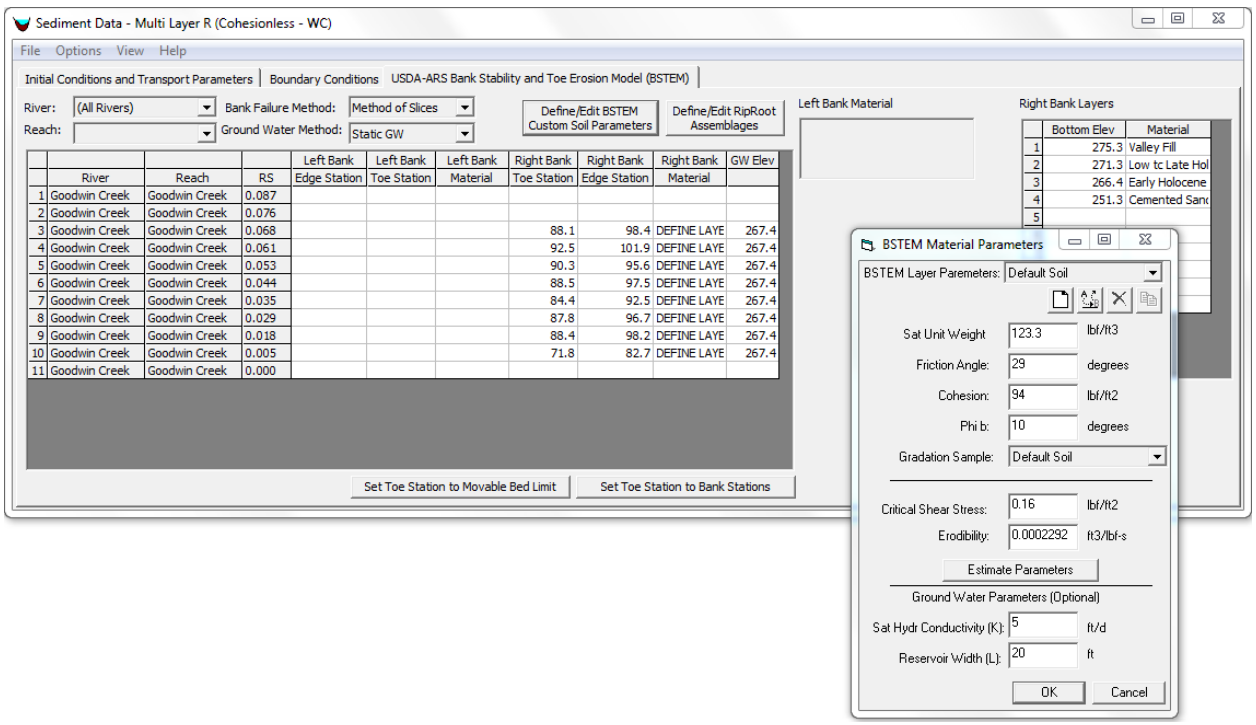

Figure 2 USDA-ARS Bank Stability and Toe Erosion Model (BSTEM) interface in HEC-RAS including the soil parameter interface and an example of soil layer definition.

Defining soil parameters is the most data intensive part of using the BSTEM algorithms. Each soil layer requires classical geotechnical parameters (unit weight, friction angle, cohesion, and bulk unit weight), ϕ^b (representing the rate of increasing apparent cohesion with increasing matric suction), and hydraulic scour parameters (critical shear and erodibility). The model can be very sensitive to these parameters, particularly *k* where values can span orders of magnitude, making them highly site specific. Therefore, HEC-RAS included three methods of increasing complexity, to specify soil properties and negotiate the trade-off between data collection costs and parameter uncertainty. First, HEC-RAS included 16 default parameters from the BSTEM database, regression estimates based on decades of USDA-ARS measurements and modeling. Computing bank erosion in an HEC-RAS sediment model can be as simple as defining bank toe and edge stations, defining a groundwater elevation, and selecting the closest soil type from a default drop down list. However, because these parameters are so site specific, defining customized soil parameters (Figure 2) is recommended. HEC-RAS populates the soil type drop down list with customized soils as well as the default types. Finally, users can specify soil stratigraphy, selecting

the layer contact elevation and either a default or customized soil type for each layer (the method used in Figure 2 and the example application below).

