Coupling Risk-Informed Design and Stochastic Erosion Modeling to Reduce Habitat Impacts

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Abstract

Flood Risk Management projects have historically sacrificed riparian and upland habitat to ensure robust protection from highly erosive, discrete flow events. In most circumstances, designers are forced to place revetment (usually in the form of riprap) high in the flow cross section to provide protection against erosive velocities and shear stresses associated with the design hydraulic loading of the system. The development of the Risk-Informed Design concept and the use of Semi-Quantitative Risk Assessments (SQRA) have allowed design teams within the USACE to shift the focus of the design away from discrete flow events and towards a quantification of the risk. This approach provides design teams with a means for further optimization of the revetment extents and subsequent habitat impacts. However, the hydraulic tools available to quantify this risk have largely remained unchanged, resulting in the continued use of conservative designs.

The design team for the Lower American River Contract 3 project in Sacramento, California developed an approach for optimizing revetment extents by quantifying lateral retreat risk during the design of the project's erosion control features. The Lower American River is a designated Wild and Scenic River with valuable riparian/upland habitat nestled within a high-risk levee system. The design team was tasked with meeting the project's risk objectives through a SQRA while limiting the removal of existing vegetation. The quantification of lateral retreat during the design event is generally not used as a design tool for flood risk management projects due to the dynamic and uncertain nature of erosion. To address this issue, the Bank Stability and Toe Erosion Model (BSTEM) program developed by the U.S. Department of Agriculture, Agriculture Research Station (USDA) was utilized to produce stochastic estimates of bank erosion and create an opportunity to reduce the extents of the required riprap. The design team was able to iterate the horizontal and vertical revetment extents using BSTEM by allowing some bank deformation for the design flow events but keeping the bank erosion risk at an acceptable level. Using fitted distributions for several erosion input parameters, the Monte Carlo analysis produced a range of potential lateral retreat estimates that were compared to the proximity of the levee prism during the SQRA process. This allowed the SQRA team to assess the system risk with the optimized design and incorporate natural bank deformation in the flood risk management project. This approach helped to reduce the total acres of habitat impacts and required mitigation. The approach identified above aligns closely with the goals of the USACE Engineering with Nature initiative to incorporate nature-based processes to achieve design goals while minimizing environmental footprints.

In this paper, the authors will present the iterative design process developed for this project with the novel coupling of BSTEM and the SQRA process in a high-risk environment to reduce habitat impacts. Challenges and lessons learned will be presented along with suggestions for active communication of project risk quantification with resource agencies, flood control districts, and citizen groups.

Introduction

The Lower American River runs through the city of Sacramento, CA and contains approximately 14 miles of federally owned levees. These levees serve to protect the communities behind them and form the boundaries of one of the most heavily used recreation rivers in California. The floodway is highly regarded for its trail and boating activities within this urban area (National Park Service, 2022). In addition to recreational benefits, the Lower American River is also a designated Wild and Scenic River with valuable waters for salmon and steelhead trout habitat and riparian and upland habitat for numerous endangered terrestrial species.

The Lower American River Contract 3-B (LAR C3-B) design team was tasked with improving the erosion countermeasure designs within the federally protected levee system while minimizing impacts to environmental and recreational resources. Historically, riparian and upland habitat have been destroyed to ensure robust protection for Flood Risk Management projects; however strong stakeholder and community input on impacts to existing vegetation led the team to pursue lower-impact countermeasure designs. To do this, optimization of the design was necessary to balance habitat impacts to upland heritage oaks, valley elderberry longhorn beetle, aquatic salmon, and steelhead trout.

The use of the stochastic BSTEM tool developed by USDA allowed the design team to account for the inherent uncertainty associated with lateral bank erosion computations for discrete flood events and enabled the assessment of risk to the levee system after the erosion countermeasure designs are installed. The results from the stochastic BSTEM tool were then reviewed during a SQRA and used to inform the evaluation of risk for each project segment. The design team was able to optimize the erosion protection feature extents using the combined stochastic BSTEM and SQRA process. This iterative process could be used on other projects to reduce the amount of revetment needed to address risk associated with bank retreat.

Bank Stability and Toe Erosion Model

BSTEM Model Development

The BSTEM Dynamic Versions 3.1.7 and 3.2.2 developed by the USDA were utilized to quantify lateral bank retreat under design flood conditions. Version 3.1.7 was used to generate stochastic lateral retreat results at each site while Version 3.2.2 was only used at certain locations for verification purposes. The BSTEM model couples slope stability and fluvial erosion processes in a numerical algorithm that incorporates hydraulic model data, geotechnical slope stability calculations, and erosion estimates from the excess shear equation, to determine lateral erosion extents. The primary inputs to this model include:

1. Cross section station and elevation information for the ground surface of the riverbank
2. Soil types and layer elevations (up to 5 soil layers)

3. Specific soil parameters including friction angle, effective cohesion, rate of increase of soil strength also called suction angle, horizontal hydraulic conductivity, saturated unit weight, soil critical shear, and soil erodibility coefficient
4. Stage and energy grade slope data when using a 1-dimensional hydraulic model or stage and shear stress when using a 2-dimensional hydraulic model, and
5. Bank roughness (effective Manning's n which accounts for the effects of vegetation in reducing the forces acting on the soil surface).

Soil types and layer elevations were determined based primarily on geotechnical borings and a 3-dimensional stratigraphic model developed for a portion of the Lower American River (URS-GEI, A Joint Venture, 2013). Generally, the team identified the closest available boring and used this to develop the soil layers in the bank. The soil layers were then compared to the 3D stratigraphic model to verify any discrepancies and further consultation was completed with the project design team's geotechnical and geological staff. In areas where the specified bank protection (i.e., riprap) was being placed, the design riprap gradation was assumed for the soil layer.

