UNSTEADY FLOW AND SEDIMENT MODELING IN A LARGE RESERVOIR USING HEC-RAS 5.0

John Shelley, Ph.D., P.E., U.S. Army Corps of Engineers, Kansas City District, john.shelley@usace.army.mil; Stanford Gibson, Ph.D., U.S. Army Corps of Engineers, Hydrologic Engineering Center, stanford.gibson@usace.army.mil; Aaron Williams, E.I.T., U.S. Army Corps of Engineers, Kansas City District, aaron.r.williams@usace.army.mil.

ABSTRACT

Sediment accumulation is a problem in many large reservoirs in the United States and around the world, including Tuttle Creek Lake in the Kansas River basin. A one-dimensional unsteady flow and sediment model was built for Tuttle Creek Lake using the Hydraulic Engineering Center – River Analysis System (HEC-RAS) Version 5.0 Beta. This paper provides an overview of Tuttle Creek Lake, describes the model setup, highlights how features new to HEC-RAS 5.0 operated in the modeling effort, and provides model results from a proof-of-concept model run. This model will be used to evaluate the technical feasibility and effectiveness of altering the reservoir operations to decrease sediment trapping efficiency.

INTRODUCTION

Sediment accumulation is a problem in many large reservoirs in the United States and around the world. Available storage is decreasing while demand for water is increasing. Downstream, channels degrade and reduced sediment supply threatens sediment-dependent aquatic species (Haslouer et al., 2005). Removal of accumulated sediment from large reservoirs tends to be prohibitively expensive. This underscores the need to optimally operate large reservoirs to decrease sediment deposition in the first place.

Tuttle Creek Lake is a large, Corps of Engineers reservoir in the Kansas River basin that provides flood control, water supply, recreation, and environmental benefits. Tuttle Creek Lake provides water supply to Manhattan, Kansas and provides releases to the Kansas River that benefit water users in Topeka, Lawrence, and Kansas City, Kansas. In addition, Tuttle Creek Lake releases water when necessary to provide navigation flows on the Missouri River.

As of 2009, the total storage up to the multipurpose pool level and flood control pool level were approximately 252,000 ac-ft and 2,118,000 ac-ft, respectively (USACE, 2012). The pre-construction estimate for the sedimentation rate in the multi-purpose pool was 4,151 ac-ft/yr

ac-ft/year. Based on repeated bathymetric surveys, the average sediment accumulation is estimated at 3,594 ac-ft/year (KWO, 2012). Since completion of the dam in 1962, 43% of the original multi-purpose storage volume has been lost to sediment accumulation. The current operational procedure for Tuttle Creek Lake traps 98% of all sediment, including fine silts and clays (Juracek, 2011). Dredging with upland disposal of the dredged material is prohibitively expensive, given the large quantity of incoming sediment load.

A one-dimensional unsteady flow and sediment model was built for this project using the Hydraulic Engineering Center – River Analysis System (HEC-RAS) Version 5.0 Beta (USACE, 2015, Gibson et al., 2006) to evaluate the technical feasibility and effectiveness of altering the reservoir operations to decrease sediment trapping efficiency. This model uses features that are new to HEC-RAS 5.0, including unsteady sediment modeling and customized RULES to calibrate ungaged inflows.

The model will assess trap efficiency response to alternate management strategies, assuring that they also meet current flood control reservoir functions. Operational changes within existing constraints may only decrease trapping efficiency slightly (Lee and Foster, 2013), but even a slight decrease in sediment trapping can save significant money compared to maintenance dredging. Small decreases in trapping efficiency over time can form a part of larger sediment management strategy.

MODEL SET-UP

Model cross-sections extend from the Big Blue River upstream of the reservoir, down through the reservoir to the confluence with the Kansas River, and on the Kansas River from Fort Riley to Wamego. Two additional major tributaries to Tuttle Creek Lake, the Little Blue River and the Black Vermillion River are included as point loads rather than modeled cross-sections. Figure 1 provides a general vicinity map of the project area including major components of the HEC-RAS model.