The model can also be sensitive to the toe station parameter. The USDA-ARS BSTEM toe station and the HEC-RAS movable bed limits should generally be the same node, to avoid immobile cross section nodes or double counting scour. HEC-RAS includes a button to copy the movable bed limits to the BSTEM toes, to keep them consistent. If these nodes coincide, channel nodes move vertically and bank nodes move laterally, with the toe/movable bed limit node tracking both degrees of freedom. HEC-RAS also includes an option that deposits (but doesn't erode) outside the movable bed limits, allowing bank stations to move laterally and vertically in one direction.

Bank failure computations can increase sediment simulation run times by as much as an order of magnitude if BSTEM runs for both banks of every cross section at every computation increment. However, HEC-RAS only computes bank processes for banks with BSTEM data, allowing users to analyze particular reaches or stretches. Additionally, the model computes bank failure at every computational increment by default, but can often provide the same results computing on a coarser temporal scale. Users can reduce run times by increasing the number of time steps between bank computations, reducing run times dramatically. HEC is actively working on methods to optimize searches, detect and skip unnecessary computations, and find other opportunities to reduce run times further.

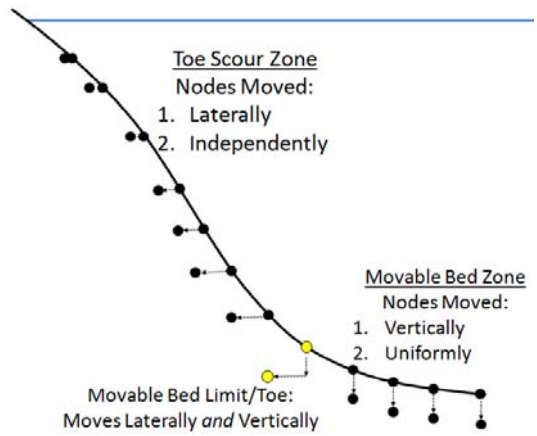

Figure 3 Differences between toe scour and bed change node updates in the coupled HEC-RAS/BSTEM model.

BSTEM algorithms are tied to the sediment transport module in HEC-RAS, requiring a sediment model to perform a dynamic bank-migration analysis. However, bank mechanics can be isolated from bed mechanics by defining the sediment transport parameters but setting the cross section(s) to 'pass through nodes.' A pass through cross section with BSTEM parameters will only adjust the cross section according to the BSTEM processes.

EXAMPLE APPLICATION

The USDA-ARS bank-process models are often tested and validated on Goodwin Creek (Simon et al., 2000; Langendoen and Simon, 2008; Lai et al., 2014), a carefully instrumented research reach in northern Mississippi with detailed hydrologic, groundwater and bank migration time-series data. ARS has measured flow on both major reach tributaries continuously since October 1981, recording flow each time stage changes by a small increment, providing a reliable, high resolution, upstream boundary condition. Up to eleven fixed cross sections were surveyed 51 times, between February 1996, and a bank stabilization project in 2007 (as well as six times since the project), recording up to 8 m of bank migration (Simon et al., 2000; 2008; 2011). The reach also has distinct stratigraphy, with four easily distinguished soil layers, each with detailed soil parameter and erodibility data from extensive borehole shear and jet tests. The soil property measurements, the temporal resolution of the boundary condition and bank migration time series, and the magnitude of the lateral bank scour and failure make Goodwin Creek an ideal site to test the coupled HEC-RAS/BSTEM model.

The initial, 1996 cross sections were used to build the HEC-RAS model and three customized soils were entered in the HEC-RAS Soil Property data base. Cross section "Toe" and "Top of Bank" nodes were

carefully identified and the "Define Layers" option (Figure 2) was selected for each cross section, populating each with the same four-soil-stratigraphy: a cemented sand and gravel conglomerate on the bottom, an early Holocene cohesive soil, a late Holocene cohesive soil, covered with valley fill.

Validation is a wrought concept with unhelpfully broad semantic range in model development (Oreskes et al, 1994; Rykiel, 1996; Gibson, 2013). In this case, 'validation' simply means an exercise to increase user confidence that the algorithms in the HEC-RAS/BSTEM coupling behave as designed by comparing them to field data and other models.

