MODELING BED DEGRADATION OF A LARGE, SAND-BED RIVER WITH IN-CHANNEL MINING WITH HEC-RAS 5.0

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INTRODUCTION

The Missouri River is a large, regulated, sand-bed river. Over the past several decades, large stretches of the lower Missouri River have degraded with bed elevations dropping as much as 7 ft (USACE, 2009a). Bed degradation on the lower Missouri River has already cost Federal, State, and local entities over a hundred million dollars in emergency slope protection, bridge pier stabilization, and water intake retrofitting. To analyze and find solutions to this problem, the U.S. Army Corps of Engineers, with support from local stakeholders, developed a one-dimensional mobile-bed hydraulic/sediment model for 165 miles of the lower Missouri River using HEC-RAS 5.0. The modeling effort utilized features new to HEC-RAS 5.0, including specification of sediment load and gradation via a DSS file and new commercial dredging features. The model calibrated, reproducing historic bed volume changes, water surface elevations and channel velocities. This paper documents novel aspects of this modeling effort. More information on the full range of model inputs and choices can be found in USACE (2014).

MODEL OVERVIEW

USACE engineers developed a one-dimensional, quasi-unsteady HEC-RAS 5.0 sediment model (USACE, 2015, Gibson et al., 2006) to predict future degradation and to screen and evaluate potential solutions. The model starts ten miles upstream from the St. Joseph, Missouri USGS gaging station and ends near the Waverly, Missouri USGS gaging station. The downstream boundary is a historically stable location on the river. The model contains 303 cross-sections which span approximately 165 river miles of the Missouri River, with six to twelve cross-sections per river bend. The model was built with 1994 bathymetry and run forward to November of 2011. Figure 1 provides a schematic of the model network with river miles, major tributaries, channel cross-sections, and USGS gages located.

Channel roughness was assigned as Manning ‘n’ values in four horizontally-varied regions: the active channel, the channel with sill influence, the channel with dike influence, and the floodplain. At very high flows, the roughness for the active bed decreases as the bed transitions from dunes to plane bed. Bedform amplitude changes were verified using multi-beam bathymetric surveys, as seen in Figure 2. Dunes which dominate normal flows (67,000 cfs on May 27, 2010) transition to a planar transport regime at higher flows (196,000 cfs on June 28, 2011) during the 2011 flood.

