MORPHOLOGICAL IMPACT OF A REHABILITATION PROJECT: SRH-2D MODELING ASSESSMENT

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Abstract. Geofluvial modeling is carried out using a coupled morpho-dynamic and bank erosion model referred to as SRH-2D. This model is used to predict the geomorphic impact of the Upper Junction City (UJC) rehabilitation project located on the Trinity River in Northern California. This geofluvial model was developed for the study and consists of two components: (1) a 2D mobile-bed model (SRH-2D) for vertical stream bed changes and hydraulic forces acting on bank toes; and (2) a bank retreat model for lateral bank erosions. The geofluvial model is first calibrated between a "pre-erosion" baseline condition from April 2009 and a measured "post- erosion" condition from August 2011. The model was found to be capable of predicting vertical bed changes and lateral bank erosion. The calibrated model is then applied to assess the potential future impacts of the river rehabilitation project on channel morphology under two scenarios: a 2011 "post-erosion" condition and a 2012 "design construction" condition. A comparison of the two provides necessary data with which to evaluate the potential design impact of the UJC project over a hypothetical evolution scenario.

INTRODUCTION

Stream bank erosion is a natural geomorphic process occurring in all alluvial channels. It is an important mechanism by which a channel adjusts its size, shape, and slope to convey the supply of both water and sediment. In recent years, both one-dimensional (1D) and two-dimensional (2D) numerical models have been used to predict channel responses, but most either ignore bank failure mechanisms or implement only simple ad hoc methods. Not accounting for stream bank failures in mobile-bed simulations may result in biased or erroneous predictions of degradation, aggradation, equilibrium channel geometry, and sediment loadings.

Most river restoration and rehabilitation projects are carried out without performing a quantitative geofluvial assessment. Physical analyses are usually restricted to hydraulic simulations only, due to the limited amount of practical and reliable geofluvial models available. A number of mobile-bed sediment transport models are available, such as HEC-RAS, SRH-1D, CONCEPTS, CCHE2D, and SRH-2D. They are versatile and offer extensive capabilities and choices in modeling the vertical changes in stream bed elevations. However, most of them do not take lateral bank erosion into consideration, except for CONCEPTS and SRH-2D, and cannot be used to predict lateral stream changes.

Recently, SRH-2D has been extended to include a bank erosion module, which is the motivation behind the present study. In this study, we investigate how the geofluvial SRH-2D model performs when tested against a field case at the Upper Junction City (UJC) rehabilitation project on the Trinity River in Northern California. Further, we demonstrate how a 2D geofluvial model like SRH-2D may be used to assess the impact of a proposed river rehabilitation project design on local channel morphology.

NUMERICAL MODEL AND MODELING DETAILS

SRH-2D Model Description SRH-2D is a 2D, depth-averaged, hydraulic and sediment transport model for river systems under development at the Bureau of Reclamation. The hydraulic flow model, documented by Lai (2008; 2010), has been widely utilized by internal and external users. The sediment transport module is used to predict vertical stream-bed changes and has been described by Lai and Greimann (2008; 2010) and Lai et al. (2011). The sediment module tracks multi-size, non-equilibrium sediment transport of suspended, mixed, or bed load for both cohesive and non-cohesive materials. The effects of gravity and secondary flows are accounted for by displacing the direction of the sediment transport vector from that of the local depth-averaged flow vector.

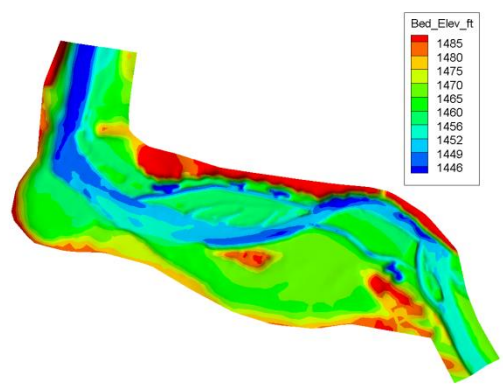
Recently, SRH-2D has been expanded for geofluvial modeling by developing and incorporating a number of bank modules (Lai et al., 2012; Lai and Wu, 2013; Lai et al., 2015). The simultaneous vertical and lateral modeling capability, i.e., geofluvial modeling, has been reviewed and summarized by Lai (2014). With the latest SRH-2D model, main channel fluvial processes may be solved with the regular 2D depth-averaged mobile-bed module, while the lateral bank erosion processes are solved with bank modules. In this study, the latest geofluival SRH-2D model is used.

Modeling Steps and Scenarios SRH-2D modeling, in general, includes the following steps: (1) selection of the solution domain; (2) mesh generation and definition of boundary conditions; (3) assigning topography, flow roughness and bed sediment gradations; (4) model calibration; and (5) model applications. The first three steps are discussed herein; the remaining two steps are reported later.