Since this was a model validation, rather than a project calibration, we adopted the parameters from the successful CONCEPTS model in Langendoen and Simon (2008) without adjustment. Langendoen and Simon (2008) adjusted the erodibility and critical shear of the toe material at the outside of a bend to compensate increased shear stresses produced by the three-dimensional flow that the 1D model ignores. The HEC-RAS validation adopted this approach and these parameters.

The toe material in Goodwin Creek is a cemented conglomerate, which controls the stream morphology and the rate of bank recession. The conglomerate has a relatively low fine content (1.4% finer than 63 μm) but has cohesive properties, amenable to jet tests and cohesive erodibity equations. However, since BSTEM uses cohesionless equations, by default, if the layer is less than 20% fine-grained material, the model was run with both the cohesionless approach and with the cohesive, erodibility approach used in Langendoen and Simon (2008) (by dropping the "% fine for cohesionless approach" factor to zero).

The Goodwin Creek analysis was run through the period (Mar 1996 – Feb 2001) replicated by Langendoen and Simon (2008) and then extended to include subsequent migration until the banks were modified as part of a bank-stabilization project in March 2006.

RESULTS

Cohesive model results are plotted with seven, measured, right-bank surveys for two representative, cross sections on Goodwin Creek in Figure 4 (XS6 and XS7, two mid-reach cross sections from Langendoen and Simon, 2008) . The location and shape of the final model cross section approximately matched the observations, estimating total bank migration and computing tension cracks where observed. The tension cracks in the prototype are longer than those the model computed. Langendoen and Simon (2008) customized the tension crack, specifying the observed crack length, but customized crack length is not available in HEC-RAS 5.0. Despite these minor differences, the results suggest the following: First, they represent a code verification step for the HEC-RAS/BSTEM model, demonstrating that it replicates prototype behavior and other model results. Second, results validate the Langendoen and Simon (2008) calibration (based on 1996-2001 measurements), demonstrating that their parameterization performed well outside of its calibrated time window (e.g. 2001-2007).

Select cross sections are plotted in Figure 4. Including all 51 repeated cross-sections would make the plot too dense to evaluate model results. It is still useful to evaluate the model against all measured data, however. Therefore all prototype measurements were plotted with the model results by interpolating the lateral migration time series at five reference elevations in Figure 5. The cross-section stations for lower elevations migrate more gradually in both the prototype and the model, as the toe consistently scours. Bank-failure events expand the higher elevations more episodically. The high bank processes track the observed stations better than the toe scour processes for both cross sections. The model also simulates more retreat at XS6 early in the time series and less later, matching the final migration but not matching intermediate steps. However, given the complexity of the processes and the uncertainty in the data, the spatial and temporal agreement for XS7 is excellent and XS6 is acceptable for most purposes.

Finally, the relative contribution of bank sediment is plotted in Figure 6, differentiating between hydraulic (toe scour) and geotechnical (mass failure) processes. Bank failure contributes almost an order of magnitude more sediment (205.6 tonnes) than toe scour (25.6 tonnes), but the rate of the former is correlated with the rate of hydraulic toe erosion, as expected. Both processes slow as the simulation progresses (a phenomenon also observed in the prototype data in Figure 5). Flows in the first two years were higher than the rest of the simulation, but model results also indicate process feedbacks. Widening cross sections and depositing upstream sediment decrease boundary shear stress and, therefore slow toe erosion and consequently, bank failure rates and overall migration.