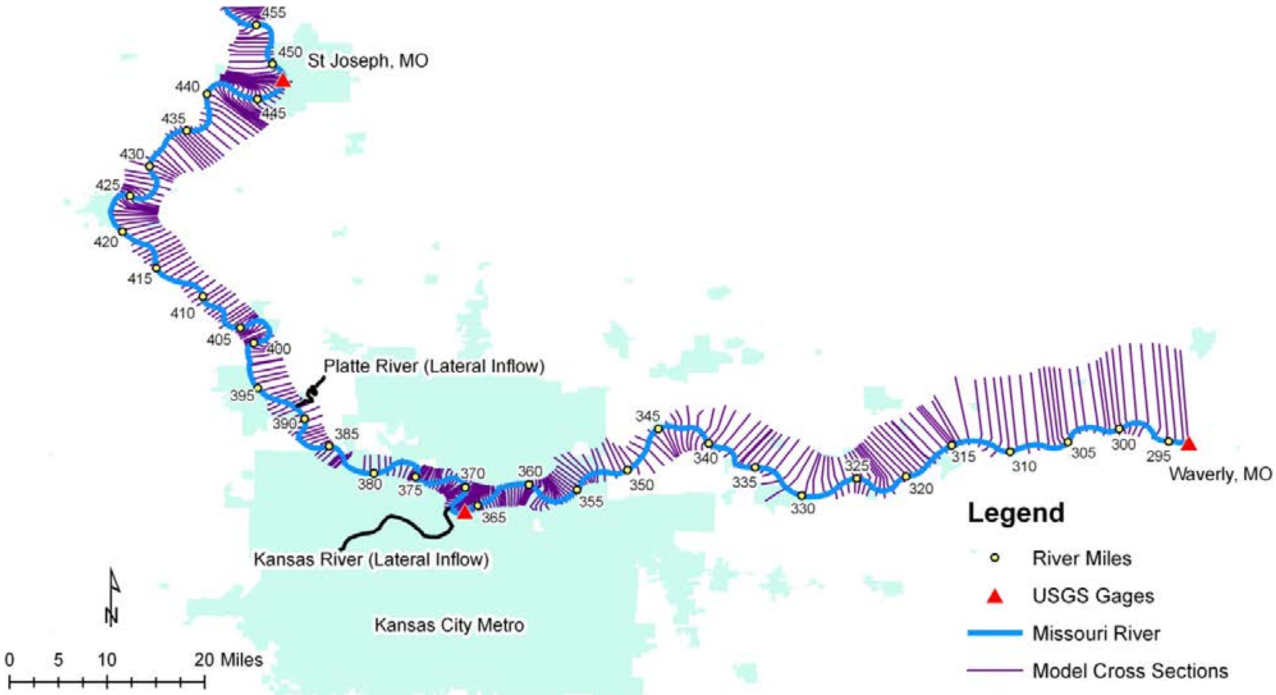

Figure 1 Model Schematic.

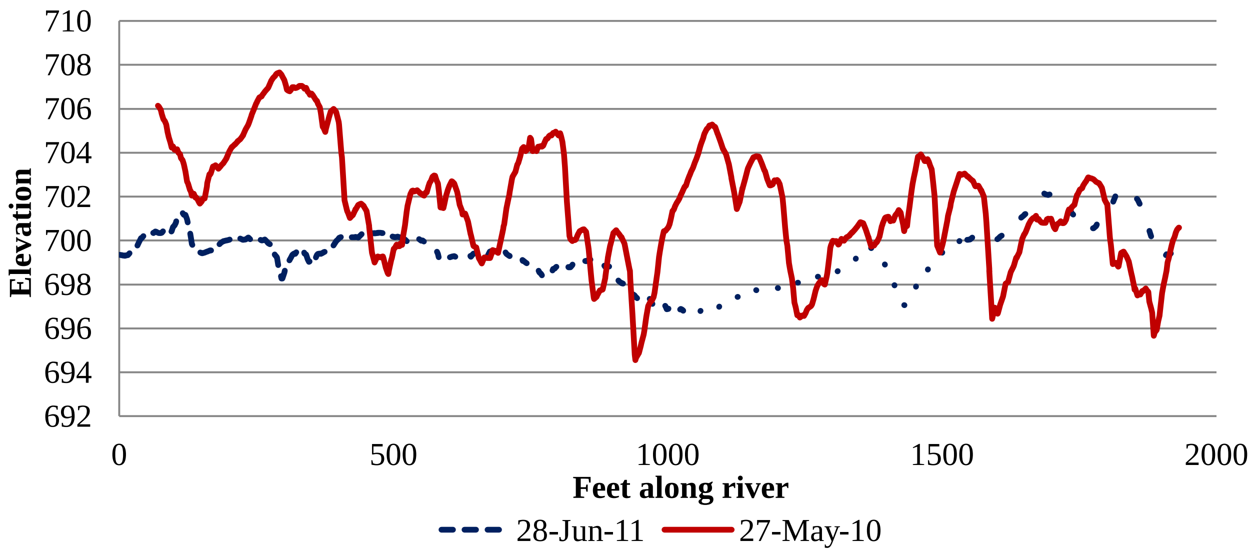

Figure 2 Flatter bedforms during flood flows just upstream of the Kansas River confluence.

The Brownlie bed roughness predictor (Brownlie, 1983), a new feature included in HEC-RAS 5.0 (Gibson, 2013) was evaluated for use in this model. Although this roughness predictor was developed for large sand rivers with bed forms that shift regimes, it over predicted roughness at high flows and under predicted roughness at low flows at the Kansas City gage. An 'n' value of 0.028 calibrated well with observed stages at the Kansas City gage for moderate and high flows, but the highest flows calibrated to a lower 'n' value. This flow dependence was modeled using the flow-roughness factor in HEC-RAS.

