Development of a Fully Unsteady Flow Sediment Transport Model for the Mississippi River below Tarbert Landing

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Abstract

The U.S. Army Corps of Engineers developed an unsteady sediment model for the lower Mississippi River. This model was developed with the goal of providing an initial demonstration of the unsteady, movable bed features of HEC-RAS 5.0.3 on the Mississippi River. The model simulated flow and bed change along the lower 323 miles of the Mississippi, from Tarbert Landing, to a downstream Gulf of Mexico boundary condition, 18 miles downstream of Head of Passes. This is the largest fully-unsteady sediment transport model developed in HEC-RAS to date. The modeling domain included thirteen sub-reaches, simulating overbank inundation by diverting high flows over numerical lateral weirs into simulated floodplain channels. The unsteady hydraulic model was calibrated to water surface elevation at four internal gages and sediment transport was calibrated to bed volume change between 2004 and 2012. The sediment calibration was also checked against internal concentration data and specific gage analyses at four gages. The model performed well, reproducing the bed volume change trend and concentrations. In this paper we discuss the development process and lessons learned.

Introduction

Sedimentation in the Lower Mississippi River directly affects commercial navigation, ecosystem services, and flood damage reduction. Additionally, sediment diversions out of the river and into the delta are being designed and constructed to build land in sensitive ecotones. Therefore, the U.S. Army Corps of Engineers (USACE) districts, the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), and their partners are investigating the flow of sediment through the Lower Mississippi River system, including the effects of natural and engineered sediment diversions from the river to the delta and in-channel dredging. Sediment models that can simulate flow and sediment diversions, as well as dredging and potential impacts to riverine sediment processes, can help design and assess these alternatives.

The USACE and their partners have developed several sediment models of the Lower Mississippi River with the HEC-6T sediment model. The release of HEC-RAS 5.0 included the capability to couple sediment transport with the unsteady flow capabilities, making fully unsteady, sediment transport available for the first time in a single, publicly released, 1D, USACE model. A fundamental limitation of using a quasi-unsteady model, such as HEC-6T or older versions of HEC-RAS, for regional systems is that the timing of flood peaks, tributary inflows, and diversion operations must be altered so events are synchronized to the correct flow in the river. Moving to an unsteady hydraulic framework allows models to calculate more accurate timing of events, structure operations, tidal influences.

The Lower Mississippi River includes several particularly unsteady hydraulic processes. We developed a fully unsteady hydraulic and sediment transport model of the lower 323 miles of the Mississippi (Figure 1), from Red River Landing to the Gulf of Mexico, to support studies and operations in this area. This paper summarizes the creation and validation of the fully unsteady hydraulic and sediment model of the Mississippi River. We also outline the next steps in the development and extension of the model.