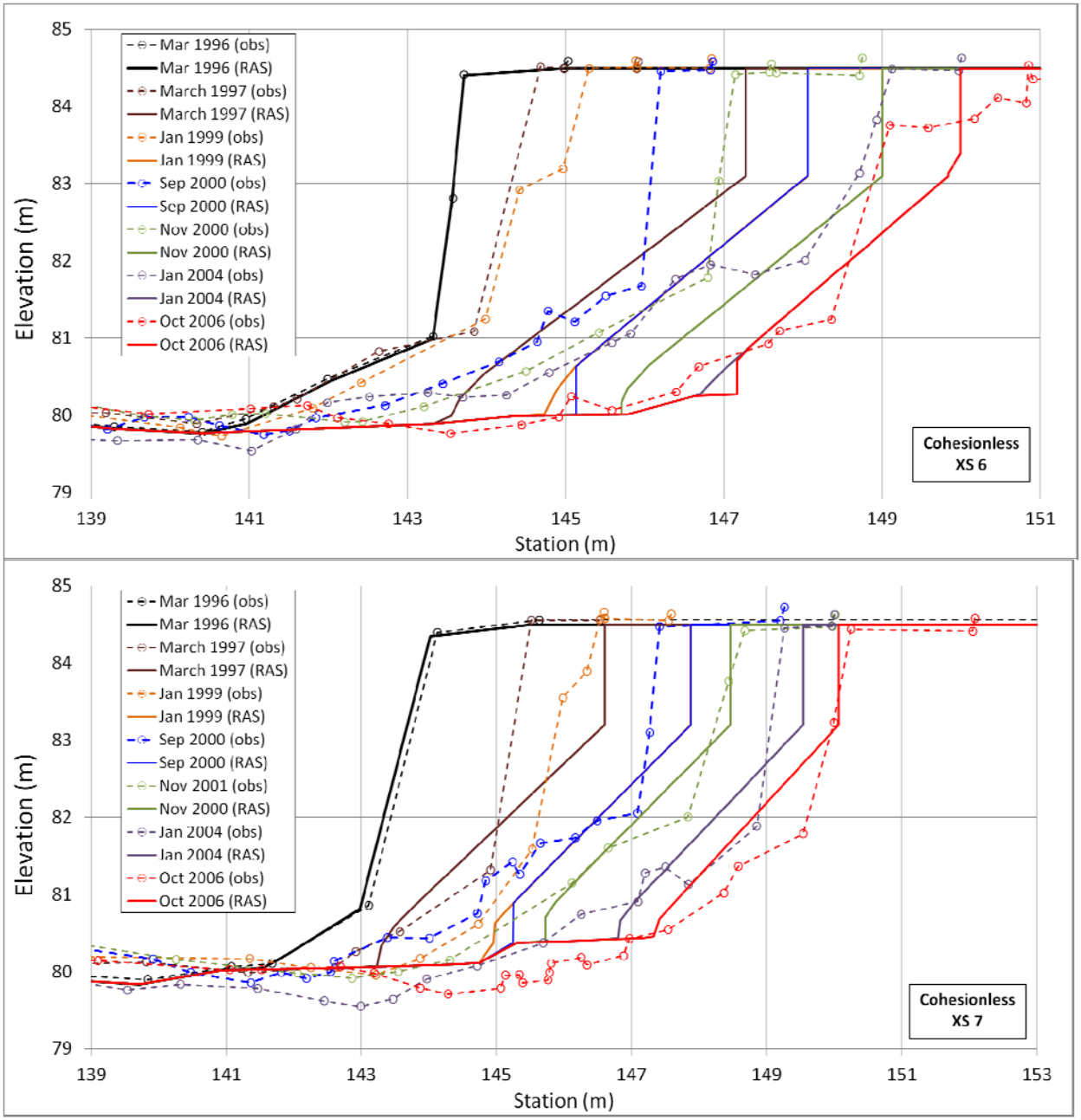

Figure 4 Select Goodwin Creek repeated right bank surveys at the two central cross sections with HEC-RAS/BSTEM cross section migration.

