MOBILE BED MODELING OF THE COWLITZ RIVER USING HEC-RAS: ASSESSING FLOODING RISK AND IMPACT DUE TO SYSTEM SEDIMENT

Stanford Gibson, US Army Corps of Engineers, Hydrologic Engineering Center; Chris Nygaard and Paul Sclafani, US Army Corps of Engineers, Portland District

Abstract A one dimensional sediment transport model of the lower 20 miles of the Cowlitz River was developed to evaluate long term sediment impacts on flood risk. Mobile boundary capabilities in HEC-RAS 4.2 were used to model sediment dynamics. The model was calibrated to bed change measurements for an observed 5 year timeframe by adjusting the parameters of the transport function selected. Several novel approaches employed to achieve this result and new features were added to HEC-RAS for the analysis.

INTRODUCTION

The May 18, 1980 eruption of Mount St. Helens deposited approximately 3 billion cubic yards of sand and gravel in the upper basins of the Cowlitz River Watershed. The rapid influx of sediment into the system and associated deposition in the Cowlitz and Columbia Rivers reduced channel capacities and ability to pass flood flows without causing damages. Emergency measures were implemented by the Corps under authority of Public Law (August 1985) including dredging of the Cowlitz and Columbia Rivers and levee raises in the lower Cowlitz. The recommended plan included the construction of a 125 ft high Sediment Retention Structure (SRS) downstream of the debris avalanche designed to reduce the volume of sediment delivered to the Cowlitz River. The SRS began impounding water and collecting sediment in 1987 and collected 80 million cubic yards of sediment by 1998. In 1998 sediment levels in the impoundment rose to the level of the spillway and the facility began regularly spilling water and sediment. The SRS continues to collect sediment. However the trap efficiency has dropped and more sand currently passes through spillway than while the facility was filling. As sand load increases in the Lower Cowlitz, the potential for increased deposition also rises.

The Water Resources Act of 2000 authorized the Corps to maintain specified levels of flood protection (LOP) for 4 levees along the lower 20 miles of the Cowlitz River through the year 2035. The primary tool for estimating future water stages at the 4 authorized levees was a mobile bed HEC-RAS model (Gibson *et al*. 2006) of the lower 20 miles of the Cowlitz River. The model geometry included 95 cross sections and 7 bridges from bathymetric data collected in 2009 and LiDAR data of the overbank collected in 2007. The lower 10 miles are leveed on both banks while the upper 10 miles flow into the floodplain during high flows. Bed gradation data came from sediment samples collected in 2005 and 2007. A long term USGS stage and flow gage located at RM 17 on the Cowlitz provided upstream flow boundary conditions. A sediment budget was developed (Biedenharn *et al.* 2010) from a USGS sediment gage located on the Toutle River (sub-basin of the Cowlitz where the debris avalanche and SRS are located) and SRS sediment volumes computed from periodic LiDAR data in the reservoir. This budget was used to develop sediment load series by grain class as the upstream sediment boundary condition for the calibration. Downstream boundary conditions came from a long-term NOAA stage gage located on the Columbia River near the confluence with the Cowlitz.

In order to evaluate alternatives for maintaining the required LOP through the planning period upstream models were developed to investigate future sediment outputs from the SRS. The Cowlitz mobile bed model will be used to determine relative changes water surface profiles to the end of the planning period (2035) for the existing condition and alternatives. HEC-RAS 4.1 can generate new geometry files based on the updated bathymetry computed from the mobile bed sediment model. The final geometry file can then be used to perform fixed bed hydraulic computations for a planning period LOP analysis.

Hydraulic Model and Calibration: A 20 mile, single channel HEC-RAS model of the Cowlitz River was constructed from 2007 LIDAR data and an August 2009 hydrosurvey dataset using HEC-geoRAS. The hydraulic model was calibrated to multiple observed stages at several gages and peak stages observed during an approximate 2.5% annual exceedance probability high water event (January 2009) before it was used for sediment analysis (Figure 1). A series of high water marks collected following the event along with the 5 recording stage gages hydrographs (4 Corps and 1 USGS) were used to calibrate the hydraulic components of the model. Calibrated n-values were highly sensitive to flow (Figure 2) in the sand . For example, water surface elevations for flows of 38,300 cfs were higher than those measured for flow of 53,000 cfs. Sand beds dominated this portion of the channel, so variability in channel roughness was attributed to bed form regime changes (i.e. transition to high amplitude dunes in the 20,000 to 40,000 cfs range which planes out at higher flows). This hypothesis was in line with qualitative institutional knowledge about the bed dynamics of this system as well as standard bed form regime equations.