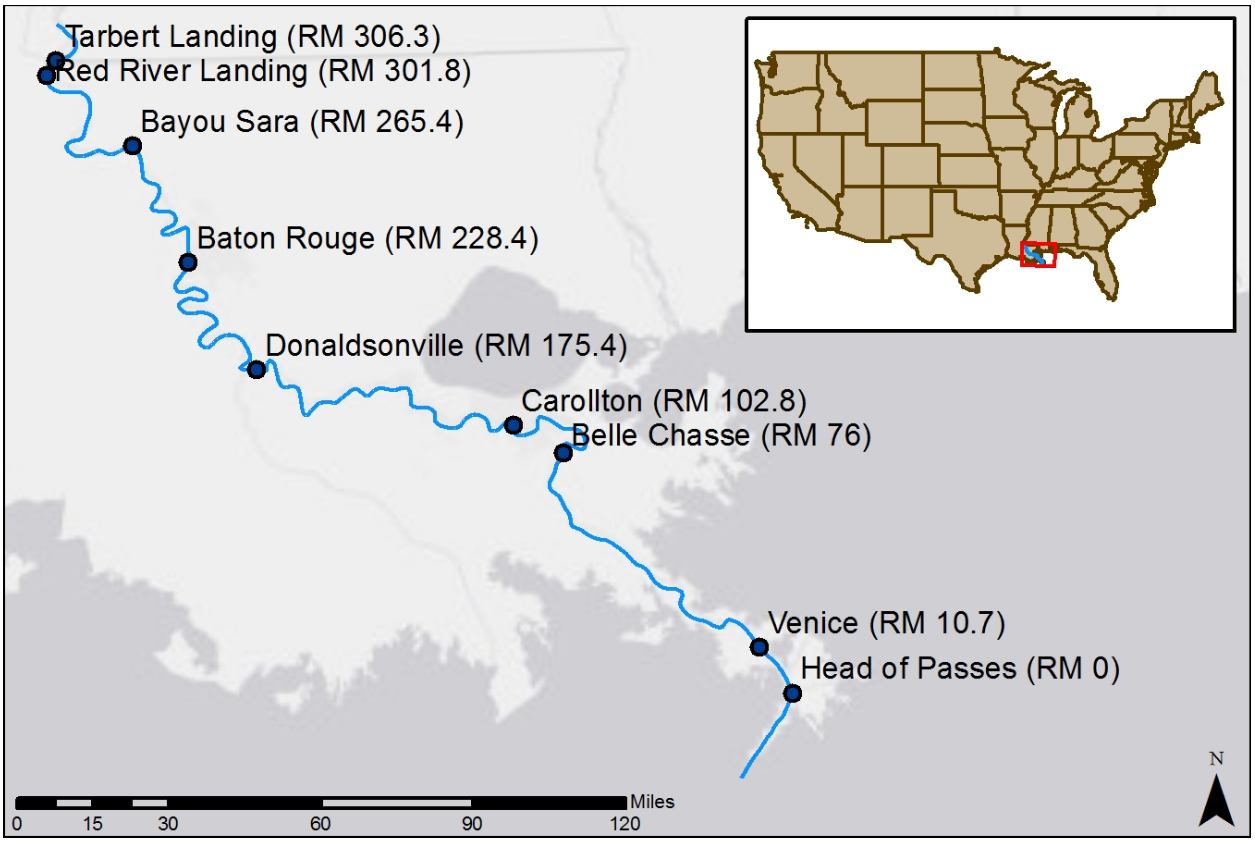

Figure 1. Location map of the study area and calibration points.

Model Development

Unsteady Hydraulic Model Development

A series of HEC-6T models of the Lower Mississippi River were developed in the past by the USACE. The USACE used these models to examine the effect of diversions at Myrtle Grove (Thomas 2012) and West Bay (Sharp et al. 2013), as well as long-term sedimentation trends in support of the Flowline assessment. Hereafter, when the HEC-6T model is referred to, unless otherwise specified, the reference is to the model modified for the Delta Management Study.

We obtained bathymetry data from the USACE New Orleans District for two different years, 2004 and 2012. We supplemented the in-channel data with lidar data provided by the Louisiana Oil Spill Coordinator's Office. Upstream flows and sediment loads at Tarbert Landing (RM 306.3) were obtained from the U.S. Geological Survey (USGS) (USGS Gage#07295100). The New Orleans District also provided flows for the Morganza floodway and Bonnet Carré Spillway. Within the 2004 to 2012 calibration window, the Morganza Control Structure only operated during the 2011 flood while the Bonnet Carré Spillway diverted flow in 2008 and 2011. Water levels at Pilots Station in Southwest Pass (National Oceanic and Atmospheric Administration [NOAA] Gage #8760922) were used to develop a downstream boundary condition for the model.

The mainline levees downstream of Baton Rouge are very close to the main channel, but the distance between the levees above that point can be over ten miles in some cases (Biedenharn et al., 2018). The unsteady-sediment geometry models all large floodplain areas as reaches. Each of these floodplain reaches is connected to the main river reach with numerical lateral structures on the upstream end, which simulate the natural levees, and junctions at the downstream end, where water surface elevations in the river and floodplain are assumed to be equal (Figure 2). Modeling the floodplains as reaches allows the model to simulate sediment transport through the overbank areas and the impact of these floodplain diversions on the sediment continuity in the river channel.

Bathymetry and overbanks were cut separately in HEC-GeoRAS for ArcMap 10.1 and combined into a single model geometry. We modified the geometry within HEC-RAS to improve stability in several ways. Modeling the downstream end of floodplain reaches with inline structures improved model stability when the floodplain reach became perched above the mainstem during low flows while still allowing the passage of sediment. The inline structures were placed at the ground elevation so that they did not affect outflows. Pilot channels were added to floodplain reaches where thalweg inflection points forced the solution to critical depth. Levees and ineffective flow areas focused the sub-cross-section conveyance distribution to calculate appropriate shear stresses in the Mississippi River mainstem.