Two sets of modeling scenarios are carried out at the UJC project reach. The first set of model runs is for model calibration and validation using the 2009 "Pre-erosion" baseline condition (named "*Pre_E*"). The *Pre_E* runs use the 2009 terrain as the initial bathymetry and the 2009- 2011 three-year hydrograph is simulated. The predicted 2011 topography is compared to the measured 2011 terrain data. The second set of runs applies the calibrated model for assessing the impact of design construction on stream morphology. Two scenarios are simulated: the 2011 "post-erosion" condition (named "*Post_E*") and the 2012 "Proposed Design" condition (named "*Design*"). The *Post_E* runs utilize the 2011 terrain as the initial bathymetry while the *Design* runs adopt the design condition topography of the UJC river rehabilitation project as the initial bathymetry. The morphological changes under *Post_E* and *Design* conditions are simulated with the same three-year hydrograph as the *Pre_E* condition. Since the topography of the proposed design condition was close to the 2011 terrain, and all model parameters are the same, a comparison of the *Pre_E* and *Design* modeling results provides the necessary data to assess the impact of the proposed design condition on future channel morphology. Note that only a three-year hydrograph is used so prediction of the form of the long-term equilibrium channel has not been attempted. Also note, the actual "As-built" or "constructed" topography was not evaluated for this study.

Solution Domain, Mesh and Initial Terrain The solution domain and one of the meshes developed for the present study are shown in Figure 1a. The solution domain is about 4,000 feet in channel length and averages 700 feet in width. The meshes are generated using Surface-water Modeling System (SMS) software. Two meshes are generated corresponding to the calibration and application modeling runs. The same mesh is used with *Post_E* and *Design* scenarios so that the differences of the model results are due mainly to the *modifications* introduced by the design condition. Meshes consist of mixed quadrilaterals and triangles with a total of 18,414 and 19,119 cells, respectively, for the *Pre_E* and *Post_E/Design* scenarios. There are three initial terrains for all modeling runs: the 2009 pre-erosion (*Pre_E*); the 2011 post-erosion (*Post_E*); and the proposed 2012 design condition (*Design*) scenarios. A 3D perspective view of the initial terrain for the *Design* scenario is shown in Figure 1b.