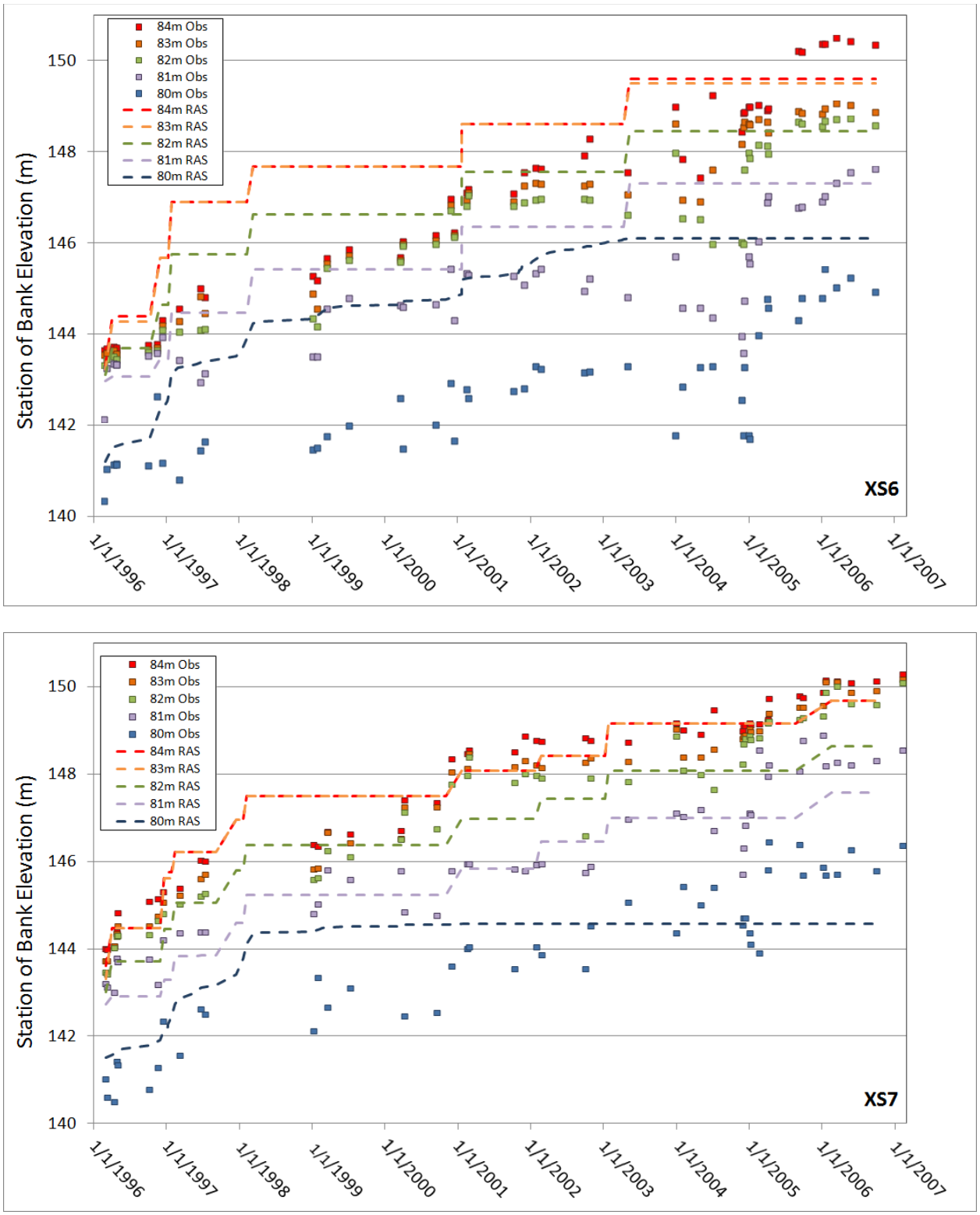

Figure 5 The lateral migration of the right bank of cross sections 6 and 7 (from Figure 4) at five different elevations. The HEC-RAS/BSTEM continuous simulation results are plotted with stations interpolated at the five elevations from all surveys between March 1996 and October 2006.