Soil parameter development was completed by a bank erosion team (BSTEM team) within the USACE Sacramento District (SPK). The SPK BSTEM team completed a detailed, multi-year effort to sample and calibrate the BSTEM parameters within the Lower American River project area using observed erosion sites. Critical shear stress and erodibility coefficient parameters were developed for use in both deterministic and stochastic modeling. While deterministic modeling is generally easier to perform it does not provide an understanding of the intrinsic variability of soils along a river bank, nor does it provide much information for determining risk. Stochastic modeling by contrast, can capture that uncertainty, allowing for a better understanding of risk when assessing designs within a Semi-Quantitative Risk Analysis (Rivas et. al. 2021b).

A detailed summary of the parameter development is provided in two separate documents developed by the SPK team (Rivas et. Al. 2019, Rivas et. al. 2021a, Rivas et. al. 2021b). Table 1 lists the slope stability parameters used in BSTEM. The fluvial erosion parameters used in BSTEM are listed in Table 2 and Table 3.

Table *1*. BSTEM Mass Erosion Parameters from Programmatic Phase 4 Validation of the LAR (U.S. Army Corps of Engineers, 2020a)

Soil Type	Friction angle (°)	Effective Cohesion (lbf/ft^2)	Saturated Unit Weight (lbf/ft^3)	Suction angle (°)	Horizontal Hydraulic Conductivity (ft/day)
Clay (CH/CL)	31.3	100.0	118.9	10.0	0.01
Silt (MH/ML)	31.5	0.7	113.0	10.0	0.10
Silty Sand (SM)	28.7	0.0	120.4	10.0	0.70
Sand (SP)	32.5	0.0	123.6	10.0	9.90
Gravel (GP)	35.0	0.0	127.3	10.0	8.50

The stochastic calculations within BSTEM can utilize five different types of distributions: uniform, triangular, normal, lognormal, and gamma. Rivas et. al. (2021b) found that most of the soil parameters were best fit by a gamma distribution, however during the deterministic calibration phase it was discovered that using the triangular distribution allowed an incorporation of the uncertainty reduction gained in calibration for the stochastic simulations (USACE 202b). By using the deterministic soil parameter values and employing this as the median value in the triangular distribution, the stochastic simulations better reflected the reduction in uncertainty gained from the calibration. The LAR C3-B analysis utilized a triangular distribution for the fluvial erosion parameters (critical shear stress and erodibility coefficient) to develop the 1000 realizations used in the Monte Carlo analysis. (Rivas et. al. 2021b) All the other soil parameters utilized a uniform distribution with the minimum and maximum values set to the values shown in Table 1. In effect this holds these parameters constant while the fluvial erosion parameters vary throughout the simulation. The fluvial erosion parameters have some of the largest uncertainties associated with their values and they are the primary driver of the observed bank erosion on the Lower American River (USACE 2020a). The critical shear and erodibility coefficient parameters for locations with riprap were determined using the critical shear and erodibility calculator included in the BSTEM model for non-cohesive particles. The calculator uses the erodibility function from Hanson and Simon (2001). The D_{50} of the riprap was used as the base particle size for this calculation. A uniform distribution was applied to the parameters representing the riprap on the bank during the stochastic evaluations. A summary of the stochastic parameters developed by the BSTEM Team are included in Table 2 and Table 3.

Table 2. BSTEM Critical Shear Stochastic Parameters from Programmatic Phase 4 Validation of the LAR (U.S. Army Corps of Engineers, 2020a)

Soil Type	Critical Shear Stress, lb/ft2	Minimum Value, lb/ft2	Maximum Value, lb/ft2	Mode
Clay (CH/CL)	0.277	0.002	0.88	0.052
Silt (MH/ML)	0.205	0.002	0.65	0.039
Silty Sand (SM)	0.160	0.003	0.65	0.003
Sand (SP)	0.105	0.004	0.48	0.004
Gravel (GP)	0.229	0.040	0.69	0.04

Table 3. BSTEM Erodibility Stochastic Parameters from Programmatic Phase 4 Validation of the LAR (U.S. Army Corps of Engineers, 2020a)

Soil Type	Erodibility, ft^3/lbf-hr	Minimum Value, ft^3/lbf-hr	Maximum Value, ft^3/lbf-hr	Mode
Clay (CH/CL)	0.045	0.01	0.086	0.042
Silt (MH/ML)	10.0	0.35	59.6	0.35
Silty Sand (SM)	7.0	0.35	40.1	0.35
Sand (SP)	5.0	0.47	36.4	0.47
Gravel (GP)	0.034	0.014	0.081	0.015

The incorporation of the stochastic parameters were the primary means for evaluating lateral retreat risk within the semi-quantitative risk assessment (SQRA) process. It should be noted that during the parameter development there were low values of critical shear stress and high values of the erodibility coefficient that could not be reasonably removed from the distribution, either because they were a statistical outlier or there were issues associated with the testing. The combination of low critical shear stress values and large erodibility coefficient values results in extreme erosion above the 90th percentile. While these reflect potential natural heterogeneity within the soil, it was felt that these combinations are not likely and the focus for the design was on the interquartile lateral bank retreats (i.e., between the 25th and 75th percentile).

Stage and energy grade slope hydrograph data were taken from a 1-dimensional Hydrologic Engineering Center's River Analysis System (1D HEC-RAS) unsteady model with a geometry that incorporated the project design features into the relevant cross sections.