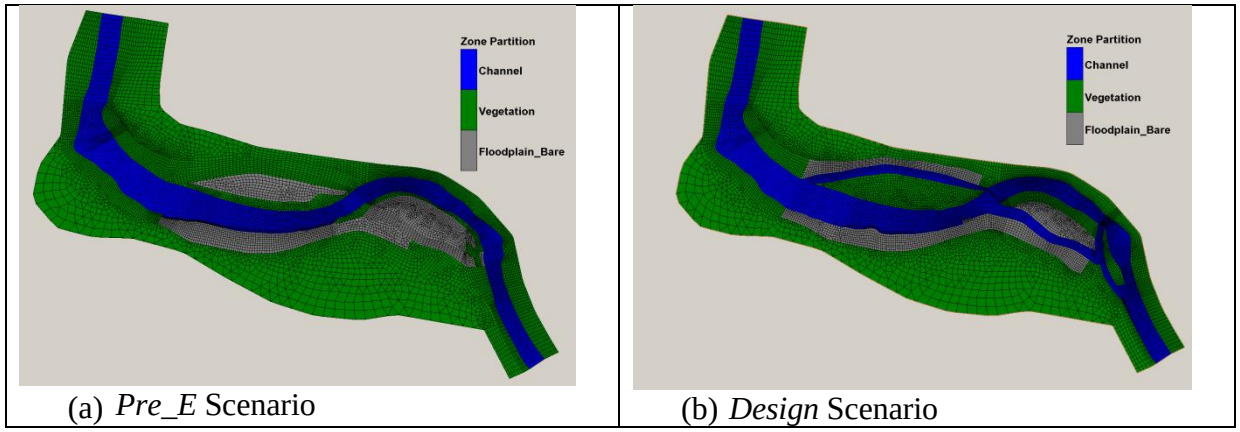
(a) Solution Domain and Mesh



(b) Initial Terrain

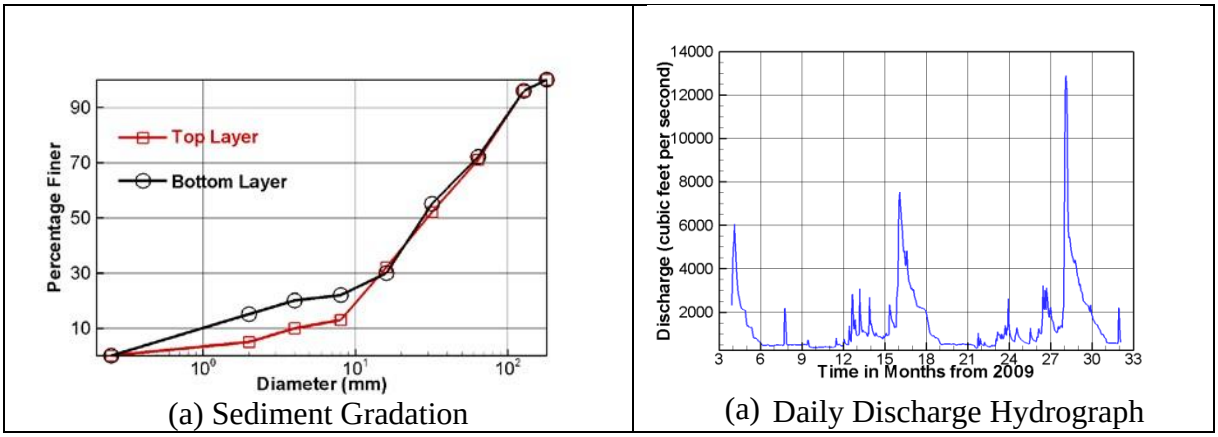
Figure 1 Solution domain (blue) and the mesh (red) for scenario PB, and 3D perspective view of initial terrain for *Design* scenario. The aerial photo was taken in August 2011

Flow Resistance and Bed Gradation The flow resistance and initial bed/subsurface sediment gradation are the two major inputs to the model. The flow resistance is computed with the Manning's roughness equation. In this study, the Manning's coefficient (*n*) is based on estimation from previous studies on the Trinity River. The solution domain is divided into three zones (Figure 2) and *n* for each zone is assigned as: 0.035 for the main channel and the bare floodplain, and 0.085 for the vegetation zone. The bed and subsurface sediments in the main channel are based on field survey data and divided into two layers. The surface layer has a thickness of 0.65 ft and the subsurface layer has an infinite thickness. The gradations of the two layers are similar, with a medium diameter about 29 mm (Figure 3a). The bare floodplain is assumed to be uniform with a sediment gradation as the subsurface layer of the main channel. Only deposition is allowed in the vegetation, so no bed gradation is needed.



(a) *Pre_E* Scenario (b) *Design* Scenario

Figure 2 Zonal partition of the solution domain for both roughness assignment and bed gradation representation



(a) Sediment Gradation (a) Daily Discharge Hydrograph

Figure 3 Bed and subsurface sediment gradation in the main channel and daily flow discharges from April 29, 2009 to September 3, 2011 at the Upper Junction City site

Boundary Conditions and Other Model Inputs Time-accurate unsteady simulations are carried out using the daily mean flow hydrograph from April 29, 2009 to September 3, 2011 (USGS gaging station 11526250), which includes three spring runoff events (Figure 3b). This hydrograph is used as the upstream flow boundary condition for all model runs. Sediment load is needed as another upstream boundary condition. Sediment rating curves developed by the Trinity River Restoration Program, based on the 2006-2007 sediment data at the Douglas City site of the Trinity River, are used. Water surface elevation (stage) is needed as the downstream boundary condition. A stage-discharge rating curve is developed using HEC-RAS modeling results for a much larger reach and is used as the boundary condition.

A total of nine sediment size classes are used to represent bed materials ranging from 0.25 to 181 mm in size. The Trinity sediment transport capacity equation developed by Gaeuman et al. (2009) is used as the equilibrium rate. The Trinity capacity equation is a modified version of the equation developed by Wilcock and Crowe (2003). For a sediment size class *k*, it may be expressed as:

$$\frac{q_{t,k}^{*} g(s-1)}{(\tau_b / \rho_w)^{1.5}} = p_{ak} G(\phi_k); \qquad \phi_k = \frac{\theta_k}{\theta_r}\left(\frac{d_k}{d_{50}}\right)^{\alpha_k} \tag{1}$$

where $q^*_{t,k}$ is the volumetric sediment transport rate per unit width, p_{ak} is the volumetric fraction of sediment size class *k* on the bed surface, $s = \rho_S / \rho_w$, ρ_w and ρ_S are the water and sediment density, respectively, *g* is the gravitational acceleration, τ_b is the bed shear stress, $\theta_k = \tau_b / [\rho_w g(s-1)d_k]$ is the Shield's parameter of sediment size class *k*; θ_r is the reference Shield's parameter, d_k is the diameter of sediment size class *k*, and d_{50} is the median diameter of the sediment mixture in bed. The function in the transport equation is expressed as:

$$G(\phi) = \begin{cases} 14.0(1 - 0.894/\phi^{0.5})^{4.5} & \phi \geq 1.35 \\ 0.002\phi^{7.5} & \phi < 1.35 \end{cases} \quad (2)$$

