Wait, the Bed Moves? - Necessity and Implications of Mobile-Bed Hydraulic Modeling for Flood Control Purposes, the San Lorenzo River, CA

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Introduction and Background

Flood flow frequency and magnitude and associated sediment transport dynamics are important factors related to flood risk on the San Lorenzo River within the City of Santa Cruz (City), California. Catastrophic flooding on the San Lorenzo River during December of 1955 (flood of record) prompted initiation of a U.S. Army Corps of Engineers flood control project on the lower San Lorenzo River (from Highway 1 to the railroad bridge; see Figure 1). The original project was built in 1959 and included levee construction and excavation of approximately 770,000 cubic yards of sediment to achieve the design grade (Copeland 1986). However, in subsequent years (up through the early 1980s) sediment deposition of approximately 450,000 to 500,000 cubic yards filled in much of the excavated channel and significantly reduced the design capacity. The San Lorenzo River watershed has a relatively high sediment yield and routine maintenance of the channel was both impractical and infeasible. Another large flood event, very similar in magnitude occurred in January of 1982. The City was spared any catastrophic damage and flooding this time around, and it was observed that the high-water levels were much lower than predicted and also that the peak water surface elevation preceded the peak discharge, which suggested that channel scour is a significant process at high flows. For example, approximately 140,000 to 190,000 cubic yards were scoured from the San Lorenzo River prior to and during the event and about half of that volume (90,000 cubic yards) was deposited in the period after (USACE 2014).

Over subsequent years (from approximately 1999 to 2005) the City, partnered with the USACE, constructed a modified project to meet or exceed FEMA standards, and they are now seeking certification of the San Lorenzo River levee system, part of which entails generating design water surface elevation (WSE) profiles. The San Lorenzo River bed is comprised of mostly sand and gravel, and observations during floods suggest that the process of channel bed scour should be considered when calculating flood profiles. However, mobile-bed modeling is not typically applied in the context of FEMA levee certification and flood hazard mapping, and to our knowledge this would be the first such application (at least in California). Building on previous work, ESA developed a hydraulics and sediment transport model (HEC-RAS, version 6.0) for contemporary conditions to evaluate hydraulics and sediment transport in the channel and establish annual chance exceedance event (ACE) base flood elevation profiles for levee certification.

This exercise has led to the development of a particularly robust sediment transport model, which in turn has allowed us to indirectly assess the sensitivity of sediment transport and storage to scenarios that reflect potential climate changes conditions, e.g., increased downstream water surface elevations or sea-level rise.

San Lorenzo River Sediment Transport Model

ESA developed an HEC-RAS (version 6.0) hydraulics and sediment transport model that was modified and improved from a previous USACE HEC-6T model (USACE 2014). Beginning with some seminal work (Copeland 1986) on sediment transport, the USACE completed an extensive hydraulic and sediment transport analysis of the San Lorenzo River as documented in the Performance Evaluation report (USACE 2014). As a predecessor to HEC-RAS, HEC-6T is not supported for National Flood Insurance Program (NFIP) certification. ESA converted the HEC-6T model into HEC-RAS and both replicated and extended the model calibration and validation. The current model integrates the fluvial processes of sediment transport and flow and the influence of coincident coastal processes (i.e., an elevated downstream boundary condition that includes regional non-tidal residual (i.e., storm surge) and static wave setup). We calibrated and compared the predicted water surface elevations and sediment changes to historic flood events separated by over three decades.

Model Calibration and Validation

The years 1982 and 2017 were two of the most significant with respect to San Lorenzo River sediment export and flows. One of the largest events on record occurred in January of 1982, and water year 2017 was the wettest on record, producing nine flow peaks representing 2- to 10-year flood magnitudes. By the third flood in water year 2017, fluvial suspended sediment showed a regime shift to greater and coarser sediment supply, coincident with numerous landslides in the watershed (East et al. 2018). Data collected during these two periods afforded a unique opportunity to assess HEC-RAS model results and performance relative to sediment observations separated by over three decades.