NEW HEC-RAS FEATURES

DSS-TIME SERIES FOR SEDIMENT

HEC-RAS 4.1 included three sediment load options at upstream model boundaries: Equilibrium Load, Rating Curves, and Sediment Load Series. None of these options provided sufficient flexibility to specify loads with gradations that vary over time. On the Missouri River, a second flow-load-gradation relationship was required to model the unique supply-limited sediment loading of the historic 2011 flood. During the 2011 flood, the mainstem dams released tremendous volumes of relatively clear water while the watershed downstream from the dams contributed very little due to drought conditions.

HEC-RAS 5.0 includes a fourth sediment load option, Sediment Load Series by DSS, which was flexible enough to accommodate non-stationary loads and gradations with some pre-processing. HEC-Data Storage System (DSS) is the base that HEC-RAS and other HEC models use for input, and output time series, and to pass data between models (USACE, 2009b). In HEC-RAS 5.0, the DSS Sediment Load Series boundary condition reads a DSS sediment mass time series for each grain class.

In the degradation model, the sediment load series for each grain class were computed in Excel using the following formula:

$$Qs_i = Qbed * Pbed_i + Qsus * Psus_i$$

where Qs_i = the daily sediment load input for grain class size i, in tons

Qbed = the daily bed material load, in tons

$Pbed_i$ = the proportion of bed material corresponding to grain size i

Qsus = the daily suspended sediment load, in tons

$Psus_i$ = the proportion of suspended sediment load corresponding to grain size i

The suspended sediment load was computed from two separate flow-load curves based on USGS water quality data. The first flow-load curve applied from 1994 through March 2011. The second, supply-limited flood curve applied from April 2011 through November 2011. Gradations for the suspended sediment load were computed from USGS water quality samples.

The bedload portion of the sediment load was computed from a bedload rating curve for the Missouri River just upstream of the confluence of the Kansas River. This bedload rating curve was computed by using successive multi-beam bathymetric surveys (Abraham et al., 2011) with the time correction suggested in Shelley et al. (2013) and is provided in Figure 3.

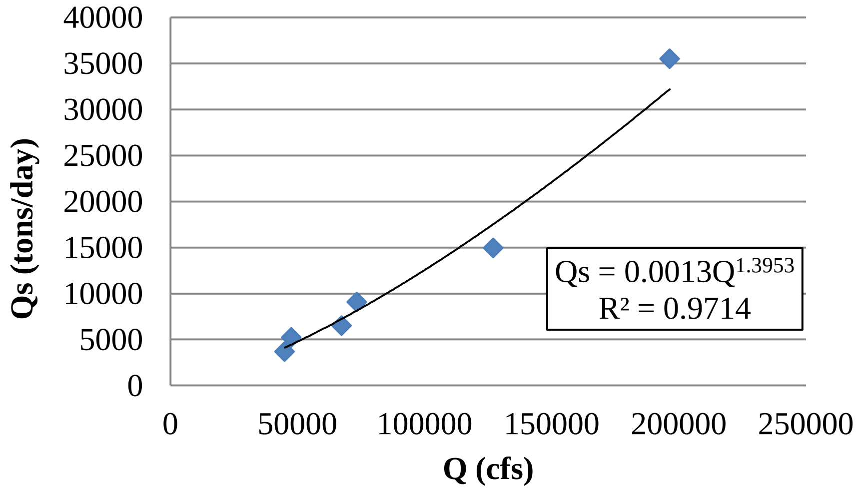

Figure 3 Missouri River Bedload Rating Curve at Kansas City (above Kansas River Confluence).