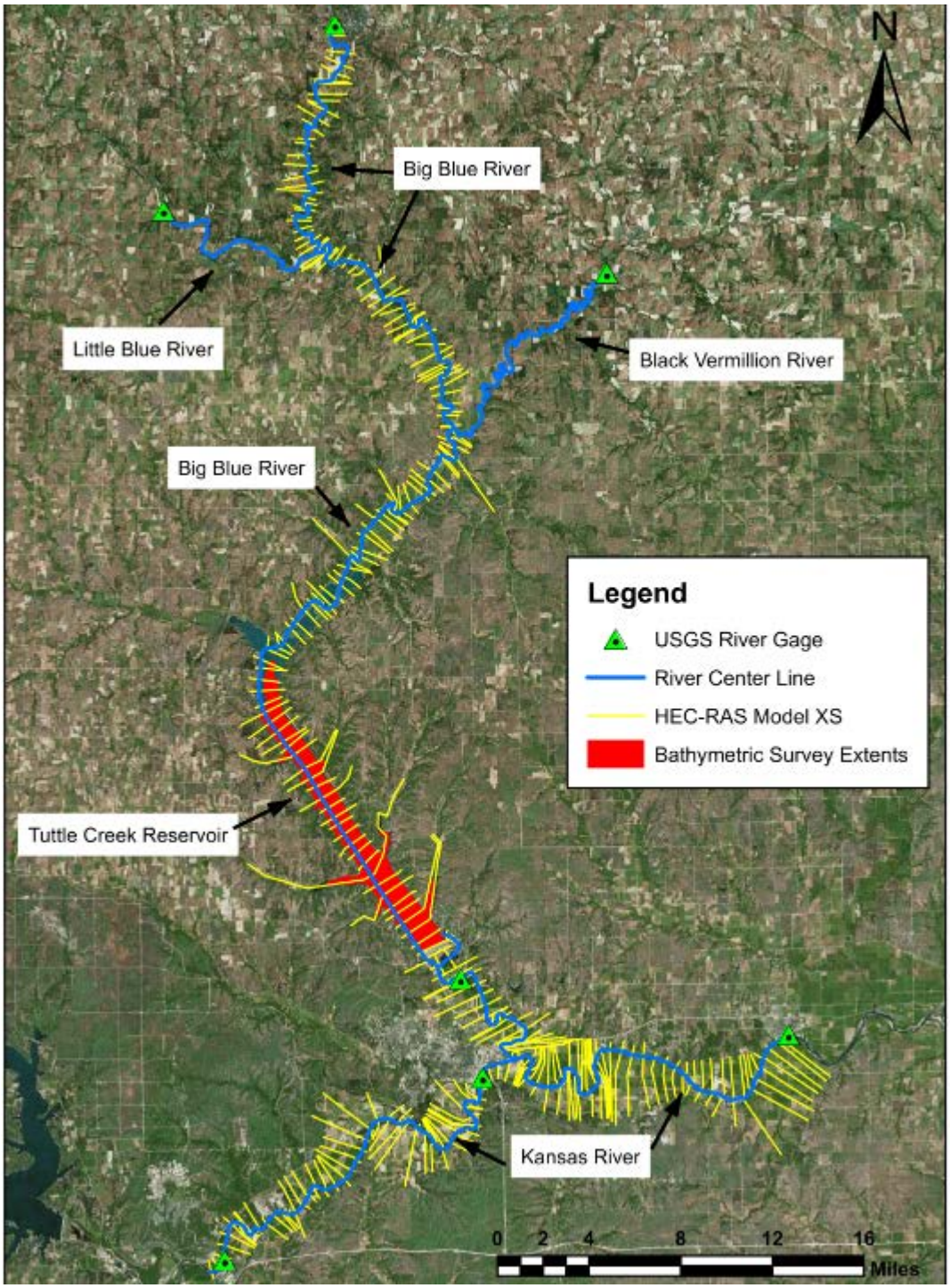

Figure 1. Model Schematic

DEVELOPMENT OF INITIAL BATHYMETRIC SURFACE

Model creation and calibration require a baseline survey to build model geometry and a final survey to compare to model output. Two recent bathymetric surveys were available, in 2000 and 2009 (Figure 2). The 2000 bathymetric survey had low point density (1.6 points per acre) and produced a surface with interpolation errors and insufficient channel detail. The 2009 survey had a much higher point density (25.8 points per acre) which provided excellent definition of the reservoir and channel bottom.