Two parameters must be defined to apply the above equation: θ_r and α_k. The parameter θ_r is a reference value above which sediment is mobilized and α_k is the exposure or hiding factor to account for reduction in critical shear stress for larger particles and increase in critical shear stress for smaller particles The standard Trinity equation used the following values:

$$\theta_r = 0.021 + 0.0155\exp(-20F_s) \quad (3a)$$

$$\alpha_k = 1 - \frac{0.7}{1 + \exp(1.9 - d_k / 3d_{50})} \quad (3b)$$

where F_s is the fraction of sand on the bed surface (the cutoff diameter of the "sand" may range from 1 to 4 mm). In this study, a constant reference value $\theta_r = 0.035$ was used. As a comparison, the Wilcock-Crowe (2003) equation used the following default values:

$$\theta_r = 0.021 + 0.015\exp(-20F_s) \quad (4a)$$

$$\alpha_k = 1 - \frac{0.67}{1 + \exp(1.5 - d_k / d_{50})} \quad (4b)$$

Other model inputs included the following. The time step is five seconds, mainly for numerical stability control. The active layer thickness is 0.15 ft, about five times d_{50} and 1.5 times d_{90}. The bedload adaptation length is based on the work of Lai (2013) derived from Seminara et al. (2002); other runs used a constant adaptation length of 80 meters.

Bank Module Inputs Additional input parameters are related to the bank properties for a coupled morpho-dynamic and bank erosion modeling. A section of the river left bank is selected for bank retreat modeling (Figure 4a) with sixteen bank cross sections simulated over six-hour time steps (Figure 4b). Field data collected by Cardno ENTRIX (2012) showed that the selected bank section consisted of essentially uniform and non-cohesive materials. A linear retreat bank module for non-cohesive materials, therefore, is used for the model, and the key input parameters are the critical shear stress and erodibility of each bank. In this study, both the critical stress and erodibility were estimated by Cardno ENTRIX (2012), and no attempt is made to improve the model prediction of bank retreat by changing either parameter.

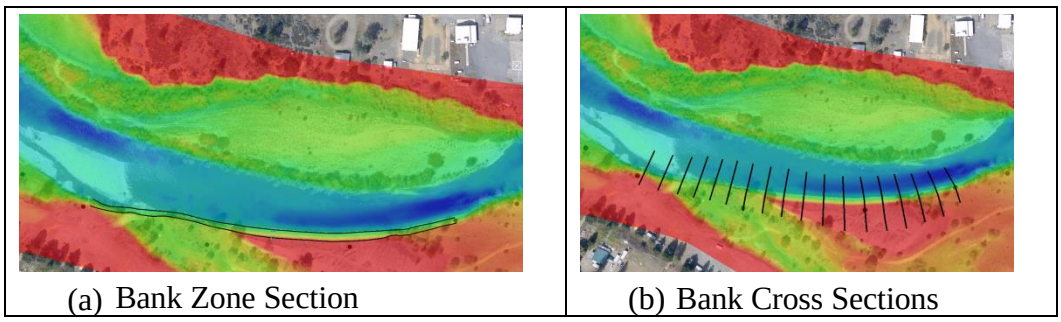


Figure 4 The bank zone section (left) and bank cross sections (right) selected for bank retreat modeling under the *Pre_E* scenario (black lines on the left figure show the bank toe and top)

RESULTS OF CALIBRATION STUDY

Model runs, with and without bank erosion modeling, are made under the *Pre_E* condition for model calibration and validation. The predicted net erosion and deposition depth during the 2009-2011 time period is shown in Figure 5 and is compared with the measured data (left three figures). The survey data suggested that three pools, marked as "Pool 1," "Pool 2" and "Pool 3," were subject to deposition while a section of the left bank, marked as "Bank Erosion," experienced significant bank erosion. The zoom-in views of the same plots are displayed on the three right figures. In addition, the predicted bed elevation changes at the deepest points of Pool 1 and Pool 2 are plotted in Figure 6.