The gradation of the incoming total sediment load is a function of the relative contributions from bed load and suspended load, which varies by flow and shifts during the 2011 flood. From these, daily load series for each grain class were compiled in a DSS file using HEC-DSSVue 2.0 (USACE, 2009b) with the Period Cumulative (PER-CUM) data type, and a 'SEDIMENT' parameter (the required C: segment of the DSS path name) HEC-RAS 5.0 read the DSS file and matched the size specific load series with the corresponding grain classes.

Sediment rating curves at two major tributaries—the Platte River and the Kansas River—were included in the model as flow-load boundary conditions with the Rating Curve option, with loads and gradations estimated from USGS measurements.

DREDGING

HEC-RAS 4.1 includes algorithms to simulate navigation dredging. The Navigation dreding feature removes the material instantly, at a specified time, down to the specified template elevation. Dredging on the Missouri River is commercial dredging (sand and gravel mining), which differs from typical navigation dredging in several important respects. On the Missouri River, bed material is extracted and sold as aggregate for construction purposes. There is no target elevation, but rather a reported (or permitted) tonnage. On the Missouri River, commercial dredging takes are recorded as a daily location and tonnage. The navigation dredging features, with instantaneous, *a priori* dredge depths, in HEC-RAS 4.1 could not adequately reproduce this process.

HEC-RAS 5.0 includes new features better suited for modeling commercial dredging of river beds. First, a dredging start and end time can be specified so that dredging occurs gradually over time, not instantly. Second, the dredging can be specified as a target tonnage instead of a target elevation, allowing the cross section shape to respond to the mass removal. Third, the cross-section maintains the natural shape of the river bottom as material is removed, rather than the flat bottom channel the navigational dredging algorithms produce.

Dredging was included in the Missouri River degradation model as monthly tonnages at each cross-section with the start date the first day of the month and the end date the last day of the month. The model calibration used the standard "flat bottom" dredging algorithm, as the "natural bottom" routine was not yet available. The impact of dredging was restricted to the actual dredging tonnage, i.e. one ton of material extracted lowers the bed by a volume equivalent to one ton. Potential dredging effects due to bed disturbance and destruction of the armor layer were not explicitly modeled.

CALIBRATION AND VERIFICATION

The calibration/verification period runs from Aug 1, 1994 to Nov 30, 2011, with an intermediate calibration point Sep 30, 2009. The principal parameters which were varied to achieve calibration were the Manning 'n' values, the flow-based 'n' adjustment factors, the level of smoothing of the gradation data, and the sediment loading from the Kansas River. Channel geometry, moveable bed extents, incoming sediment load and gradation at the upstream model boundary, sediment transport function coefficients, and dredging were not used as calibration parameters.

EARLY HYDRAULIC CALIBRATION

A major high-flow event occurred within a year of the model start. Figure 4 compares model results to the water surface elevation at the USGS Missouri River gage at Kansas City. The computed water surface elevations are from the mobile-bed model run and therefore include slight bed changes over the course of the first year. However, as these changes are relatively small, Figure 4 is an indication of the ability of the model to reproduce channel hydraulics, more than the ability of the model to reproduce sediment fluxes.