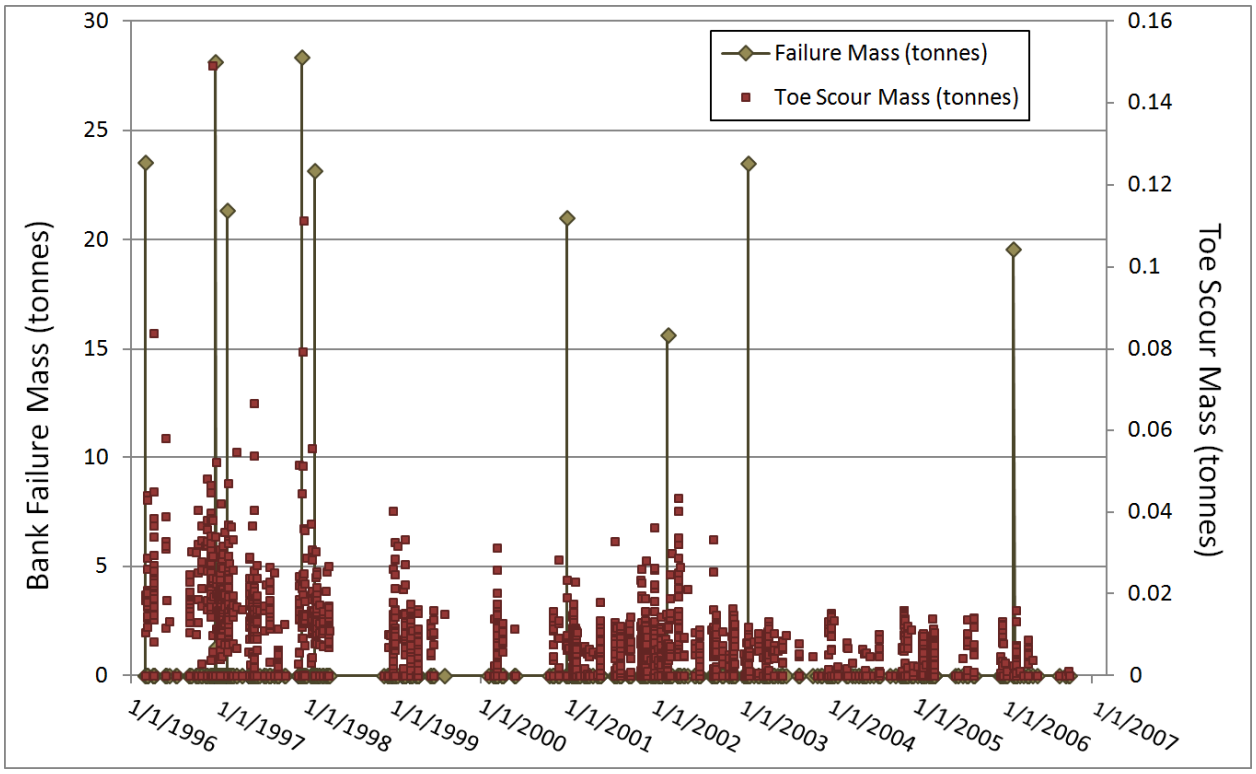

Figure 6 Time series of toe scour and bank failure contributions from the cohesive simulation for XS7 above. The toe scour contribution dropped over time as the channel widened and the ten failures contributed almost an order of magnitude more sediment over the simulation.

The cohesive model results reported above were based on excellent soil and flow data and model parameters that are not only based on copious, careful measurements, but already calibrated by Langendoen and Simon (2008). The cohesionless toe scour prediction in the coupled HEC-RAS/BSTEM code with the transport equations have over predicted scour in most model applications to date, often dramatically. Hundreds of feet of bank migration are not uncommon with some transport functions. Therefore, whether the data-driven cohesive or equation-driven cohesionless method is used, calibration (e.g. comparison to repeated cross sections or historic aerial photographs) is still essential. Additionally, the authors are experimenting with bank 'mixing algorithms' that apply transport-capacity calculations to clast-sized bank materials.

Despite these limitations, the cohesionless methods successfully bracketed prototype migration. Wilcock and Crowe (2003) seemed the most appropriate transport function *a priori*, with its surficial transport formulation (building mixing processes into the equation) and its bimodal flexibility. This method under predicted migration by 30 to 50%, (Figure 7) indicating that the transport equation performed as intended, mainly missing cementation effects in the toe conglomerate, which it was not designed to capture. Alternately, Engelund and Hansen (1972) over predicted bank migration by 50 to 100% (Figure 8). The range of results between the best fit equations underlines the importance of site specific data, but the cohesionless methods bounded the results.