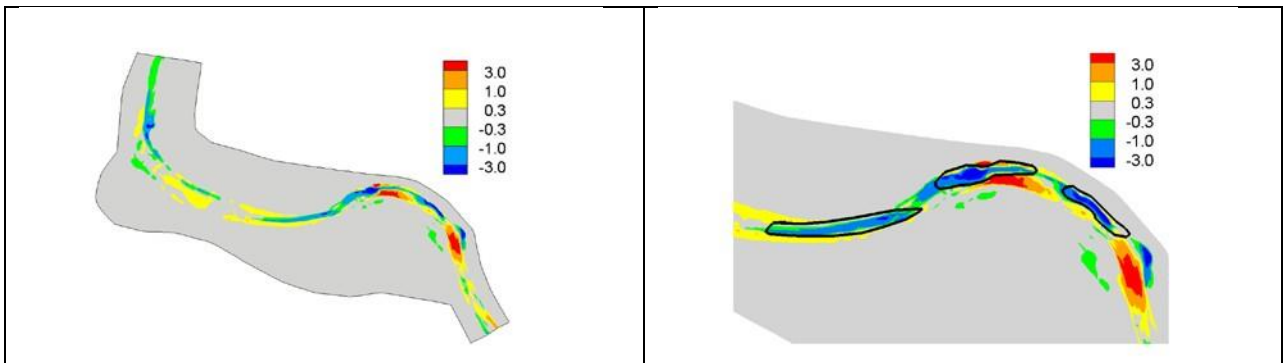
The results show that erosion on the left bank cannot be predicted without using the bank module, but is predicted reasonably well when the bank module is used. The model predicts that the eroded bank sediments are deposited in the stream near the bank and are not transported very far downstream. More than 50% of the eroded bank sediments are large gravels and small cobbles that are difficult to entrain once deposited in the stream. Therefore, the impact of the eroded bank sediments on the downstream half of the reach is relatively small. Upstream of the bank erosion zone, the with- and without- bank model runs produce similar results. Therefore, the without-bank run may also be used to assess the model capability to predict the riffle-pool

processes at this site.

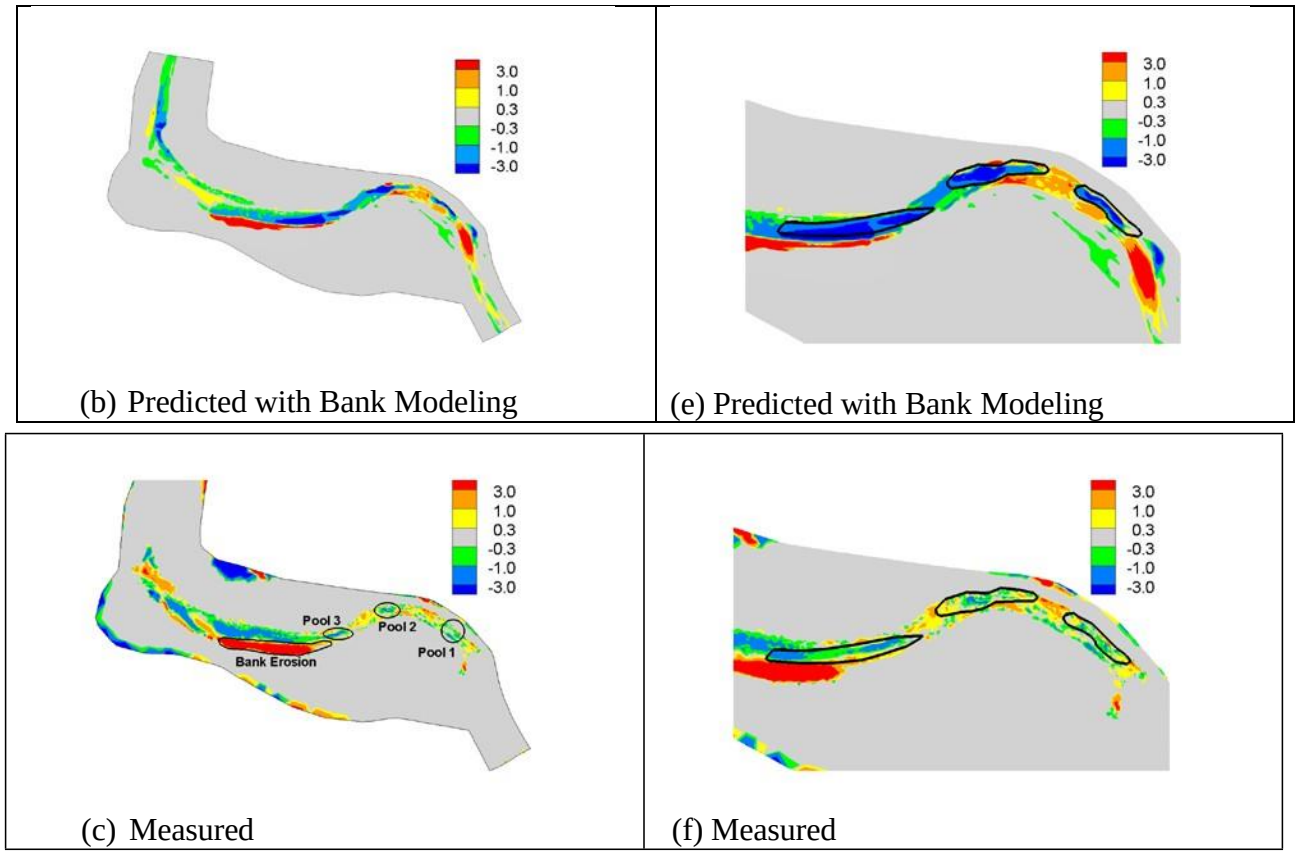
Two major discrepancies are identified between the model predictions and measured sediment. First, the model predicts much more deposition than the measured data in three pools. Second, the riffle erosion downstream of Pool 2 is not predicted by the model. The predicted bed elevation changes at the deepest points of the first two pools are plotted in Figure 6. A total of five and eight feet of deposition are predicted in Pool 1 and 2, respectively; the corresponding measured depositions are approximately 2.2 and 3.2 feet. The over-prediction of the pool filling process is a consistent problem with any depth-averaged numerical models because such models do not take the horizontal vortices into consideration (Logan et al., 2010). 3D models may have the potential to improve the predictions; but this is yet to be proven. Other factors might contribute to the over-prediction of the pool filling process. High uncertainty in the initial bed gradation specification of the riffle areas is one of them. Over-prediction of erosion at riffles might lead to increased deposition in the downstream pool. The sediment transport capacity equation may also be the cause of the poor predictions, as most existing equations are based on reach-averaged or depth-averaged variables.