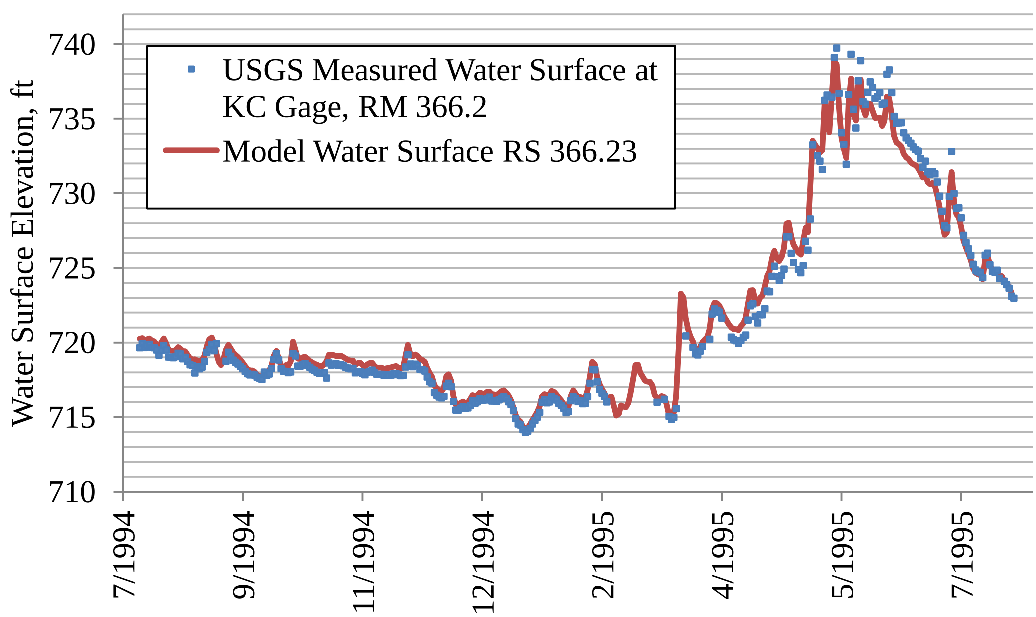

Figure 4 Water surface at Kansas City gage during first year of calibration period.

The average absolute difference between measured and modeled water surfaces is 0.67 ft. Agreement is better for steadily increasing and decreasing flows than rapidly fluctuating flows. In this particular event, input from the Kansas River and overbank storage issues were not reflected well in the model and causes rapid fluctuations near the peak. Notwithstanding this limitation, the model reproduces channel hydraulics reasonably well.

LONG-TERM HYDRAULIC CALIBRATION

Model water surface elevation agreement over the full calibration time period verified the temporal fidelity of bed change in the model. The model reproduced water surface elevations at the Kansas City gage with an average absolute error of 1.3 ft over the duration of the calibration period. For low flows less than 30 kcfs, the average absolute error is 1.0 ft.

VELOCITY CALIBRATION

Channel velocities were measured during and after the 2011 flood via ADCP. Figure 5 shows that the model channel velocities match measured velocities reasonably well for both a high flood discharge (153 to 225 kcfs) and a more moderate discharge (58 to 64 kcfs).