Our current model represents decades of collective work (parameterization, calibration, validation, computational improvements, etc.) and performs very well in replicating the complex process of sediment transport in the lower reach of a coastal river. The USACE calibrated the previous HEC-6T model to observed high-water marks for the January 1982 event (peak flow of approximately 30,000 cfs at Big Trees[1] or between a 25-year and 50-year event) as well as to observed sediment changes in the period before and during the event (which comprised mostly channel degradation, or scour). The model was validated by comparing predicted and observed bed changes in the re-aggradation period after the January 1982 event. ESA followed the same calibration approach for the HEC-RAS model, calibrating and validating the model using the January 1982 event and associated conditions in the same manner employed by the USACE (2014). The HEC-RAS model generally performed as well as, or better than, the USACE HEC-6T model simulating the January 1982 event WSEs and associated sediment conditions (Figure 2). The HEC-RAS model was further calibrated to high-water marks observed for the February 6-8, 2017 event (peak flow of 19,000 cfs at Big Trees, approximately a 10-year event and the largest

[1] https://waterdata.usgs.gov/monitoring-location/11160500/#parameterCode=00065&period=P7D

peak during the record winter of water year 2017) (ESA 2017) and validated by comparing the predicted sediment flux to measurements made by the U.S. Geological Survey (East et al. 2018) (Figure 3).

Modeled changes in maximum water surface elevation (not shown) were generally not sensitive to variations in the sediment transport and bed mixing options within HEC-RAS (version 6.0), though the predicted changes in sediment volume and flux were very sensitive. In particular, weighting some of the transport capacity partitioning by the gradation of the incoming sediment load, instead of all with the bed gradation for a given cross-section, improved the sediment transport model results. Though this option is intended primarily for wash load, this nonetheless suggests this option may, indirectly, also be useful to better reflect or improve upon the computation of bed material transport and mixing.

Coastal Boundary Condition Adjustment

ESA coastal engineers reviewed the prior work and recommended updates to the coastal boundary condition applied in the previous USACE (2014) work. The purpose of this exercise was to provide an updated time-varying tidal signal that includes representative wave setup and non-tidal residual (NTR) that is likely to coincide with large fluvial flow events – specifically the 10-, 50-, 100-, and 500-year fluvial flows. The prior model (USACE 2014) applied a time-varying tidal signal based on the observed tidal signal without any further adjustment. The timing of the flood peak with the tide signal was programmed (or phased) so that the peak flow would coincide with the 50-percent annual chance exceedance tide elevation.

Based on analysis of local wave and NTR data, we adopted a simple approach where a constant static wave setup and NTR are added to the time-varying tide signal. The NTR was selected from Table 1 for a given fluvial flow event of interest (e.g., 100-year, etc.) and the wave setup was selected as a constant value of three feet. Addition of the selected NTR and wave setup of three feet to a typical tidal signal yields a conservatively high tidal boundary condition that represents likely water levels during an extreme fluvial flow event (Figure 4), which was used to adjust the downstream boundary condition in the model.

Table 1. Estimated Non-Tidal Residual for Several Fluvial Flow Return Periods and Static Wave Setup.

Exceedance Probability (%)	Peak Fluvial Flow (cfs)	Estimated Non-Tidal Residual (feet)	Return Period (year)	Static Wave Setup at Shore (feet)
0.2%	62,910	2.6	500	3
1%	47,120	2.3	100	3
2%	39,900	2.2	50	3
10%	23,200	1.8	10	3

Selected Results

Using the calibrated sediment transport model, we assessed the sensitivity of the predicted bed change over the course of the 1- and 10-percent ACEs to the downstream boundary condition.