Model results show that riffle erosion downstream of Pool 2 is predicted after the 2009 and 2010 runoff seasons; the area, however, changes to depositional after the 2011 runoff. The reason for the failure of the numerical model to predict the riffle erosion in the area is unclear. Possible causes include potential inaccuracy in the initial bathymetry and/or bed gradations, neglecting the impact of bank vegetation, or overestimating of the upstream sediment supply at high discharges. We speculate that the most likely cause is the mature vegetation along the nearby right bank which was inundated only during high discharges in 2011 but not represented by the model.

Downstream of the bank erosion zone, model results are less accurate because of uncertainty in the accuracy of the stage-discharge rating curved used to define the downstream boundary condition.



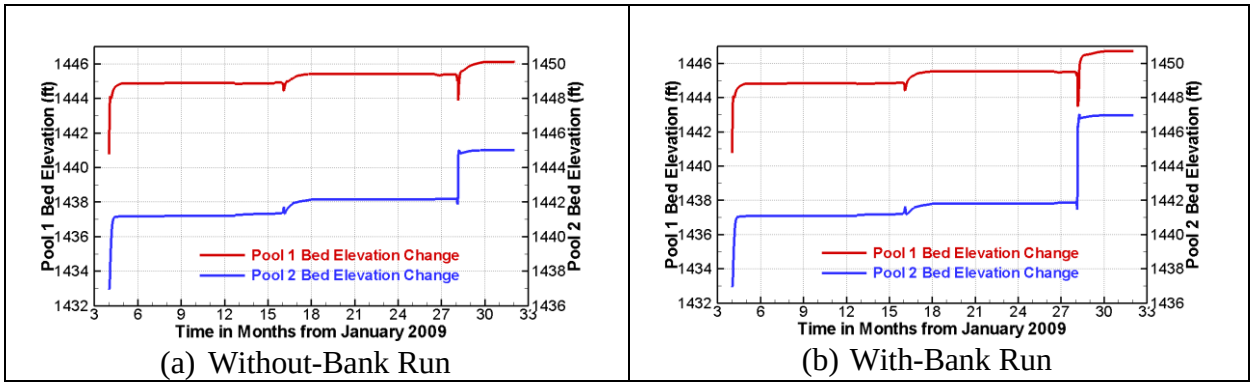
(a) Predicted without Bank Modeling (d) Predicted without Bank Modeling



(b) Predicted with Bank Modeling (e) Predicted with Bank Modeling

(c) Measured (f) Measured

Figure 5 Predicted and measured depth of net erosion (positive) and deposition (negative) in feet, with the *Pre_E* scenario runs (Left); and pool filling after 2009-2011 three-year runoff events (Right)



(a) Without-Bank Run (b) With-Bank Run

Figure 6 Predicted bed elevation variations in time at the deepest points of Pool 1 and Pool 2