The effective Manning's n values were based upon a database developed from previous calibration work (USACE 2020a). For the purposes of this design project the riverbanks were assumed to be void of vegetation while the levee face could account for poor grass establishment. The effective Manning's n roughness values ranged from 0.03 for bare soil on the riverbank to 0.035 for the grass surface. A lower effective Manning's n value provides less energy dissipation and therefore higher applied shear stress in the BSTEM model, which increases the susceptibility to fluvial erosion. The effective Manning's n assumptions used for the evaluation of flood risk management performance at this project location were intended to provide a conservative erosion condition (i.e., favoring more erosive conditions) given the potential variability in vegetation establishment in the project area.

In certain locations the BSTEM model dynamic version 3.2.2 was used to calculate lateral erosion using only the excess shear equation (avoiding the slope stability process in BSTEM) and a shear stress hydrograph calculated from the HEC-RAS 2D model. This was done by setting the effective cohesion to an extremely large value (1,000,000 lbf/ft^2) such that the calculated geotechnical stability was always greater than unity and thus did not fail, allowing the evaluation of bank retreat driven only by fluvial erosion processes. The results of this simplified analysis (non-stochastic) showed good agreement with the 50th percentile stochastic results and therefore provided additional confidence in the BSTEM results for the SQRA Cadre.

Preliminary Design

Prior to the evaluation of the lateral retreat results by the SQRA Cadre, the design team needed to develop a proposed layout that best met the risk needs for the project. To do this, the team developed a set of lateral retreat goals for the design to meet. These goals tried to balance the Flood Risk Management goals with the potential for habitat impacts. The following goals were utilized as guidelines for the preliminary design iterations at the 160,000 cfs (1/325 year AEP) design event:

- No impact to the levee prism for the 75th percentile stochastic BSTEM results;
- In areas with significant habitat (i.e. presence of heritage Oak trees), limit the amount of rock to ensure the 50th percentile stochastic BSTEM results do not impact the levee prism. For this situation a geotechnical stability analysis was completed using the 75th percentile results post erosion to determine viability of the levee during a flood.

In many locations, the first iteration of the design layout did not achieve these goals. In this situation, the design team would raise the elevation of the revetment top if less lateral retreat was needed or lower the revetment top if additional lateral retreat distance was available. Example BSTEM modeling results are shown for conditions where the revetment top was raised (Figure 1) and where it was lowered (Figure 2).

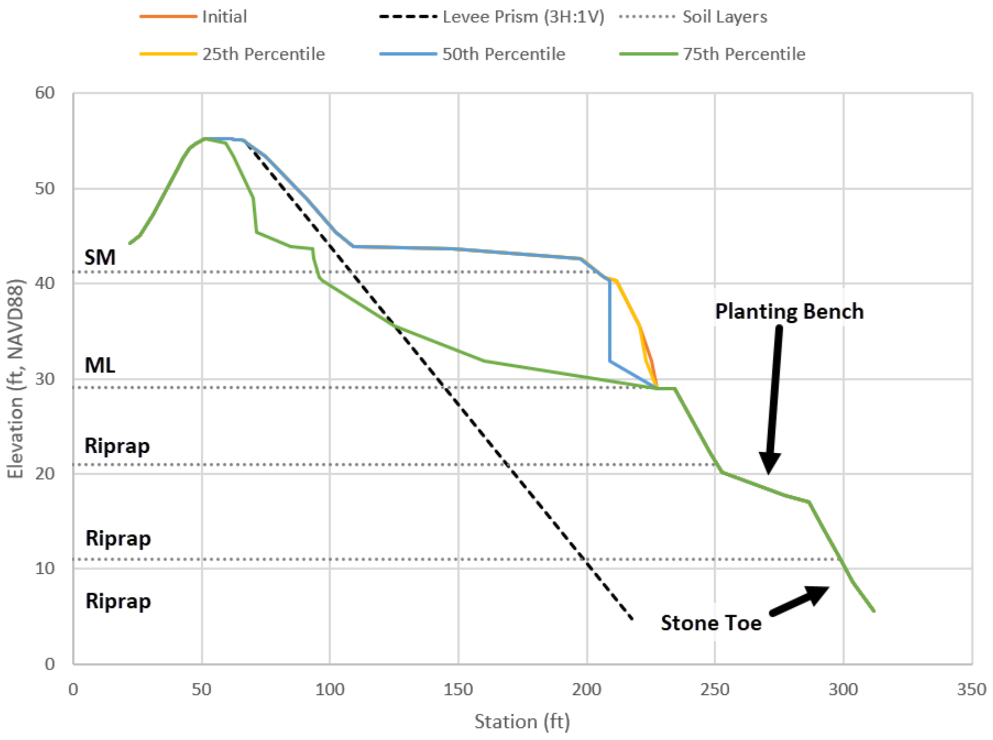

Figure 1. Example BSTEM Modeling Results for the 160,000 cfs flood event (1/325 AEP) at River Mile 8.66