The upstream hydraulic boundary is a daily flow record from the USACE gage at Tarbert Landing, which reports the instantaneous flow each morning. The downstream stage boundary condition is located at the Pilots Station gage location but is populated with long-term average monthly elevations (Table 2)

Bonnet Carré flows were modeled using the same flow-flow rating curve as the HEC-6T model. Distributary hydrology downstream of the Bonnet Carré Spillway at RM 130 is much more complex and uncertain, however. In the post-2006 diversion development period, only 40% of water passing Tarbert Landing continues into the Gulf through Southwest Pass during low flow. The Unsteady HEC-RAS model includes 12 modeled diversions between Bonnet Carré and the Gulf. We simulated these diversions with flow-flow diversion rating curves.

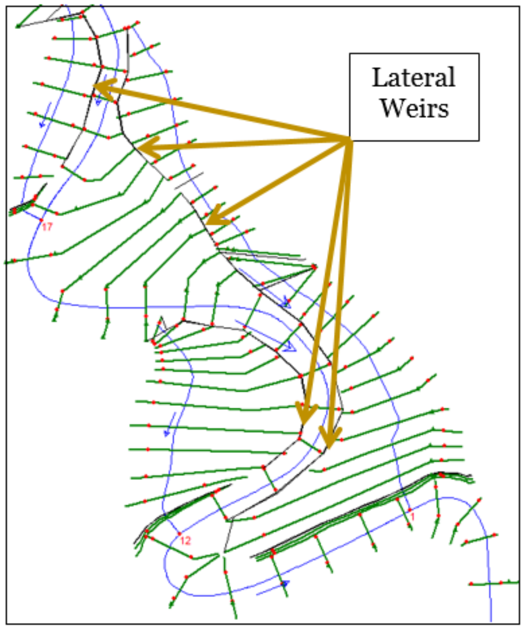

Figure 2. Model geometry approach to floodplain flow.

Table 1. Downstream boundary condition used in Unsteady HEC-RAS model.

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Average Elevation NAVD88	-0.4	-0.4	-0.2	0	0	0.1	-0.1	0.2	0.5	0.4	0	-0.3

Sediment Model Development

The project reach included excellent, synoptic, bed gradation data (Nordin and Queen 1992). The 323-mile study reach included 161 bed samples, a sample every 2 miles. Despite the inherent noise in this data, the sample density was sufficient for us treat the initial bed gradation—often a source of significant uncertainty—as a fixed model parameter.

The initial upstream sediment boundary condition came from the HEC-6T model. The HEC-6T boundary condition defines sediment load with a flow-load rating curve. The rating curve is convex, indicating the system may be supply limited at high flows (Gibson and Cai 2017). A standard power function defines the flow-load relationship up to 600,000 ft3/s. However, the curve has a hard inflection point at 600,000 ft3/s. Above this flow, the flow-load relationship is nearly linear, with a power of less than 1.

During the model development and validation process, we updated the upstream boundary condition to leverage the careful analysis of the rating curve from the previous studies while accommodating the lower measured wash load. The sand mass (fine sand [FS] to very fine gravel [VFG]) was fixed from the HEC 6T rating curve by multiplying the percent of sand by the total load at each point on the flow-load curve. The team then fit a new total load rating curve to the Old River data. The bed sand fractions (FS to VFG) were prorated (retaining their relative proportion) to maintain the same sand mass as the HEC-6T curve for each flow. Then the very fine sand (VFS) load was estimated and the balance of the total load mass was distributed evenly between the five silt and clay grain classes. This produced a rating curve that conserved the sand fractions from previous analysis but generated computed wash loads (defined as clay to VFS) at the model boundary consistent with the more recent measurements. Bringing boundary condition wash load into line with the measurements aligned the concentration calibrations downstream.

After determining that the model was insensitive to the placement of the movable bed limits, we placed them at approximately a bank full discharge. No deposition was allowed outside of these limits.