i.e., the unadjusted tidal elevations versus higher tidal elevations after adjusting for wave setup and NTR. The model simulation time window was 55 hours (comprising approximately two semi-diurnal tidal cycles) and the design flow input hydrographs were those presented by USACE (2014) (which were developed by scaling the January 1982 event hydrography to the ACE peak flows). The results indicated that, although flood-induced bed scour lowers the flood profile, the elevated coastal boundary condition reduced cumulative bed scour of the lower reach of the San Lorenzo River by up to 35 percent and 73 percent for the 1-percent and 10-percent ACE events, respectively (Figure 5), which increased flood elevations near the river mouth. For most of the modeled reach (e.g., beginning at a point approximately 1,000 feet upstream of the railroad bridge) the maximum water surface elevation profile (not shown) was generally not sensitive to the downstream boundary condition. However, the difference and reduction in net bed scour over the course of the modeled event was notable for approximately 6,500 feet upstream of the ocean (or up to approximately Soquel Avenue and Branciforte Creek), which suggests the largest difference was the modeled sediment deposition on the receding limb or after the peak.

Discussion

Conditions on the San Lorenzo River dictated use of a mobile-bed hydraulics model to accurately predict water surface profiles and changes in sediment flux and storage. Without use of a mobile-bed model, it is unlikely that accurate flood profiles for use in the NFIP levee certification process could be generated.

Use of the same sediment rating curve boundary condition (including the sand load fractions) resulted in good agreement between predicted and observed conditions during two significant sediment events separated by over three decades. However, East et al. (2018) noted a shift in the sediment regime of the San Lorenzo River to a measurably higher sand content during the record wet water year of 2017. This suggests these types of shifts may be transient (as suggested by East et al. 2018) but also comparable to similar processes that may have occurred historically.

Sediment transport and storage on the lower San Lorenzo River are important processes that have been studied over many decades and play a pivotal part in controlling flood water surface elevations. It has been observed that the San Lorenzo River bed scours significantly during peak flood events and refills or aggrades with sediment to some degree in the periods after. The downstream water level (ocean) during and after a flood event exerts significant control on the evacuation and storage of sediment in the lower river and using our calibrated model we have shown that higher downstream water levels during a flood significantly reduce the amount of scour in the lower San Lorenzo River. This suggests that, over time, the balance between scour and deposition on the lower river may change in response to different conditions and there may be less net scour. For example, this could happen in the relatively short-term after multiple large flood events with high coincident ocean levels, or over the longer-term with sea level rise and/or larger fluxes of water sediment for the watershed. Though the process of scour should be considered on an event basis, with respect to hydraulic modeling for example, the current general magnitude and nature of this process may change with higher average ocean levels and reduce the extent of “self-scouring” on the lower San Lorenzo River.

Figure 1. USACE San Lorenzo River Project area (from USACE 2020).