The following procedure compensated for insufficiencies in the 2000 data. First, a surface was interpolated from the 2009 survey points. The vertical change from 2000 to 2009 was computed at each 2000 bathymetric point using the 2009 surface. Then, these individual point changes were interpolated to create a surface of bed change from 2000 to 2009. Finally, this bed change surface was subtracted from the 2009 surface to create a more representative 2000 surface. Figure 3 illustrates model cross-section 18.17 cut from the original 2000 surface and from the 2000 surface created using the using the bed change method described above. As seen in Figure 3, the bed change method produced a more reasonable cross-section shape and a physically justifiable deposition pattern. Accordingly, the model cross-sections were derived using the 2000 bathymetric surface developed using the bed change method.

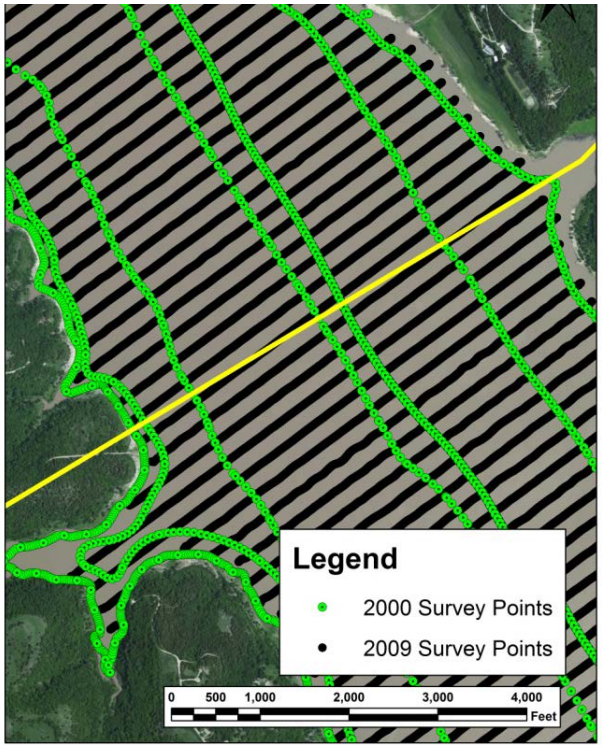

Figure 2. Comparison of 2000 and 2009 Bathymetric Survey Points, Model RS 18.17

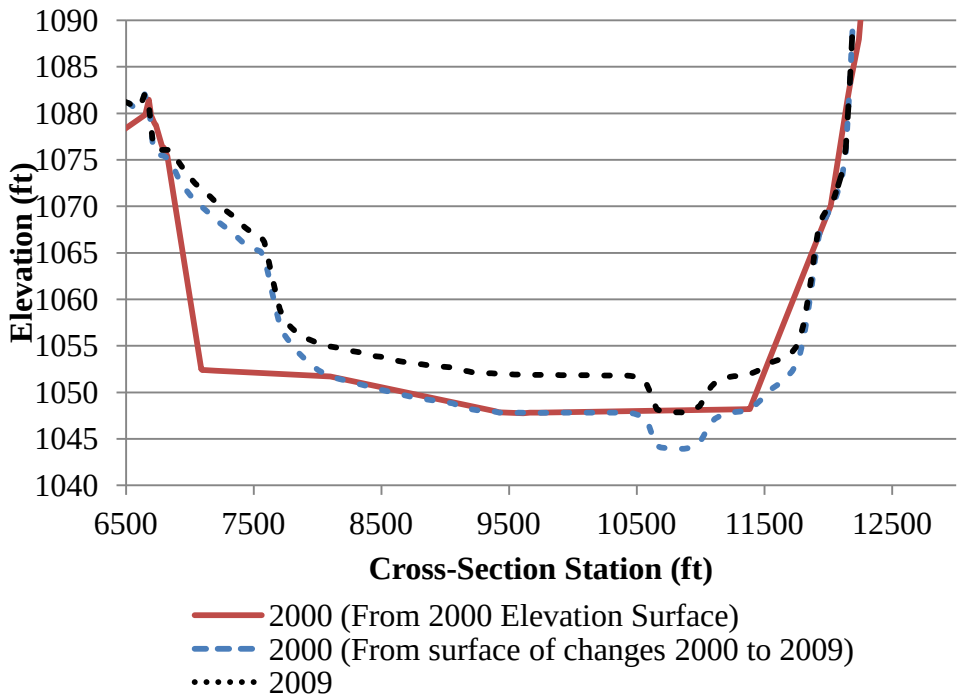

Figure 3. Cross-section Comparison of Surface Interpolation Methods, Model RS 18.17

FLOW AND SEDIMENT BOUNDARY CONDITIONS

Data from USGS gaging stations produced the relationships between flow and suspended sediment load at the three major tributaries to Tuttle Creek Lake seen in Figure 4. Daily suspended sediment loads were associated with daily inflows to the reservoir. Bed load data was not available and values were estimated as a percentage of suspended sediment loads.