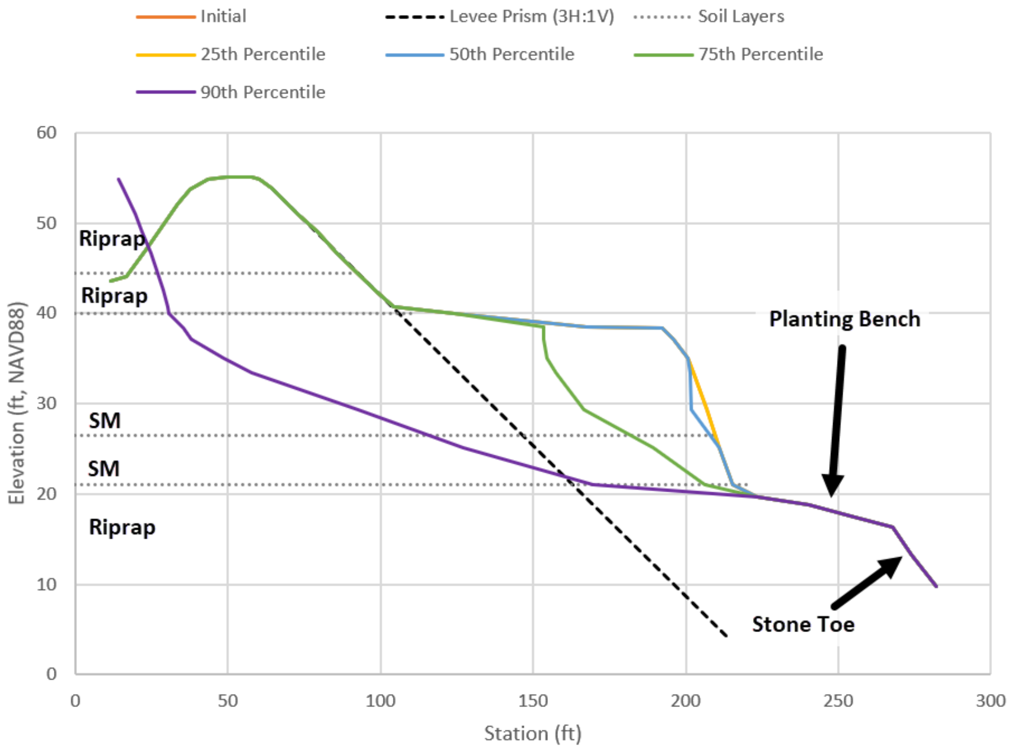

Figure 2. Example BSTEM Modeling Results for the 160,000 cfs flood event (1/325 AEP) at River Mile 8.0

The results presented in Figure 1 are for a project location with limited overbank width and high velocities against the riverbank. A planting bench and riprap placed up to approximately the 2/3 bank height was proposed. The site has heritage oaks and valley elderberry longhorn beetle habitat that limit the extents available for project impacts. The results show the 75th percentile lateral retreat is anticipated to impact the levee prism. Based on the design criteria, this amount of lateral retreat is a concern from a flood risk management perspective. The results required close scrutiny by the SQRA Cadre to ensure the risk objectives are met at this location given the desire to limit habitat impacts. A geotechnical analysis of the post erosion stability of the levee was also conducted using GeoStudio Slope/W software (version 2020) to help the SQRA Cadre in its risk evaluation of this location.

The results presented in Figure 2 are for a location with a wider overbank and less shear stress. A planting bench is proposed in this location and riprap is only proposed up to the approximate ½ bank height. The results show the 75th percentile lateral retreat is not anticipated to impact the levee prism. This location does impact the levee prism for the 90th percentile lateral retreat and was still evaluated by the SQRA Cadre. However, the design team had greater confidence that the preliminary design at this location would achieve the risk objectives.

Semi-Quantitative Risk Analysis

The guidance that outlines the LAR C3-B risk informed design actions is USACE ECB 2019-15 (USACE, 2019). The overarching risk objective of the American River Common Features Act of 2016 (ARCF 2016) is to reduce the probability of breach prior to overtopping without significantly increasing the probability of overtopping, thereby reducing the total risk. The ARCF risk objectives for LAR C3-B river segments and project sites estimated by the SQRA process is the maximum order of magnitude estimate for the probability of breach prior to overtopping, which is set at 3.0E-6 to 3.0E-5 with a centroid of 1.0E-5. This requirement applies to the Potential Failure Mode (PFM) for the levee foundation (PFM3) and the levee embankment (PFM 2). PFM 2 is defined as riverside erosion above the levee toe in the embankment. PFM 3 is defined as riverside erosion below the levee toe in the foundation.

SQRA combines limited numerical estimates with qualitative descriptions, such as those shown in Table 4. These estimates and descriptions are referred to as the Event Tree. Engineering Regulation (ER) 1110-2-1156 defines an event tree as a model of a potential failure mode consisting of a series of sequential nodes that each represent an identifiable physical component within an erosion event (USACE 2011). The event tree for PFM 2 and 3 for this project location are shown in Figure 4. The event tree for this analysis consisted of six nodes: Flood Loading, Channel Protection Failure, Initiation, Progression, Detection and Intervention, and Breach. The stochastic BSTEM analysis informed Assigned Probabilities of the Progression node. Each node was given a descriptor and assigned probability based upon each SQRA Cadre member's understanding of the event and erosion countermeasure features present. The assigned probabilities for each node are multiplied together to determine the order-of-magnitude risk estimate value.

Table 4. Event tree node descriptors and assigned probabilities

Descriptor	Assigned Probability
Virtually Certain	0.999
Very Likely	0.99
Likely	0.9
Neutral	0.5
Unlikely	0.1
Very Unlikely	0.01
Virtually Impossible	0.001