The HEC-RAS model leveraged the unsteady flow hydraulics to simulate flow and sediment diversions. We used the following sediment diversion rules to specify the grain size classes diverted: (1) Diversions upstream of RM 120, except Bonnet Carré, diverted all fine grain classes (<VFS) in proportion to the diverted flow, but kept sand in the channel, (2) Bonnet Carré diverted very fine sand and smaller particles in proportion to flow, (3) downstream of RM 120, flow-weighted diversions pulled out clay to medium silt while coarser material transported downstream. The exceptions to this were Ft. St. Philips, where coarse silt was also diverted, and the major diversions at Baptiste Collette, Grand Pass, West Bay, Cubits Gap, Pass A Loutre, and South Pass, which all diverted sands in addition to silts and clays.

The rates of subsidence, or sinking of the land, vary spatially, with rates generally increasing with proximity to the Gulf. The primary and secondary causes of this subsidence are active areas of research. The study team added subsidence capabilities to HEC-RAS as a precursor to this study. This model introduced subsidence downstream of RM 185.6, increasing subsidence rates gradually downstream, reaching a maximum rate of 18.5 millimeters per year (mm/yr) at Head of Passes.

The Unsteady Sediment HEC-RAS model cohesive parameters were adopted directly from the HEC-6T model. The HEC-6T model varied the deposition thresholds for clay and silt longitudinally to better match observed dredging and deposition. This rate was set to 0.01 lb/ft2 above RM 11.5 (near Venice, LA), increased to 0.02 lb/ft2 between RM 11.5 and Head of Passes, and increased further to 0.035 lb/ft2 downstream of Head of Passes. While HEC-RAS can use different cohesive parameters at individual cross sections, this iteration of the model used one threshold for all cohesive grain classes throughout the domain.

The model uses the Copeland (labeled Exner 7 in HEC-RAS; Copeland, 1993) method for bed mixing and armoring because it was developed for large, sand-bed rivers and had been used previously on the Mississippi River.

Historical water temperature data, taken from the HEC-6T model, were grouped and averaged by month. These monthly average temperatures were converted into a recurring monthly time series.

Dredging on the Lower Mississippi River focused on the lower 250 river miles during the simulated time window. The model used dredging templates from the HEC-6T model and updated them based on the cross sections in the new model. The dredge algorithm in HEC-RAS cut each cross section down to the dredge template elevation each year.

Dredging operations in the Mississippi River re-entrain dredge material, allowing the river to transport it downstream. HEC-RAS can re-introduce sediment but discharges sediment from each dredge event into one cross section. Therefore, the modeling team divided dredging each year into 12 local dredge reaches. Dredged sediment was reintroduced downstream of the reach for all sites above Venice, LA. Dredged material below Venice was removed from the model, to reflect the practice of placing this material outside of the active channel near Head of Passes or an offshore disposal area.

Model Validation

Unsteady Hydraulic Validation

We used the flows from 6 February through 3 August 2008, which included a moderate flood, for the initial hydraulic calibration of the Unsteady HEC-RAS model. All of the flow diversions constructed before 2005 were included in the calibration geometry. Water surface elevations in the unsteady flow model were calibrated to the 2008 dataset by adjusting channel Manning's n roughness values.

To further improve the calibration throughout the full flow range, we included flow-roughness variation in the model. The final calibration values are listed in Table 5 and Table 6. Channel roughness varies between a maximum of 0.035 and a minimum of 0.018 and is considered reasonable for a mobile sand bed river. Overall, roughness increases with flow at the upstream end of the model and decreases with flow at the downstream end of the model. Direct relationships between flow and roughness are common in sand bed rivers as bed form amplitude increases with flow (at least until the river reaches a plane bed regime and n-values drop). The inverse relationship between flow and n-value downstream may be compensating for error in the floodplain diversion hydrology. The difference may also be influenced by the variation in batture width, the area between the river at low stage, and the levees. At the upstream end of the model, the batture is several miles wide while the levees are typically adjacent to the river downstream of Baton Rouge. At high flows, this may have the effect of focusing the flow in the channel and reducing bed-form roughness.

Overall model calibration is good throughout the range of flows and stages for the extended timeframe (Figure 3). Additional information on the calibration is available in Dahl et al. (2018). Given the high quality of bathymetric and topographic data available, flow measurements appear to be the most significant data uncertainty affecting stage calibrations. In particular, the magnitude and timing of flow diversions is the primary data uncertainty in the hydraulic model.