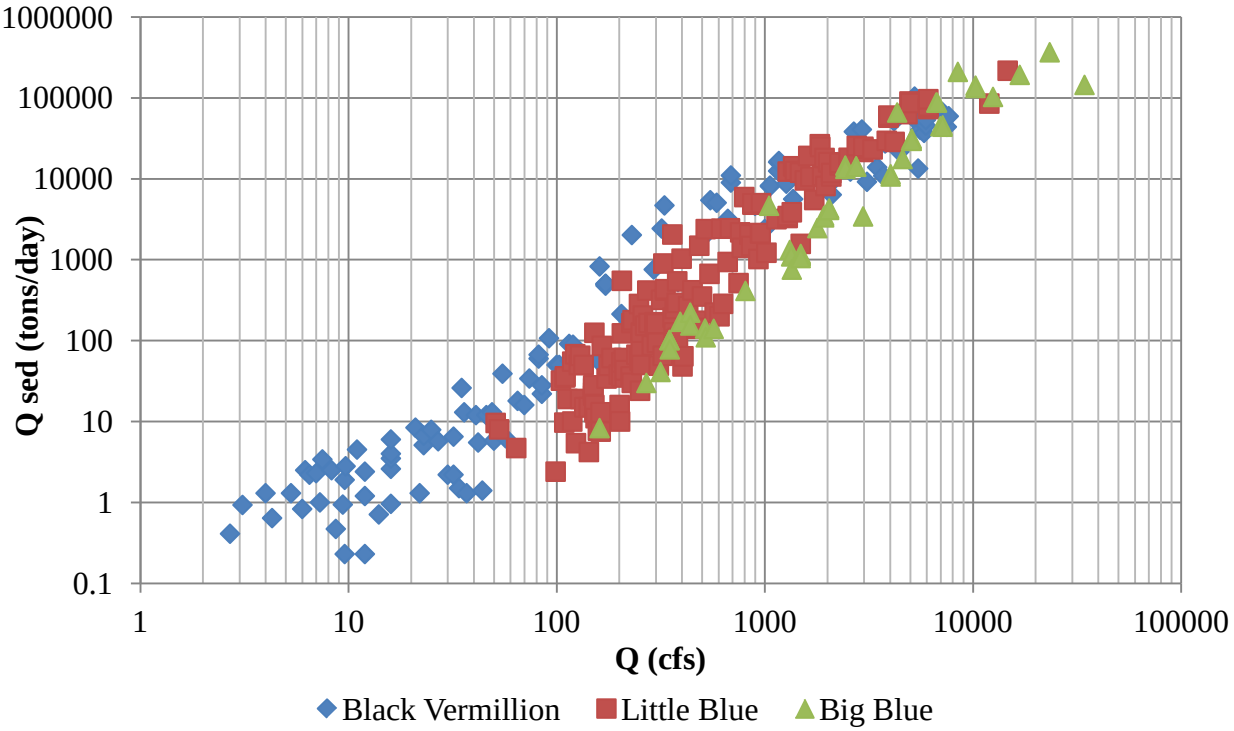

Figure 4. Suspended Sediment Loads on Three Major Rivers Flowing into Tuttle Creek Lake

Boundary load gradations were inferred from detailed gradation data collected by USGS from 2008 – 2010 (Juracek 2011). As seen in Figure 5, the sediment size composition on the Big Blue River and Little Blue River depend on the flow