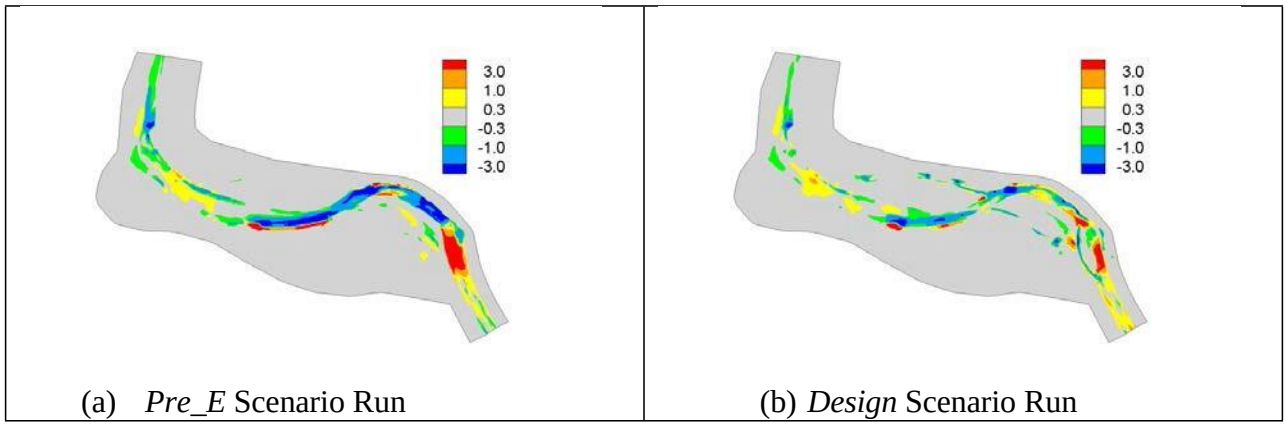
ASSESSMENT OF PROJECT IMPACT

Description of Project Impact Assessment Runs The calibrated model is next applied to assess the impact of the rehabilitation project on stream morphology at the UJC site. It is expected that the pool-filling processes would not be well predicted but processes such as bank erosion; the side channel filling with coarser sediments; and vertical stream bed change downstream of the

pools would be predicted reasonably well. Two scenarios are simulated: the 2011 post-erosion condition (*Post_E*) and the 2012 design (*Design*) condition. The two use the same model inputs except for the initial terrain. Therefore, the differences of results between the two are due to the modification for the design topography at the UJC rehabilitation project.

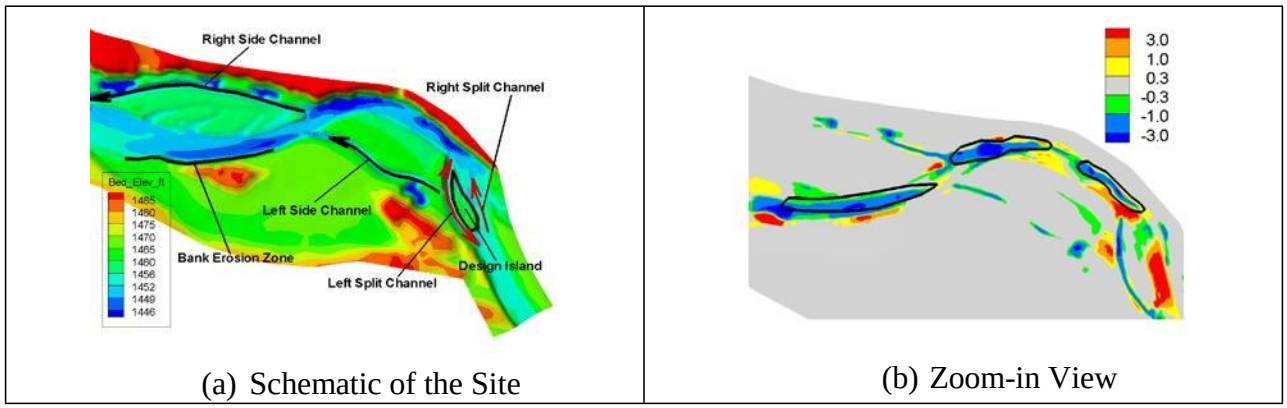
Summary Findings The predicted net erosion and deposition during 2009 through 2011 for the two scenarios are compared in Figure 7, and Figure 8b shows a zoomed-in view of the *Design* run. The differences of the predicted net erosion and deposition between the two runs are plotted in Figure 9b. Positive depth in Figure 9b means that the bed elevation of the *Design* scenario is lower than that of the *Post_E* scenario. The following conclusions may be drawn based on the model results (for location terminology, refer to Figure 8a):

- Deposition was predicted in both the left and right side channels, as seen in Figure 7b. The model results after 2009 and 2010 runoffs are further plotted in Figure 9a. A comparison of the predicted deposition in the two side channels between Figure 9and Figure 7b shows that the predicted deposition occurred mainly during the 2011 runoff event. The peak discharge is 6,040 cfs and 7,520 cfs, respectively, in 2009 and 2010; while the peak is 12,900 cfs in 2011. Therefore, the predicted side channel deposition is mainly due to flows higher than 12,000 cfs.
- The only side channel deposition that might be of concern for the project is the entrance zone of the downstream right side channel. Increased deposition is expected with flows higher than 12,000 cfs.
- The predicted side channel deposition may not be a concern for other locations in the two side channels. With regard to the upstream left side channel, the entrance to the side channel is predicted to erode (Figure 8b) if the initial bed materials in the entrance are the same as the main channel (d_{50}=29 mm). However, much coarser sediments were used in this area when the project was built in 2012. Slight deposition is predicted downstream of the entrance zone in the left side channel (including the pool). However, only fine sediments, less than 10 mm, are deposited. For the downstream right side channel, deposition is limited to the entrance and three side channel pools. Again, only fine sediment deposition is predicted, and they are not considered to be of concern.
- A major potential impact of the design condition (*Design*), based on the model results, is that the main channel downstream of the designed island could experience deposition in some areas and erosion in others (see Figure 9b). However, the left bank zone is not predicted to experience higher rate of lateral erosion than the 2011 post-erosion condition due to the design condition (compare results in Figure 7). On the contrary, the *Design* is predicted to lead to slightly less bank erosion. Less deposition in the stream near the bank erosion zone is probably due to less bank erosion predicted with the *Design* scenario. Note that the model does not consider other bank sections.
- The model predicts some deposition in the channel to the left of the designed island and erosion in the channel to the right. In view that the 2011 *Post_E* scenario is predicted to be erosional in the same area, erosion in the right spilt channel may not be a concern. The deposition on the left split channel might be an important risk to consider since the deposited sediment sizes are not small. The model predicts that sediment deposited in the left split channel will have a d_{50} of around 15 to 17 mm.