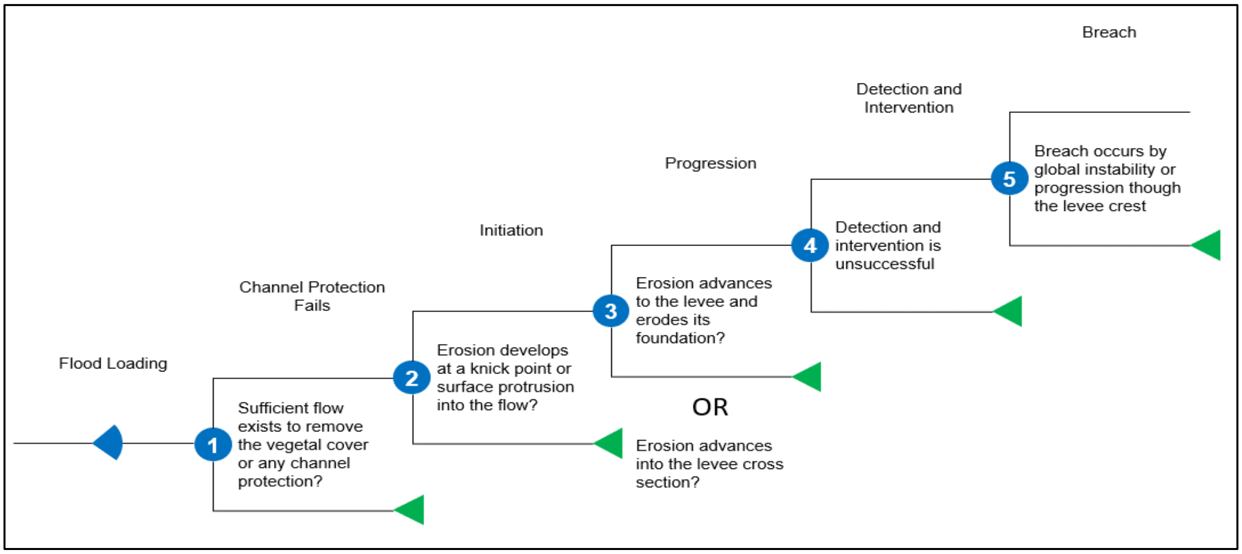

Figure 3. Riverine Erosion Event Tree used in the LAR C3-B project for PFM 2 and 3

Results

Coupling the SQRA and Stochastic BSTEM process

The results of the BSTEM analysis were used by the SQRA Cadre to ensure the project met the design goals for risk to the levee as determined in the Engineering and Resource Design Guidelines (ERDG) (U.S. Army Corps of Engineers, 2021) and defined in the previous section. To assess the risk related to PFM 3 (riverside erosion below the levee toe in the foundation) the Cadre looked at the St. Paul District's 2D RAS model velocity data, stochastic BSTEM results, vegetation cover, and overbank width. Velocity data was compared to the critical velocity values for observed vegetation to determine if soil initiation was expected which would trigger the flaw node within the riverine erosion event tree. If a flaw was expected, initiation of riverbank soils was considered likely, and the SQRA Cadre turned to the stochastic BSTEM results to determine the likelihood of erosion progressing into the levee prism. Due to the wide spread of values for the critical shear stress and erodibility coefficient (Table 2 and Table 3) higher percentile results would likely provide very conservative estimates for how a soil layer would behave within a given cross section. BSTEM assumes a horizontally homogenous soil layer in any given model run; in areas where there is a wide overbank this assumption may not provide an accurate representation of the modeled area. This may be an overly conservative assumption when looking at higher percentile stochastic results. This assumption and potential level of conservatism was taken into consideration when assessing the progression node of the riverine erosion event tree. The SQRA process was conducted for a total of 12 predefined project reaches. As previously noted, the 75th and 50th percentile levee prism impact thresholds were used by the design team for the purposes of having a quantifiable criterion to assess the preliminary design. The SQRA took these modeled stochastic results and determined whether the design team's preliminary assessment of acceptable risk using these thresholds was adequate.

One challenge with utilizing the stochastic BSTEM analyses within the SQRA was determining what the percentile results represented within the context of a risk assessment that needed to establish a semi-quantitative value for risk. For example, the team inherently understood that if the 50th percentile BSTEM result showed impact to the levee prism, it did not mean that there was a 50 percent likelihood that lateral retreat would result in a failure and breach of the levee. Instead, it represented a 50th percentile lateral bank retreat scenario from the 1000 tested scenarios of various combinations of the selected critical shear stress and erodibility coefficient distributions. One major assumption of the BSTEM model was that both the soil layer type and the soil layer properties were homogenous at the thickness specified by the design team and for the lateral extent to which erosion was displayed. For example, the results in Figure 1 assume that the ML layer is between elevation 29 and 42 feet and that the 50th percentile values for the lateral bank retreat are representative for the entirety of the overbank area. Each of the 1000 individual bank retreat results assume a constant critical shear stress and erodibility coefficient value for each soil layer. Since soil is known to be heterogeneous, it is unlikely that a constant value would be valid for the entire thickness and along the entire eroded length. Thus, extreme erosive and non-erosive combinations of these parameters are unlikely to be continuous throughout the modeled soil layer. Therefore, the interquartile range likely represents a more reasonable estimate of the expected lateral retreat once erosion is initiated.

River Mile 8.66 Example

Many of the initial design concepts did not include any riprap above the planting bench. With high velocities and a relatively narrow overbank the SQRA Cadre determined that this design did not meet risk objectives. The LAR C3-B design team assessed numerous iterations of the riprap design elevation within the project area shown in Figure 1 to balance habitat impacts with risk objectives. Figure 1, Figure 4, and Figure 5 illustrate the iterative nature of utilizing the stochastic BSTEM results to determine acceptable riprap elevations. In Figure 4 no rock is included above the planting bench and the 50th percentile results extend into the levee prism. This would minimize habitat impacts but be deemed unacceptable under the project's defined risk criteria. In Figure 5 the entire riverbank has been replaced with riprap and erosion is predicted to occur only at the 90th percentile. This design would have met the project's defined risk criteria but would have required the removal of all existing vegetation at the site, resulting in expensive offsite mitigation, stakeholder dissatisfaction, and public outcry. The results in Figure 1 show the final result of the iterative process with the revetment top elevation set to roughly 2/3 of the top of riverbank elevation.