rate, while the Black Vermillion River load gradations are independent of flow. In Figure 5, solid lines represent gradations developed from measurements, while dashed lines represent extrapolation included for modeling purposes.

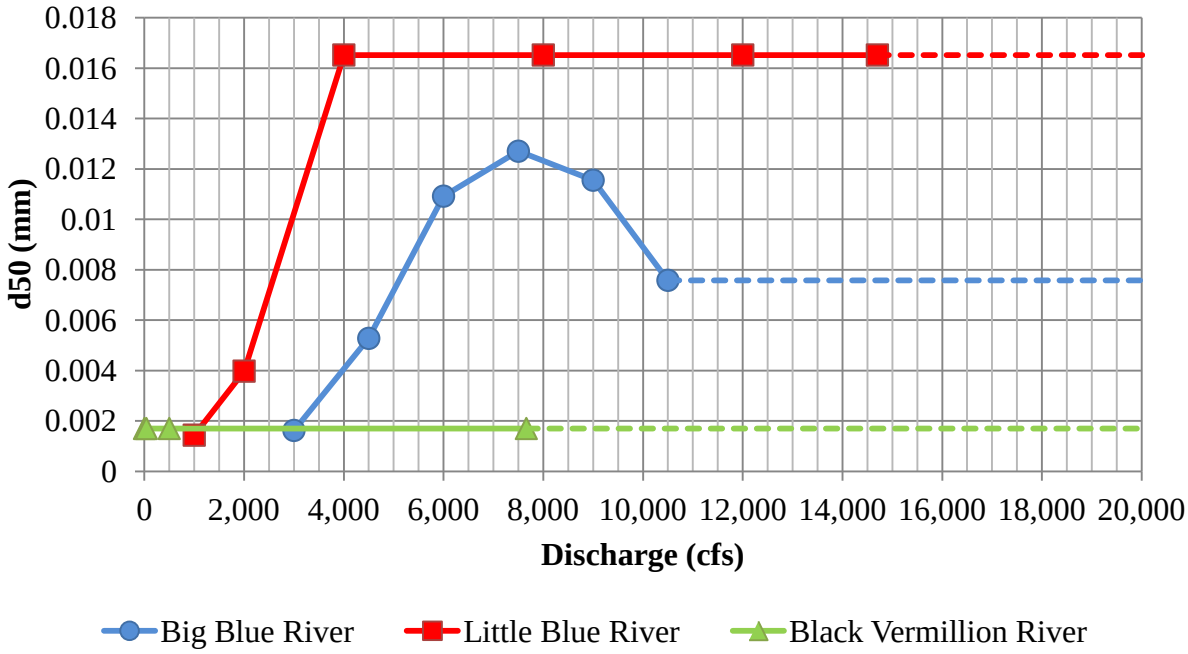

Figure 5. Suspended Sediment Median Grain Size (D50) on Major Tuttle Creek Tributaries.