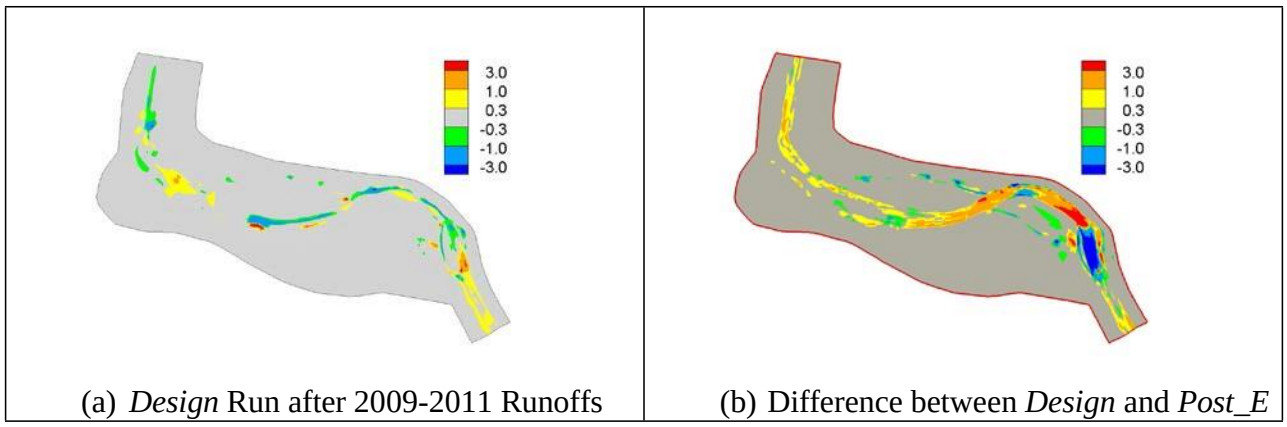
(a) *Pre_E* Scenario Run (b) *Design* Scenario Run

Figure 7 Predicted net erosion (positive) and deposition (negative) depth in feet with the two scenarios



(a) Schematic of the Site (b) Zoom-in View

Figure 8 Schematic showing the terminology used to identify different features of the design construction (Left); and a zoom-in view of the predicted net erosion (positive) and deposition (negative) depth in feet with the *Design* scenario (Right)



(a) *Design* Run after 2009-2011 Runoffs (b) Difference between *Design* and *Post_E*

Figure 9 Predicted net erosion (positive) and deposition (negative) depth in feet with the *Design* scenario after 2009 and 2010 runoffs (Left); and the differences of the predicted depth of erosion and deposition in feet between *Design* and *Post_E* scenarios (Right)

CONCLUDING REMARKS

A coupled morpho-dynamic and bank erosion model is carried out for the Upper Junction City (UJC) rehabilitation project on the Trinity River. The objectives of the study are twofold. First, the study is to test SRH-2D geofluvial modeling capabilities and verify whether the bank erosion module can correctly simulate observed bank erosion in study area. Second, after model calibration, SRH-2D is applied to assess the impact of the UJC rehabilitation project on channel morphology.

Calibration and validation modeling runs are carried out by comparing the 2011 measured terrain data with predicted topography obtained by simulating changes to the 2009 pre-erosion baseline (PB) condition caused by 2009 through 2011 hydrology. The necessary bank erosion model inputs, mainly the critical shear stress and erodibility, are estimated from the field measurements. The geofluvial SRH-2D model is shown to be capable of predicting bank erosion and bed level changes. The model can predict pool-filling processes only qualitatively.

The SRH-2D is also applied to assess the impact of the rehabilitation project on channel morphology. Due to potential uncertainties of numerical models, only a relative comparison can be made between the two scenarios. Relative comparisons are often more accurate than the absolute prediction with channel morphology changes. The model results have led to a number of important conclusions with regard to the impacts of the design on stream morphology.

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