By leveraging the results of the stochastic BSTEM analyses to determine revetment top elevations the design team was able to preserve 0.8 acres of riparian habitat, reducing the overall riparian habitat impacts by approximately 20%. This difference is magnified by the 2:1 mitigation requirement for any riparian area disturbed by project construction and by the lack of readily available on-site mitigation areas.

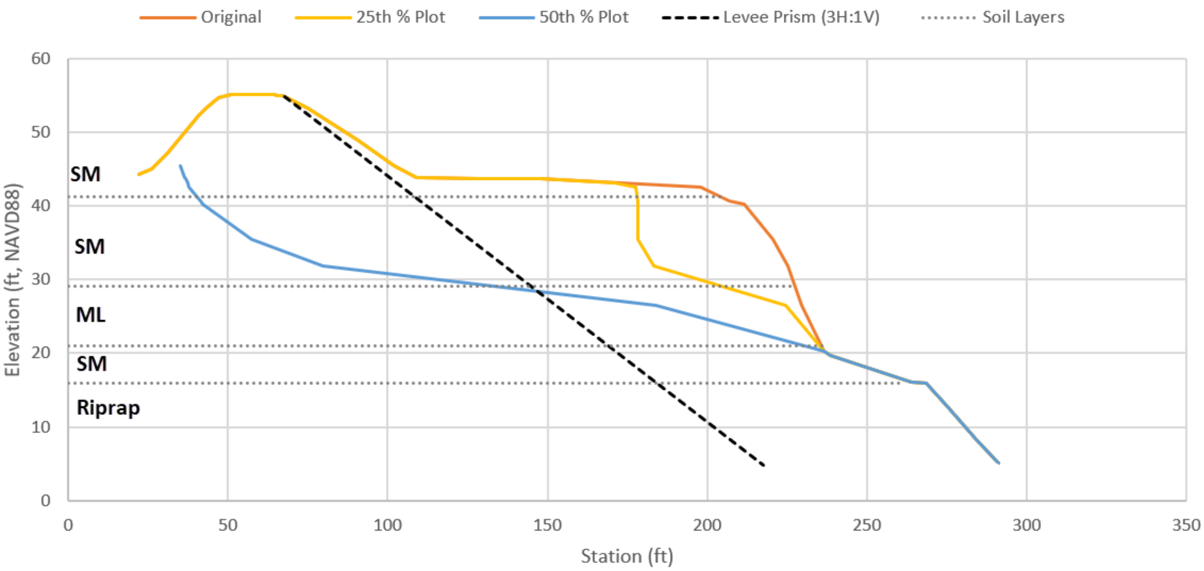

Figure 4. Stochastic BSTEM results of 35% design concept stone toe and planting bench

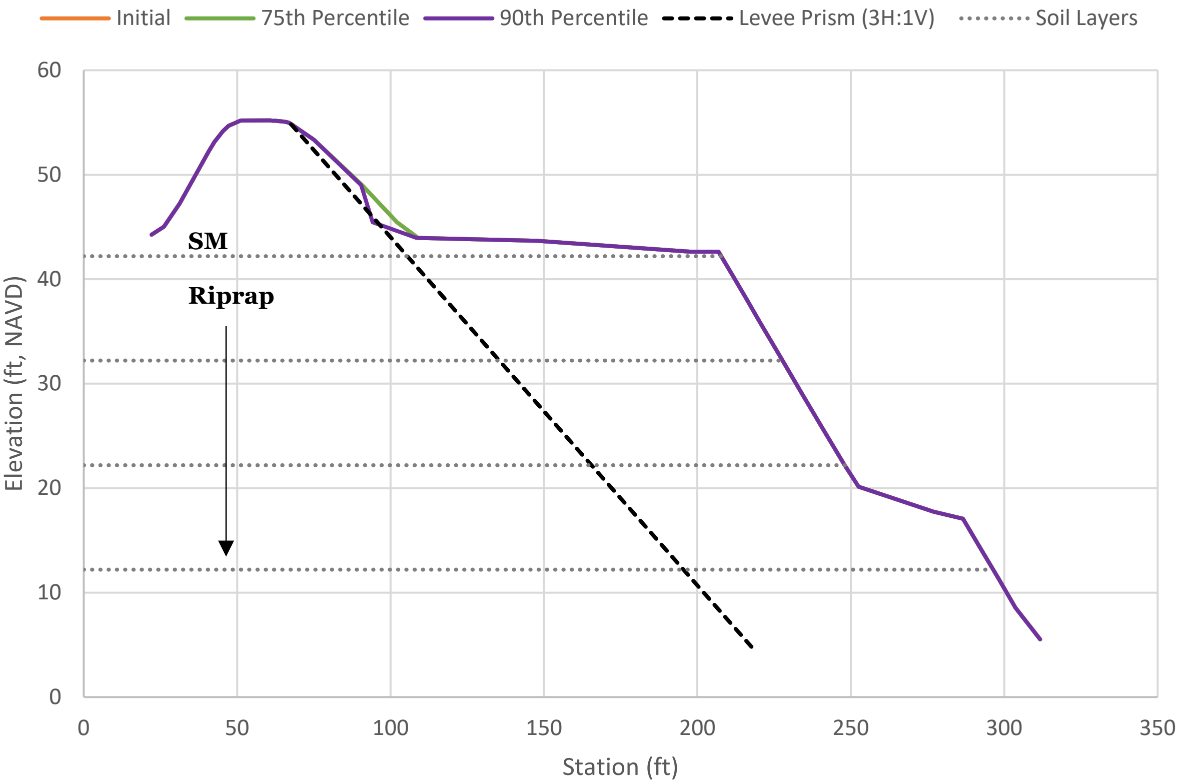

Figure 5. Stochastic BSTEM results of riverbank revetment with top elevation equal to top of bank

River Mile 10.083 Example

The location presented in Figure 6 has significant heritage oak and Valley Elderberry Longhorn Beetle habitat in the overbank. An initial concept was proposed that included a buried riprap revetment in the overbank that provided protection up to approximate elevation 30 ft, NAVD88. This design ensured the 50th percentile lateral retreat would not impact the levee prism, however the 75th percentile retreat would cause levee prism impacts. The stochastic lateral retreat results from BSTEM and the overall design was presented to the SQRA Cadre and this location was determined to not meet project risk objectives. At this location, overbank velocities were high enough to expect some erosion initiation above elevation 30 ft, NAVD88 and, when coupled with the potential levee prism impacts for the 75th percentile BSTEM results, did not provide sufficient confidence in the erosion design to meet project risk objectives.