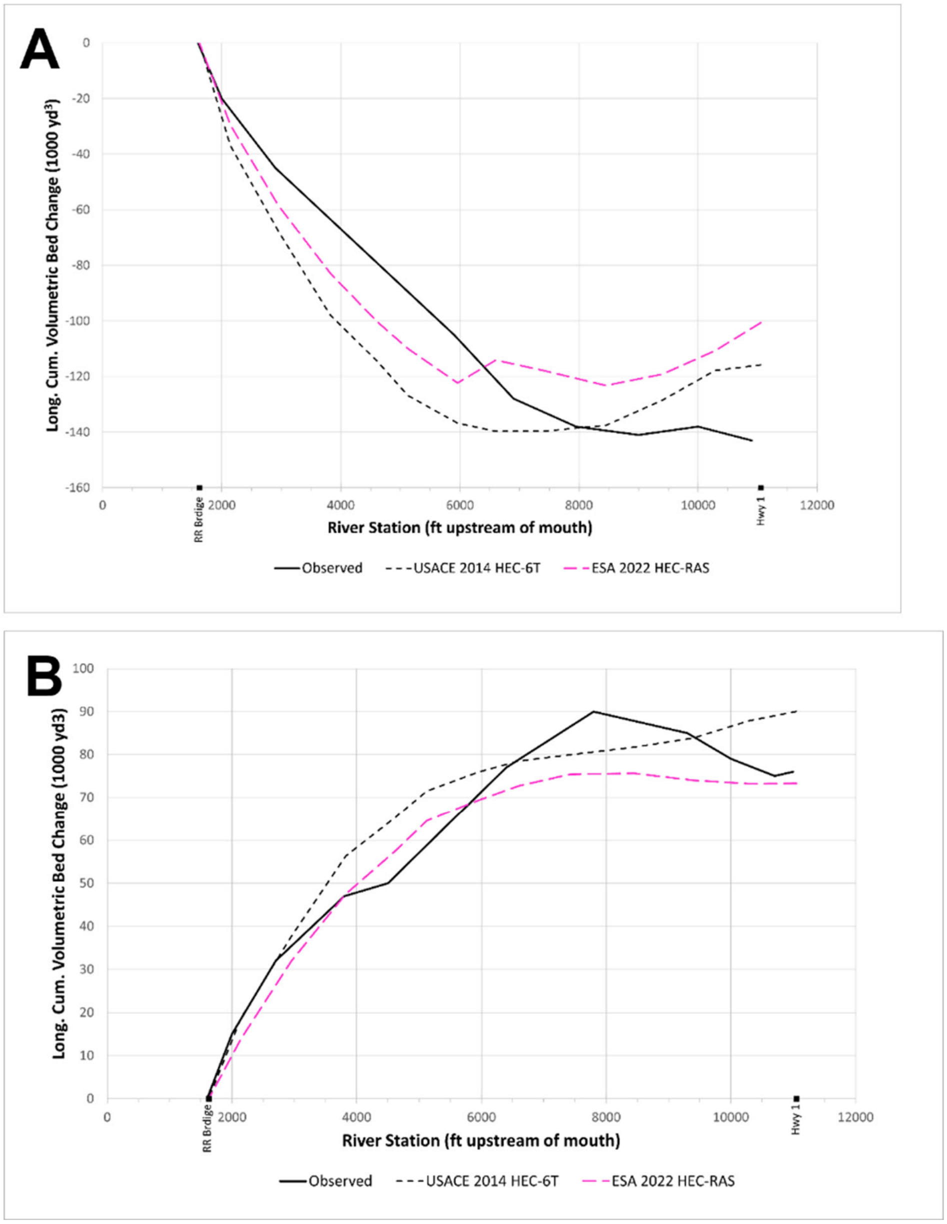

Figure 2. Comparison of predicted and observed longitudinal cumulative volumetric bed change between A) June 1980 and January 5, 1982 and B) between January 5, 1982 and December 1982