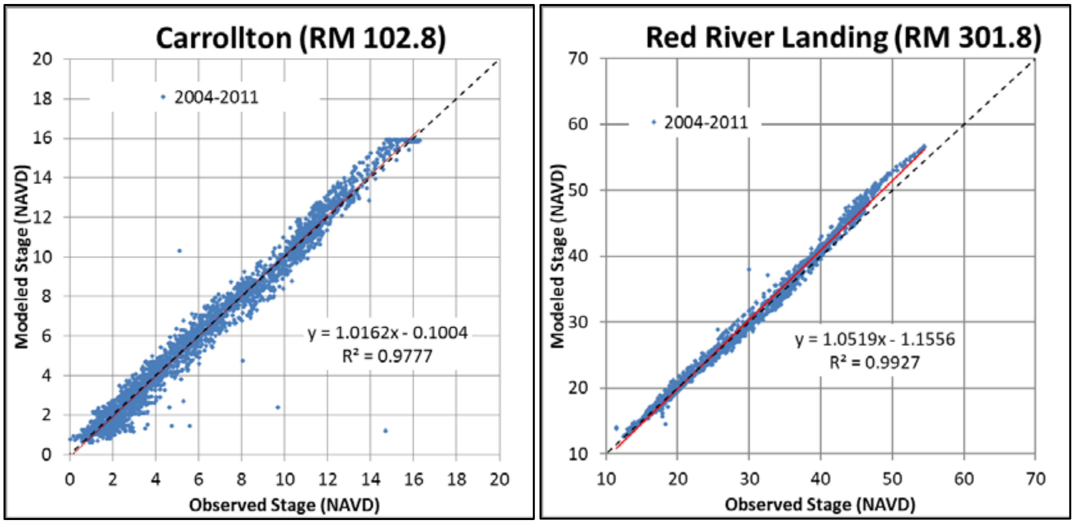

Figure 3. Representative hydraulic calibration locations. The line of perfect agreement between the observed and modeled flows is indicated by the dashed line.

Sediment Calibration

The primary result that we used for sediment calibration were longitudinal cumulative volume change. We also compared the model results to observed suspended sediment concentrations. The calibration period was a net depositional period in the river, with some erosion in the upstream end of the model reach. However, the recent history of this reach includes both depositional and degradational periods.

Longitudinal Cumulative Volume Change: There are a number of sediment transport functions which should be applicable to this system, including Toffaleti, Toffaleti-MPM, and Laursen-Copeland. After initially testing of these and other functions, we decided to use Laursen-Copeland, because it was the best fit to the longitudinal cumulative volume change. The Laursen-Copeland method accommodated the upstream boundary conditions, limiting scour through the upstream 130 miles of the model to approximately 1,000 million ft^3, similar to the upstream scour observed in the data.

The HEC-6T model uses three different cohesive deposition thresholds, ranging from 0.010 to 0.035 lb/ft^2. By default, HEC-RAS only allows a single cohesive deposition threshold for the entire model, although it is possible to alter it for different cross sections. The modeling team used the default value of 0.020 lb/ft^2.

We calculated the longitudinal cumulative volume change for the model domain between 2004 and 2012 using the USACE Kansas City District (NWK) Cross Section Viewer (Shelley and Bailey 2017). The longitudinal cumulative volume curve accumulates volume change from upstream to downstream. It smoothes noise from individual cross-section perturbations into discernable regional trends and, more importantly, allows modelers to compare volume change between surveys and model results with different cross-section resolutions and locations. The longitudinal cumulative volume curve computed from the 2004 and 2012 cross sections is shown in Figure 4 along with the calculated longitudinal cumulative volume change produced by the calibrated model. The model captures the overall trend of deposition and erosion. Note that there are some uncertainties in the calculation of the measured volume change; bed elevation change can vary laterally, longitudinally, and temporally, especially in the presence of moving bed forms. The use of volume change, especially longitudinal cumulative volume change, can help to mitigate these factors.