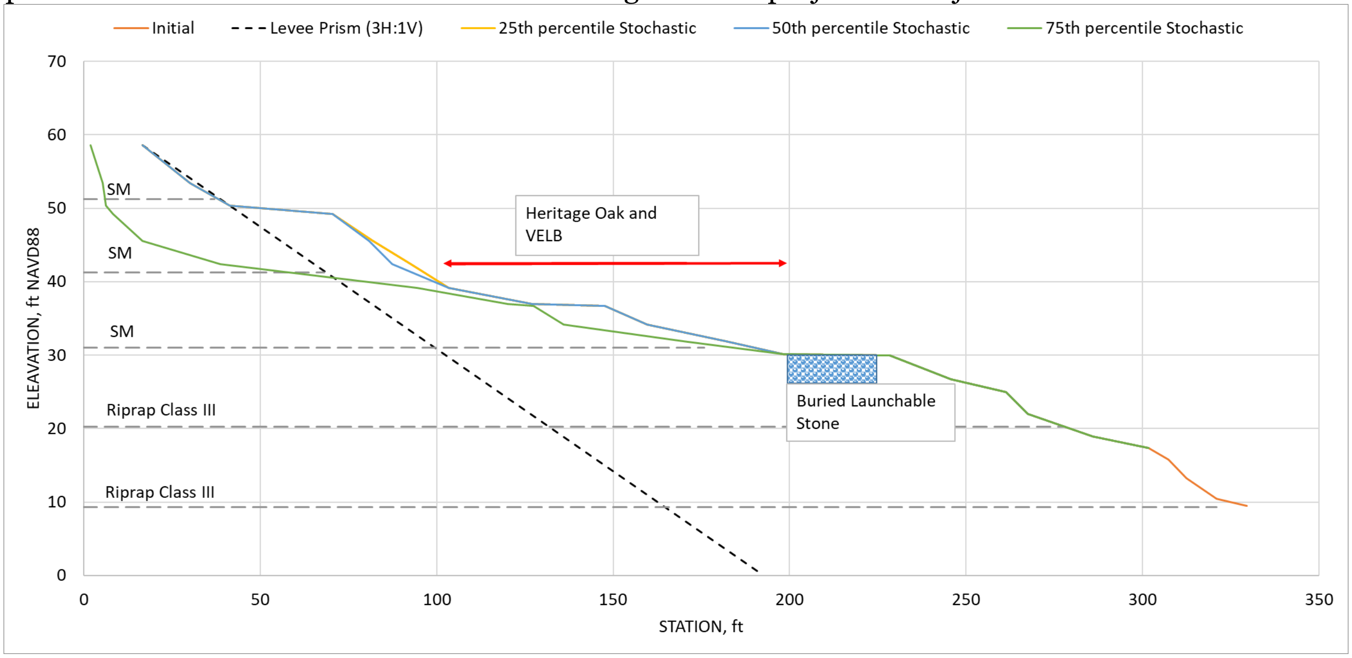

Figure 6. Example BSTEM Modeling Results for the 160,000 cfs flood event (1/325 AEP) at River Mile 10.0833 (initial concept)

Based on this information, the design team subsequently moved the buried launchable stone further landward and provided tie-backs that extend toward the levee. This revised design resulted in more habitat impacts than the initial concept as the revetment but allowed the project to meet risk objectives when it was re-presented to the SQRA Cadre for risk elicitation. The use of tie-backs did allow the designers to avoid impacts to some heritage oaks through careful placement of the revetment alignment.

Discussion

The two examples described above for river mile 8.66 and 10.083 required design iterations with both BSTEM and the SQRA Cadre. The design iterations at river mile 8.66 focused on the use of BSTEM to provide the necessary documentation for the SQRA Cadre to verify the design achieved the project risk objective (probability of breach prior to overtopping as defined in the project design guidelines). For river mile 10.083, the design iterations required a focused effort by the SQRA Cadre (avoiding another BSTEM iteration) to develop a design approach that met the project risk objectives. Both approaches resulted in a design that minimally achieved the risk objectives and therefore minimized the habitat impacts. The iterative approach the design team developed for this project is summarized in the Figure 7 flowchart.