NEW HEC-RAS FEATURES

UNSTEADY SEDIMENT

HEC-RAS 4.1 included a quasi-unsteady flow model for use in sediment modeling, simulating hydrodynamics with a series of steady flows. This simplification adequately describes many hydraulic systems because sediment-response time scales are so much longer than hydraulic-response time scales. However, reservoir scenarios are inherently unsteady, requiring explicit volume tracking and mass conservation to simulate system behavior. HEC-RAS 5.0 integrates sediment transport features with the unsteady flow module. This not conserves volume by coupling sediment transport with the Saint-Venant equations, but also makes a suite of reservoir modeling tools native to the unsteady flow modeling environment available in the context of sediment transport simulations.

RULES FOR CALIBRATION OF UNGAGED FLOW

HEC-RAS 4.1 included the RULES editor, a simple scripting language for building operational procedures for reservoir gates in unsteady flow. With the inclusion of sediment modeling in the unsteady flow environment, the RULES scripting language is available for reservoir sediment models (Gibson and Boyd, 2014). In this model, custom RULES allowed the solution to a

hydraulic calibration challenge. Inflow from the three gaged tributaries systematically summed to less than the recorded flow downstream of the reservoir, suggesting ungaged inflow contributions. However, reservoir storage effects prevented a straight-forward calculation of the daily ungaged inflows. Rather, custom code in the rules editor computed the daily series of ungaged inflows based on historic daily reservoir stages.

PROOF-OF-CONCEPT SEDIMENT MODEL

Sediment transport was added to the unsteady flow model for the calibration period (20 July 2000 to 14 September 2009). As a proof-of-concept, loads and gradations were significantly adjusted to approximate total volume and longitudinal distribution of reservoir deposits (Gibson and Pridal, 2015). Figures 6 and 7 plot model and measured values for the local and longitudinally-summed cumulative volume of bed change. These results will change as hydraulics and operations are refined. As seen in Figures 6 and 7, HEC-RAS 5.0 can model sediment transport during complicated unsteady reservoir operations and can approximate historic sedimentation.

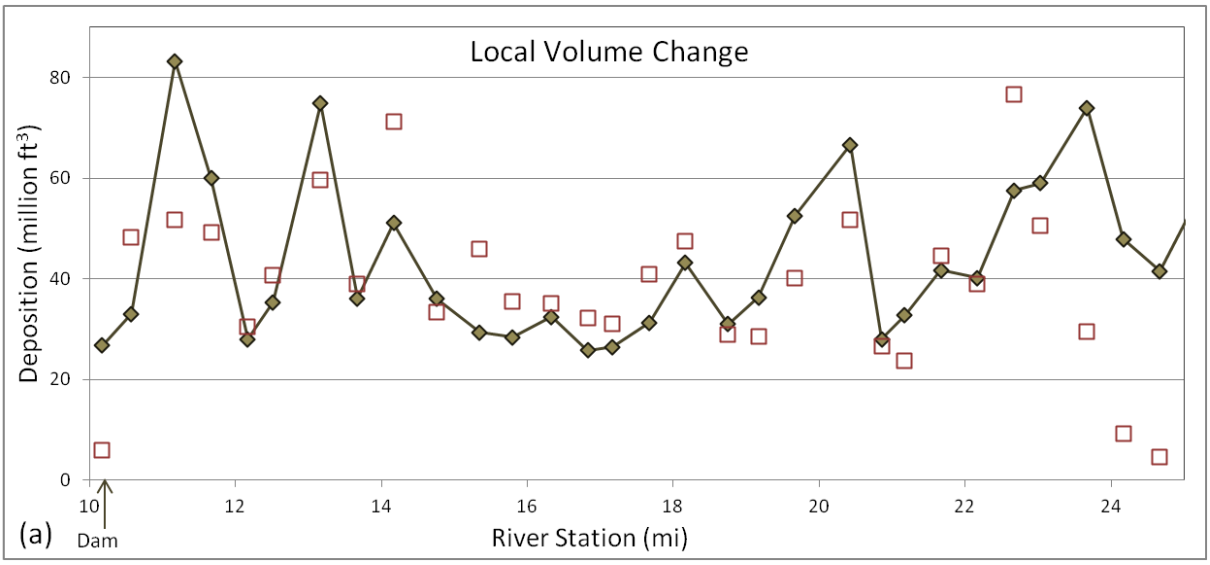

Figure 6. Model results compared to measured local deposition volume change from July 20, 2000 to Sept 14, 2009