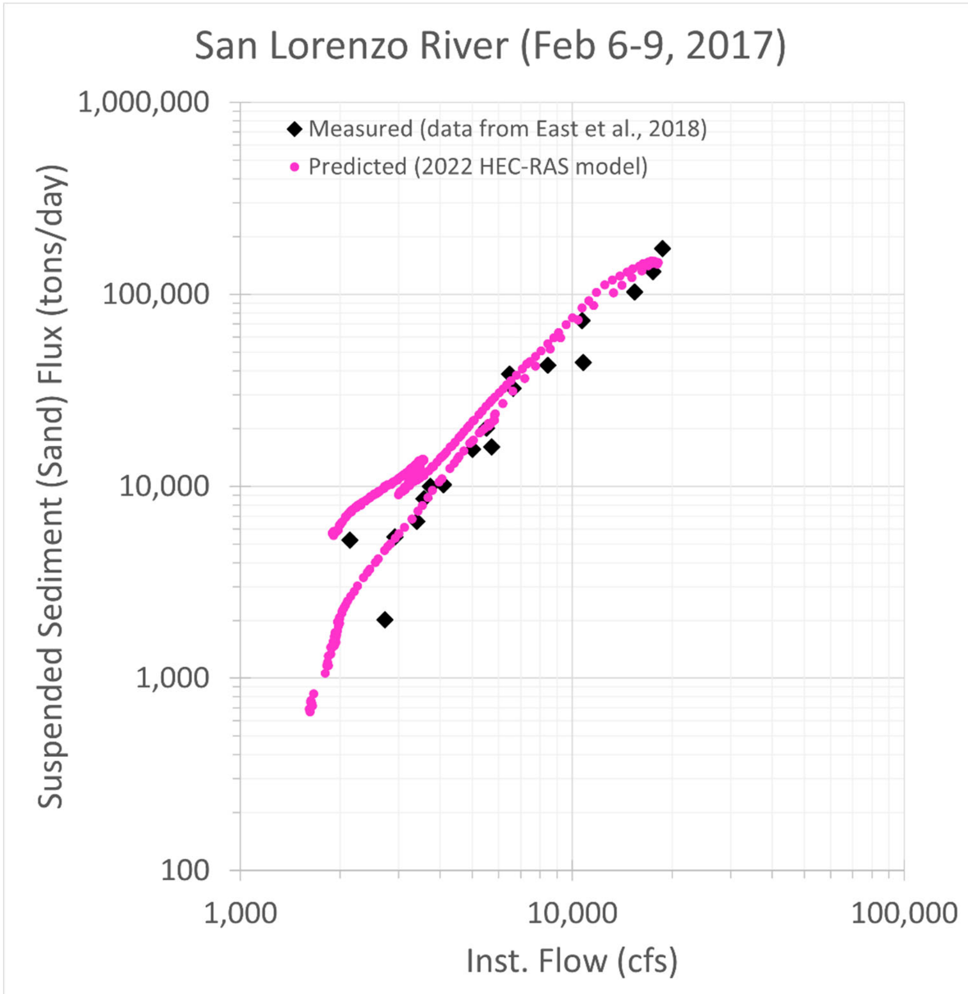

Figure 3. Comparison of modeled and measured sediment flux during the February 6-9, 2017 event. Measurement location is the pedestrian bridge between Water Street and Soquel Avenue.

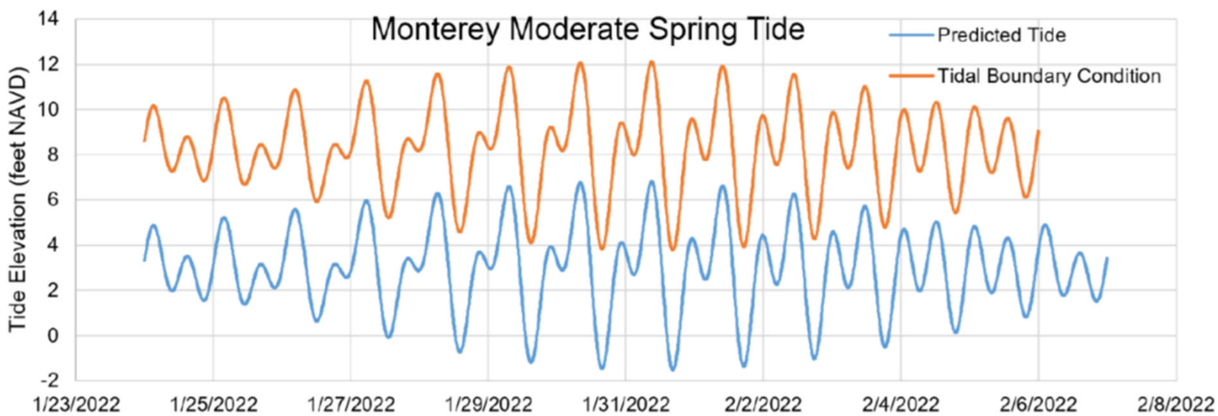

Figure 4. Predicted tide at Monterey, CA, compared to a modified tidal boundary condition coinciding with a 100-year fluvial event, where the tide signal is adjusted to include three feet of static wave setup and 2.3 feet non-tidal residual.