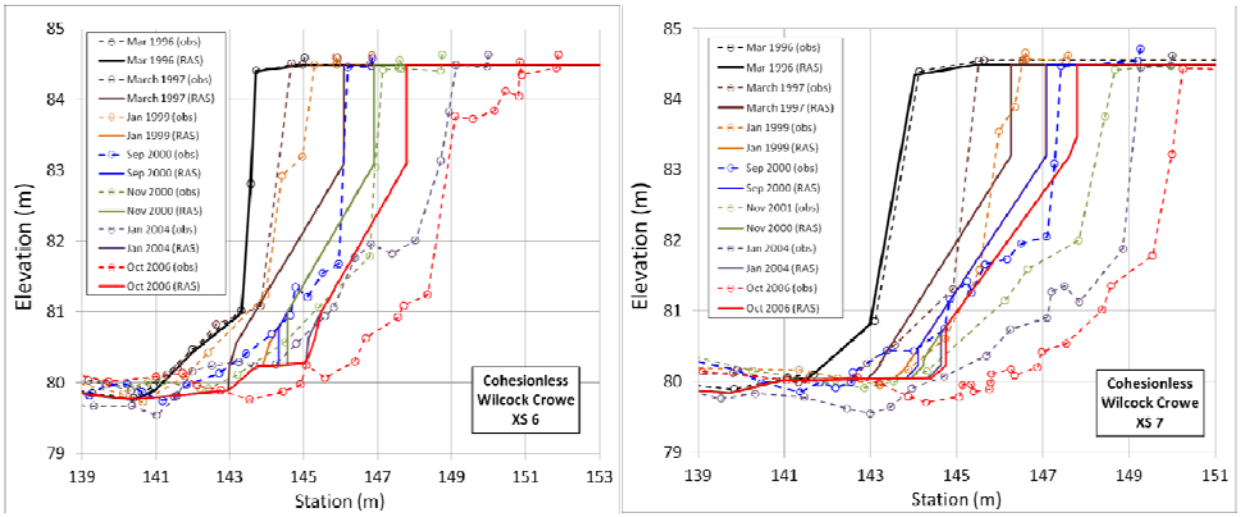

Figure 7 Measured cross sections from Figure 3 and simulated cross sections, computed with cohesionless methods base on the Wilcock and Crowe (2003) transport equation.

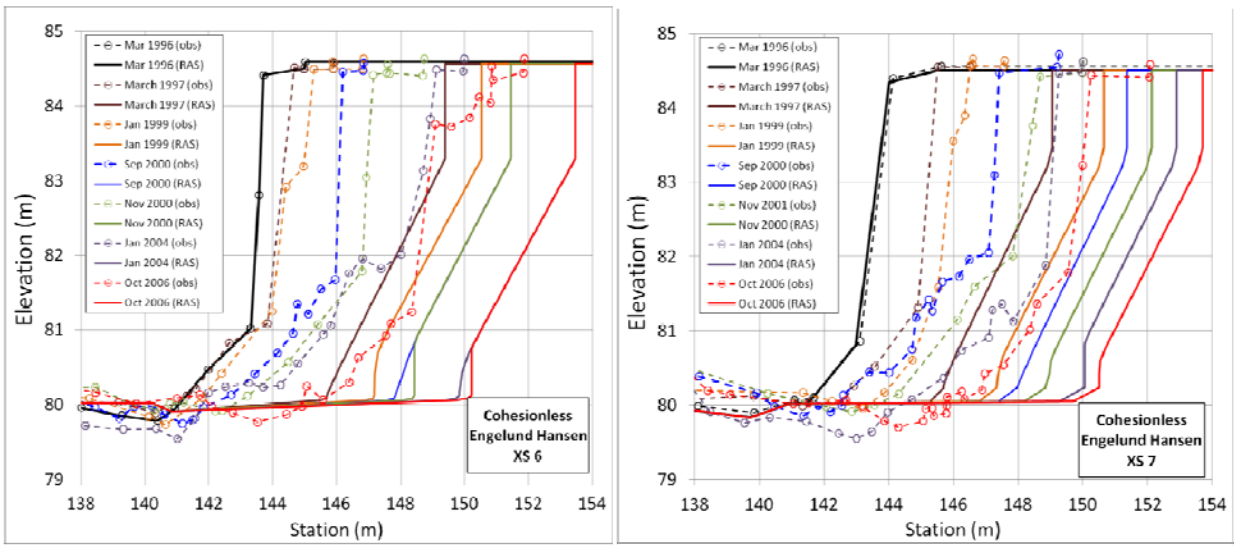

Figure 8 Measured cross sections from Figure 3 and simulated cross sections, computed with cohesionless methods base on the Engelund Hansen transport equation.

CONCLUSION

The USDA-ARS Bank Stability and Toe Erosion Model (BSTEM) has been integrated into HEC-RAS. The joint model simulates coupled bed and bank processes, and the feedbacks between vertical bed erosion and deposition, lateral toe scour, and geotechnical bank stability. Bank migration at Goodwin Creek, Mississippi was simulated with the coupled model using the parameters and benchmarks in Langendoen and Simon (2008), and then continued for five years beyond. The coupled HEC-RAS/BSTEM model performed well, replicating the calibration and demonstrating its subsequent robustness. HEC-RAS 5.0 includes these capabilities, making them broadly available.

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