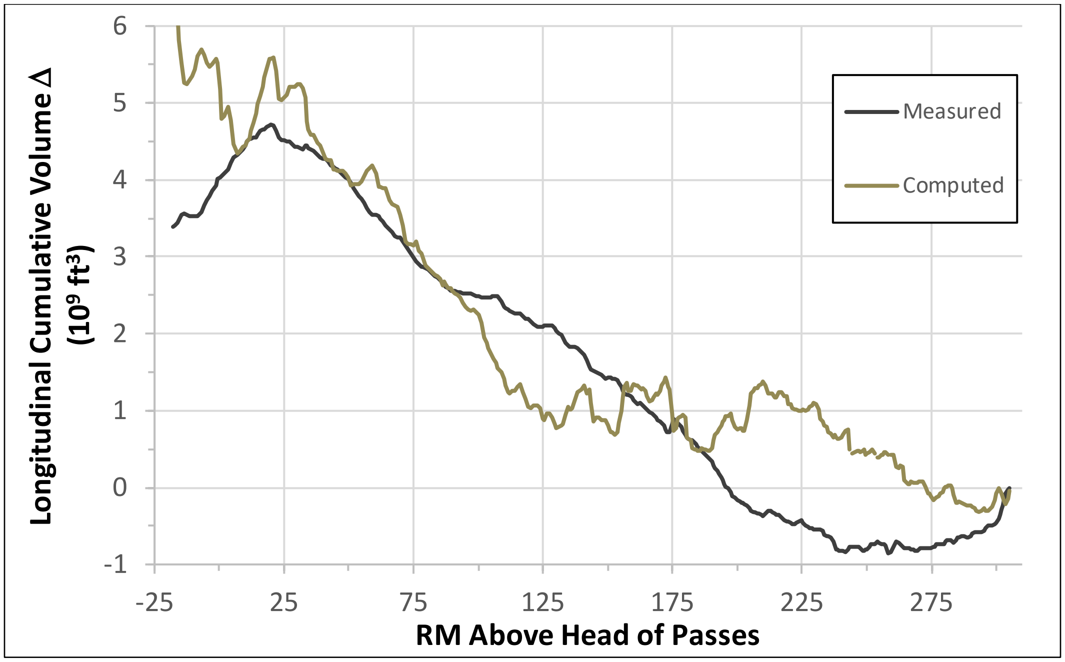

Figure 4. Comparison of computed and measured longitudinal cumulative volume change. Note that the large upward trend in computed volume below Head of Passes is due, at least in part, to subsidence, which is not reported separately in HEC-RAS.

The model performed well with the best estimate parameters and the Laursen-Copeland equation with one substantial divergence. The model reproduced the total sediment volume change of the entire reach and the local erosion or deposition trends in most sub-reaches. However, the model deposited too much sediment in the tight channel bends near and through New Orleans. The modeling team could not disperse this deposition downstream by changing any of the sediment parameters within reasonable ranges. Other sediment modelers with experience in this reach suggested that other current sediment models deposit more sediment in these tight river bends than observed, regardless of the dimensionality of the model. In particular, the 1D model does not reproduce the multi-dimensional dynamics that keep these pools deep. Therefore, the bathymetric cross sections were modified through this reach to reduce them to their equivalent 1D cross sectional area.

Suspended Sediment Concentrations: A sediment transport model should be evaluated against all available physical evidence. Therefore, we also compared the model concentrations to observed sediment concentrations at Belle Chasse, near RM 76, downstream of New Orleans.

In the total load plot (Figure 5-bottom), the model captured the concave quality of the flow-concentration curve and performed well in the moderate-to-high flow range, tracking the central tendency of the data.