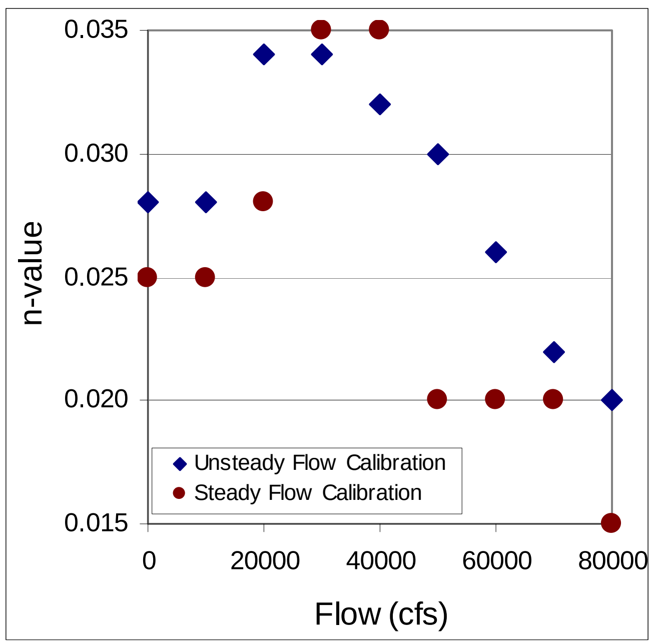

Figure 1 Calibrated n-values for a range of

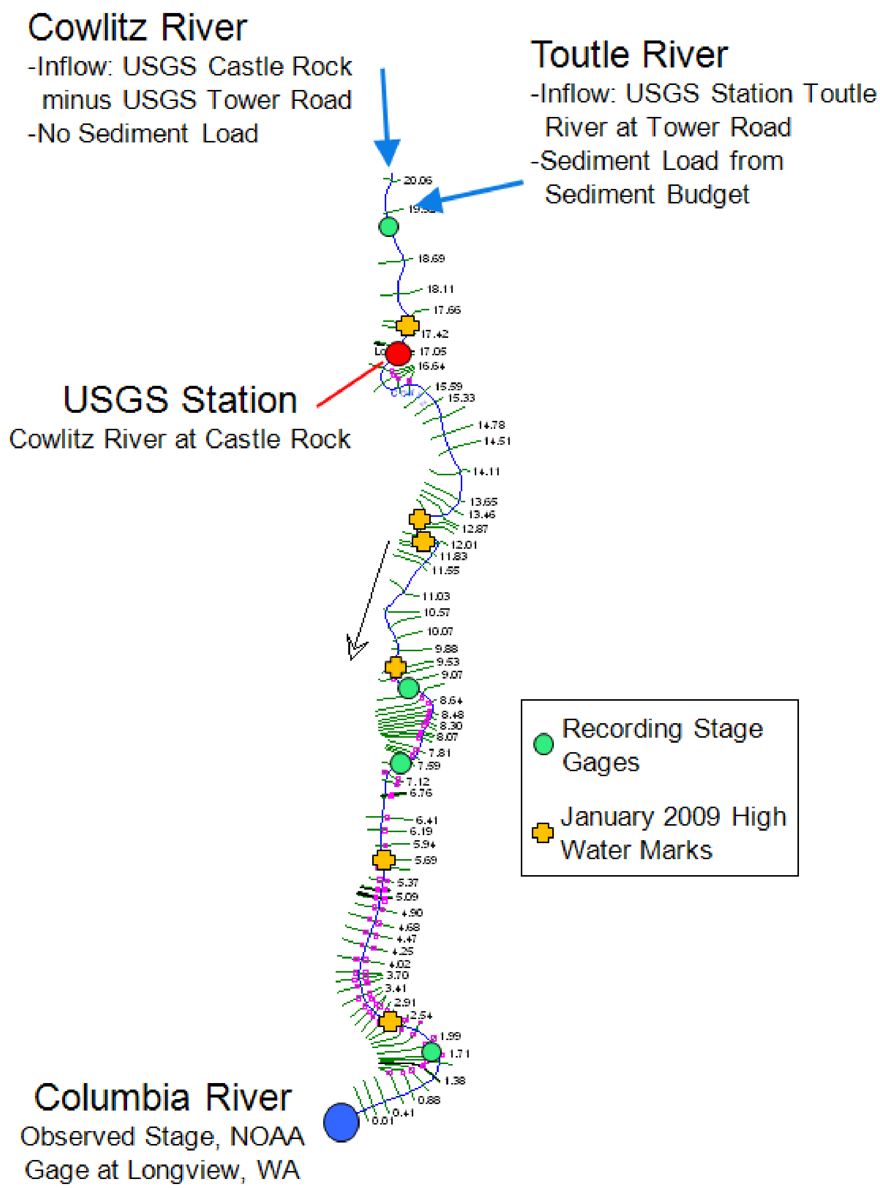

Figure 2 Model and data schematic of the lower twenty miles of the Cowlitz River.

The HEC-RAS vertical variation in Manning's roughness based on flow functionality was utilized to calibrate the model throughout the flow range. The unsteady calibration accounted for storage effects. Therefore, it generally produced higher n-values. However, because the mobile bed feature in HEC-RAS utilize a quasi-unsteady approach (that approximates a hydrograph with a time series of steady flows) the values from the steady flow calibration were used.

Sediment Calibration The Toutle River drains the Mount St Helens debris avalanche transporting high sediment loads into the model reach near Cowlitz River mile 19.5. For sediment calibration, flow and sediment load upstream boundary conditions were split between the Cowlitz and Toutle Rivers as shown in Figure 2. The USGS monitors the Toutle River for stage, flow and suspended sediment at the Tower Road gage. Upstream sediment load was computed based on a sediment budget of the system that analyzed deposition rates in the SRS, sediment gage measurements, bank failure loads and residuals (Biedenharn *et al*. 2010). Sediment load series were developed for the historical flow record by grain class. A developmental feature in HEC-RAS 4.2 (Gibson *et al*. 2010) was used to read sediment load series by grain size from an HEC-DSS file. Model bed gradations came from sample data collected throughout the model reach in 2005 and 2007.

Calibration data were abundant for this reach of river. As part of the Corps monitoring efforts on the lower Cowlitz, cross section data has been collected on a frequent basis. Comparison of deposition and erosion between these datasets allow for reach-long sediment trend calibration (Figure 3). The sedimentation calibration period selected extended from the August 2003 until the June 2008 hydrosurveys. The longest possible time frame used for the primary calibration because understanding long term trends was the primary goal of the project. Two intermediate hydrosurveys occurred in April and December of 2006. However, the April 2006 survey only covered the lower half of the model domain and the December 2006 survey covered the entire lower 20 miles of the Cowlitz but occurred shortly after a major event. The November 2006 event resulted in the largest suspended sediment loads observed at the Tower Road gage on the Toutle River since the SRS was constructed in 1987 and it seems that the channel was still in