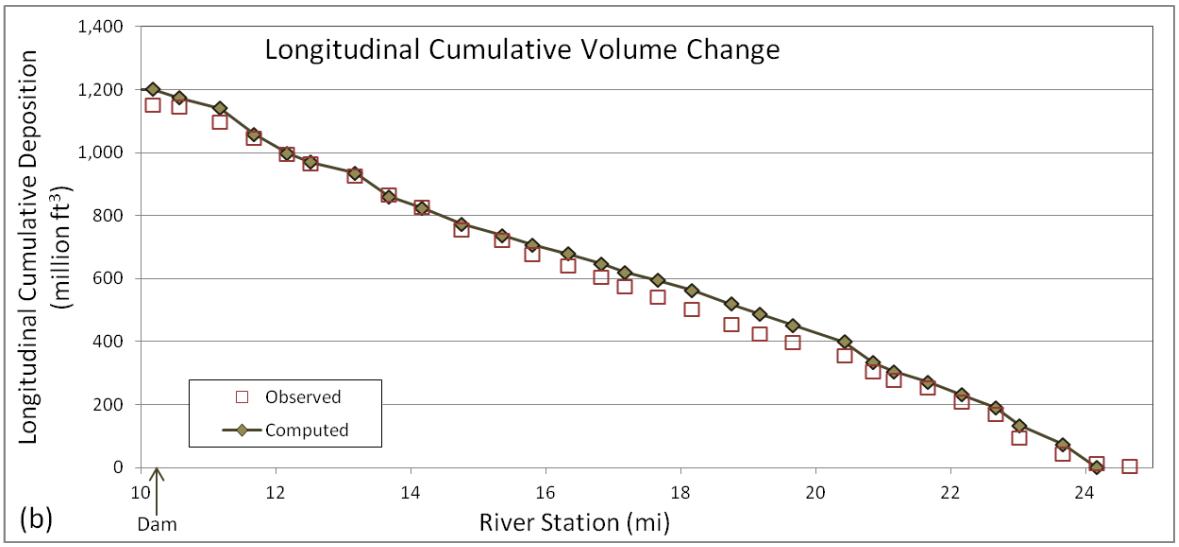

Figure 7. Model results compared to measured to longitudinal cumulative (summed from upstream to downstream) deposition volume change from July 20, 2000 to Sept 14, 2009

The addition of sediment to the stable unsteady flow model introduced numerous model instabilities, which required additional troubleshooting. The sediment model required a smaller time step, interpolated cross sections, and other stabilizing measures to run, which translated to longer run times. However, once the model achieved stability, the unsteady hydrodynamics and operational rules provided computational fidelity and alternative flexibility beyond what is possible in a quasi-unsteady approach.

CONCLUSION/NEXT STEPS

This paper described the initial development of a one-dimensional HEC-RAS 5.0 mobile-bed model for modeling and predicting sediment accumulation in Tuttle Creek Lake. This model utilizes new features in HEC-RAS 5.0 including Unsteady Sediment and new features in the RULES editor. Additional measures to ensure model stability were required beyond those necessary to produce a stable hydraulic model. As of this writing, calibration is in the early stages and all results are preliminary. This model demonstrates the utility of HEC-RAS 5.0 for sedimentation analysis of large reservoirs. Future work will quantify the reduction in sediment accumulation possible at Tuttle Creek Lake through changes to reservoir operational procedures.

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