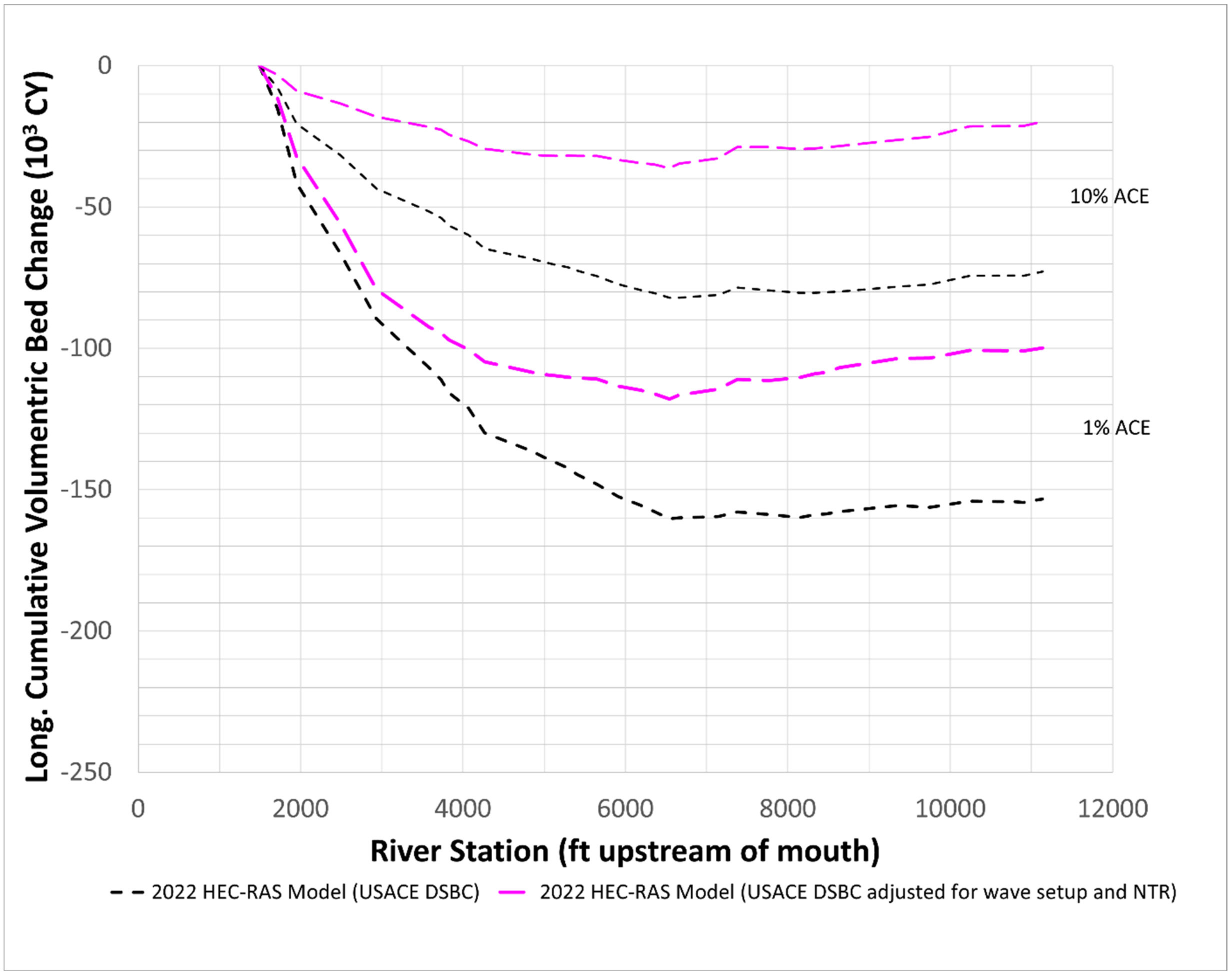

Figure 5. San Lorenzo River HEC-RAS sediment transport results for the 1-percent and 10-percent annual chance exceedance events.

References

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