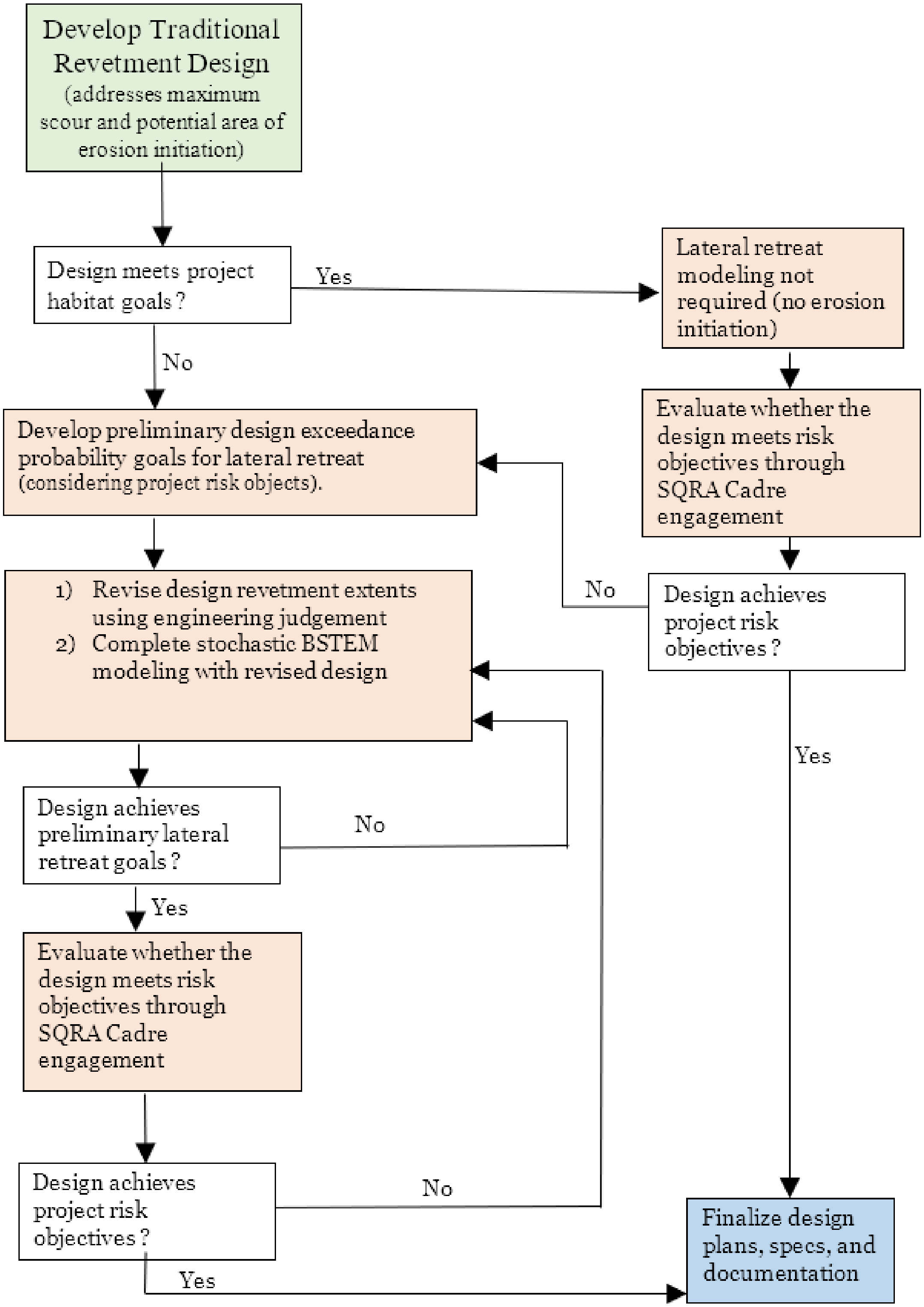

Figure 7. Flowchart of the Coupled BSTEM and SQRA Cadre Approach for Revetment Design

Conclusions

Using a coupled BSTEM lateral retreat and SQRA process, the LAR C3-B design team was able to develop a design procedure, outlined below, that preserved critical habitat for endangered species while still meeting flood risk management objectives.

1. Develop an initially robust revetment design that address maximum scour potential and potential area of erosion initiation
2. Evaluate if the robust design meets the goals for habitat protection
3. If revetment extents need to be reduced to meet habitat goals, develop exceedance probability goals for lateral retreat to inform a design revision
4. Revise the robust design to better account for habitat impacts. Evaluate this design using stochastic BSTEM.
5. Iterate design revetment extents in BSTEM until it meets the goals developed in Step 3.
6. Once lateral retreat exceedance probability goals are achieved complete the SQRA process.
7. Communicate and discuss soil parameter values and distributions, stochastic realizations, and stochastic BSTEM model results with the SQRA Cadre to identify whether design meets project risk objectives
8. Iterate between design, BSTEM modeling, and SQRA to optimize the balance between stakeholder input requests regarding habitat impacts and project risk objectives
9. Translate results to final design and project cost-benefit (for example, the ability to save on mitigation work)

This approach reduced the total acres of habitat impacts and associated required mitigation. The quantification of the lateral bank retreat helped to preserve natural vegetation in riparian and upland areas where it provides habitat value, rainfall erosion control, and also aesthetic value to the community. The stochastic BSTEM analysis provided the hydraulic computations needed to inform the SQRA Risk assessment and verify the project met risk objectives with less robust revetment designs. The reduced use of revetment will allow natural riparian processes to occur and facilitates many of the objectives outlined by the USACE Engineering with Nature initiative.

While useful for this project, the BSTEM tool is likely best suited to large projects for the present time. While a national collection of datasets has been compiled (Briaud et al. 2019), there is still a large range in the critical shear stress and erodibility coefficient values for a given soil type. The large variation in the parameter values suggests that local data collection and/or calibration of the model sets is likely required. For the larger WRDA 2016 project, both time and funds were available for soil parameter data collection and processing which facilitated having a parameter set that could be utilized for this particular project. The development of the soil parameters used in this analysis was a multi-year process requiring significant field investigation, laboratory analysis, and hydraulic modeling, that was largely completed prior to the start of design. As additional individual project datasets are tested and calibrated, the national dataset may be improved sufficiently to make it more applicable to smaller projects with varying soils. Given the heterogeneity of soils, however, it is likely that some degree of calibration or validation will be needed to have confidence in the stochastic results.

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