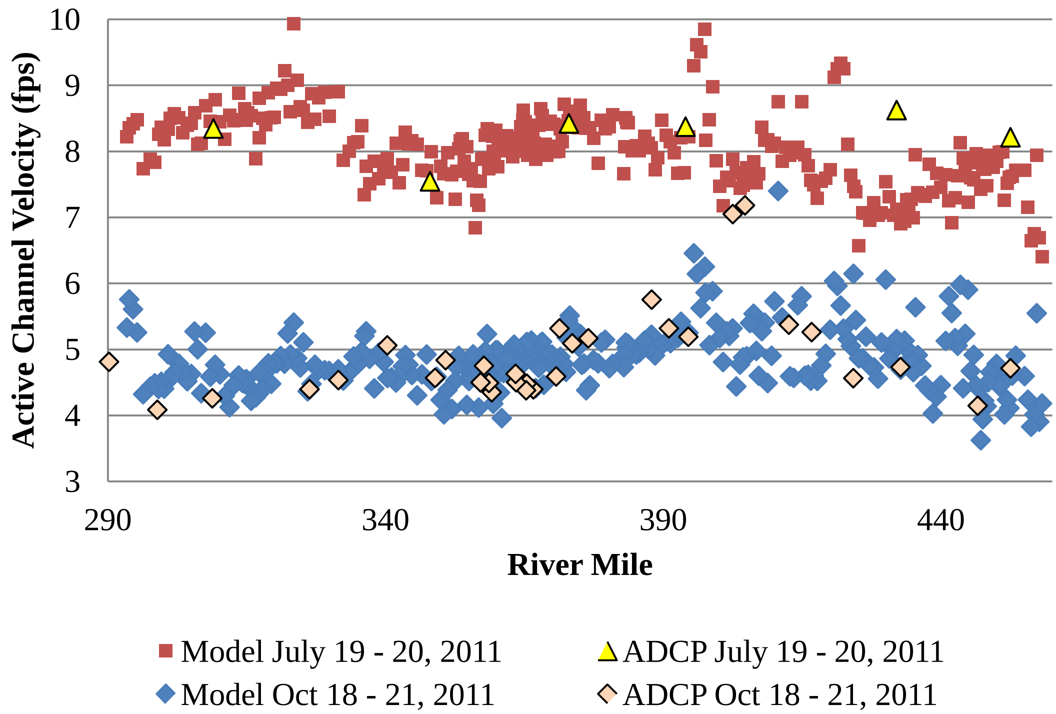

Figure 5 Velocity Comparisons.

SEDIMENT MASS CALIBRATION

The calibrated model simulates the magnitude and location of measured bed sediment change from 1994 to 2009 and 1994 to 2011, as indicated in Figure 6.

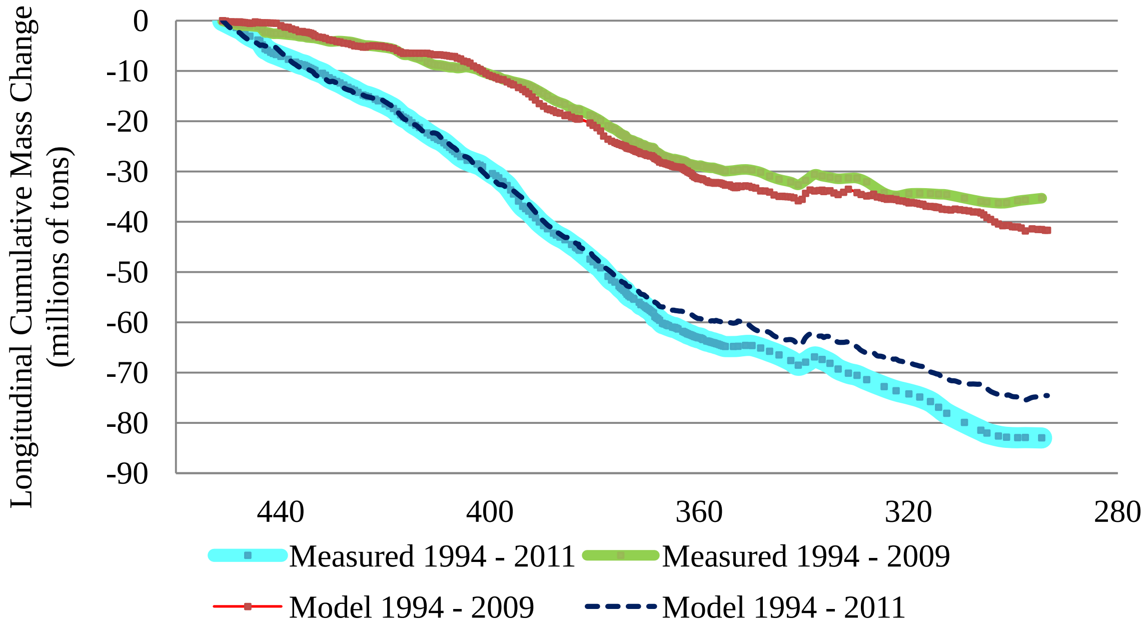

Figure 6 Mass Calibration.

The model outputs for water surface, mass change, and velocity over the calibration period approximate the prototype using realistic initial conditions and boundary conditions and appropriate model parameters.

CONCLUSION

This paper described the development of a one-dimensional HEC-RAS 5.0 mobile-bed model to simulate and predict degradation on the lower Missouri River. This model utilizes new sediment input and dredging features in HEC-RAS 5.0. Simulated water surface elevations, channel velocity, and sediment mass change, over the calibration period approximate the prototype using realistic initial conditions and boundary conditions and appropriate model parameters. This model demonstrates the utility of HEC-RAS 5.0 for bed degradation analysis in large, complex river systems with in-channel mining.

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