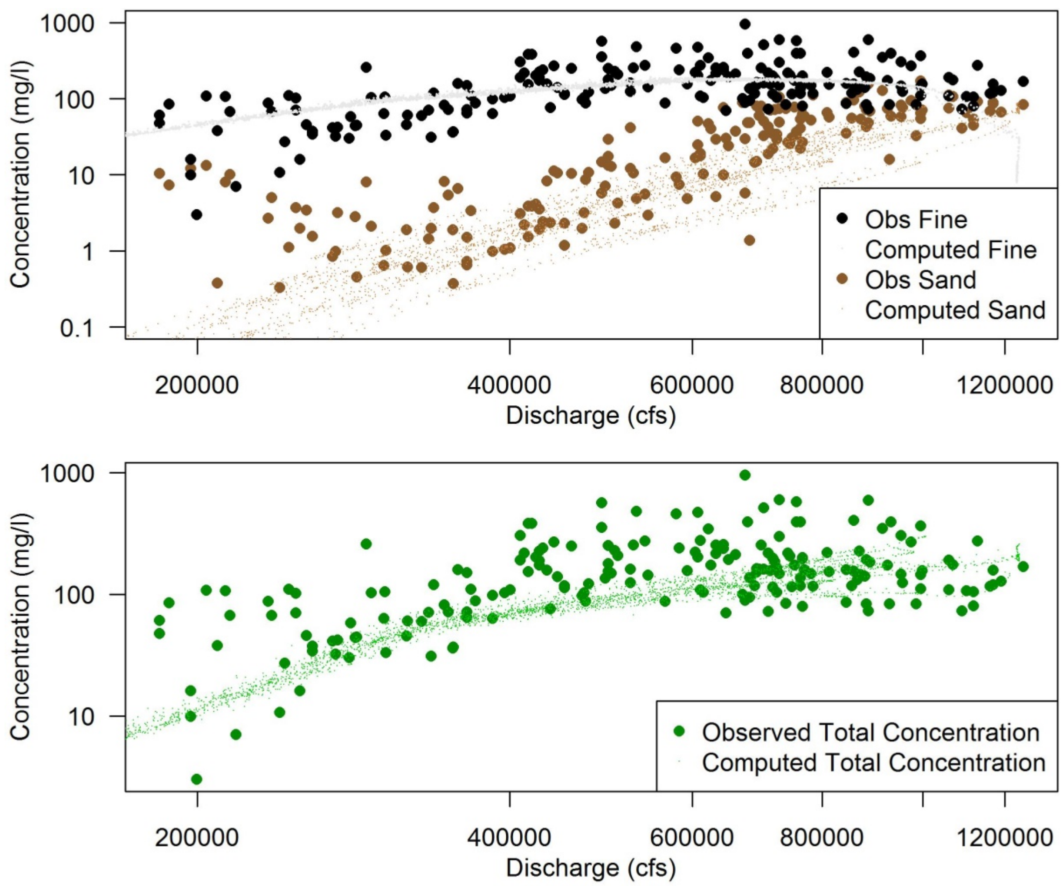

Figure 5. Measured and computed concentrations at Belle Chasse between 2004 and 2012, for the total sediment load (bottom) and portioned at 63 microns, for a sand/fine split (top).

The sand-fine split (Figure 5-top) offers additional insight. Generally, concentrations of sand in the model were towards the low end of the observed concentrations. Concentrations of fines in the model fell in the middle of the observed data. The computed concentrations qualitatively match the inflection point in the observed data near 600,000 ft3/s.

Further information on the sediment validation, including comparison to specific gage analysis, can be found in Dahl et al. (2018).

Conclusions

This study demonstrated that HEC-RAS is an effective tool to simulate sediment transport on the complicated Lower Mississippi River system. The model was able to capture the general trends in sediment deposition through the study reach as well as sediment concentrations at Belle Chasse. The model also captured the stage and flow dynamics, as evidenced by both the hydrographs at Baton Rouge and comparison with specific gage data.

If districts within MVD would like to leverage the advanced capabilities in HEC-RAS, to save effort by building a sediment model on an existing HEC-RAS hydraulic model, or to simply work faster in an HEC-RAS interface and workflow because of its continuity with their experience and education, the HEC-RAS sediment capabilities are a viable option.

The efforts during this study also identified a number of opportunities for improved understanding of the Lower Mississippi River system and improvements to the modeling capabilities of HEC-RAS. General understanding of the sediment transport in the Mississippi River could be greatly enhanced by continued study and monitoring of the effects of flow diversions on sediment. It may be possible to see additional improvements in the Unsteady Sediment HEC-RAS model results by leveraging the lessons learned from the ongoing Adaptive Hydraulics (AdH) models being conducted at the ERDC-CHL. Similarly, ongoing work at the ERDC-CHL on flocculation of cohesive sediment should help to inform future iterations of the model. The differences in observed flows at Tarbert Landing and Baton Rouge may be addressed by implementing the recommendations in Lewis et al. (2017). Including the Old River Control Complex and extending the model boundary upstream to Natchez, MS, may also help to compensate for the discrepancies in observed flows. Finally, one of the problem areas during the development of the Unsteady Sediment HEC-RAS model was the tendency of the model to deposit in deep holes in the lower river. These deep holes tend to occur at tight bends in the river such as Carrolton Bend (~RM 104-105) and Algiers Point (~RM 94-95) and where the river encounters confining material (Gibson et al. 2019). This behavior is not unique to 1D sediment models and has been observed in both two-dimensional and three-dimensional (3D) sediment models of the area, warranting further investigation.

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