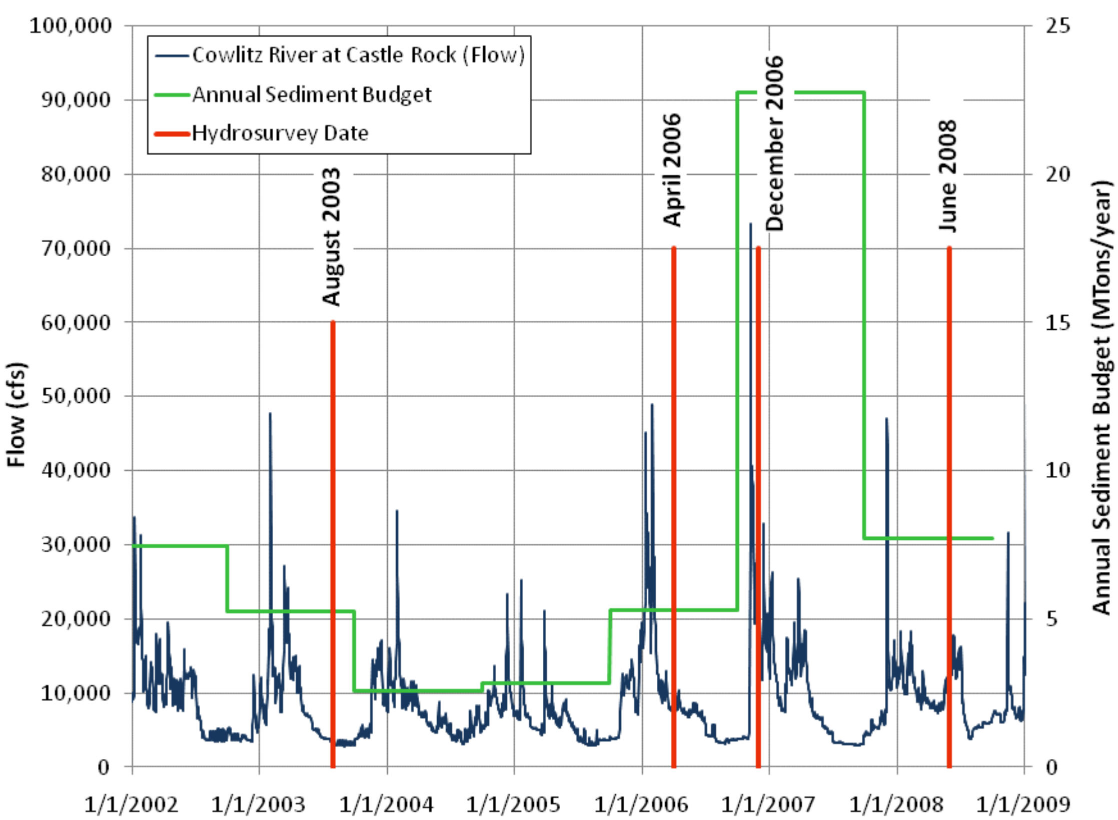

Figure 3: Timing of hydrosurveys used for calibration with respect to flow record.

substantial disequilibrium when the survey was taken, making it very difficult to match with the continuity based algorithms used for sediment routing in HEC-RAS. Therefore, these intermediate surveys informed the calibration process, but proved more difficult to match than the long term data.

The Laursen-Copeland (LC) transport equation (Laursen, 1958) was selected to model this reach because of the dominance of very fine sand and coarse silt as well as the occurrence of gravel and cobbles. LC is the only commonly used transport function that was developed over the coarse silt range and out performs other functions for non-cohesive fine materials. It is also a 'blended function' that includes separate transport relations for sand/silt and gravel/cobbles. LC is a versatile function and it outperformed the other options in early evaluations, but unsurprisingly required calibration to replicate the site specific conditions on the Cowlitz River. The primary calibration coefficient was the critical shear stress (τ_c) in the LC equation:

$$C_m = 0.01\gamma\left(\frac{d_s}{D}\right)^{\frac{7}{6}}\left(\frac{\tau' - \tau_c}{\tau_c}\right) f\left(\frac{u_*}{\omega}\right) \qquad (Eq.\,1)$$

Figure 4: Point bar on the Cowlitz.

Transport functions are extremely sensitive to this variable and mounting evidence points to it being highly site specific (Curran and Wilcock, 2005). Grain class interactions, depositional structures (e.g. particle imbrication), vegetative anchoring and a wide variety of other physical phenomena can cause the critical shear stress to vary dramatically from site to site. Therefore, it is the most physically defensible parameter to alter in order to hone the sediment transport function reflect site specific transport behavior. Infrastructure was added to HEC-RAS to expose the critical shear stress as a user editable variable.

However, it became apparent that, while good results could be achieved by altering the τ_c in the LC equation (default $\tau_c = 0.039$) within a physically defensible range for moderate sediment loads, the equation did not compute sufficient transport for the higher load events. Unlike the vast majority of excess shear transport functions the 'engine' of LC $((\tau' - \tau_c)/\tau_c)$ is not raised to a power (or more precisely, it is raised to a power of 1). Most famously, MPM raises the excess shear 'engine' in its relation to a power of 1.5:

$$q_b^* = 8(\tau^* - \tau_c^*)^{3/2} \quad , \quad \tau_c^* = 0.047$$

and Parker (2010) famously demonstrated that most other transport functions of this type follow MPM's by raising an excess shear relationship to the power of 1.5.

$$q_b^* \sim (\tau^*)^{3/2} \tag{3}$$

Therefore, while the model was calibrated by altering the critical shear within a physically defensible range, the extreme nature of the loads (well outside of the range for which any of the transport functions were developed) required modification of the LC equation by increasing the exponent and adjusting the coefficient. These adjustments were made in the Transport Function Calibration and Modification editor available in HEC-RAS version 4.1 (Figure 5).

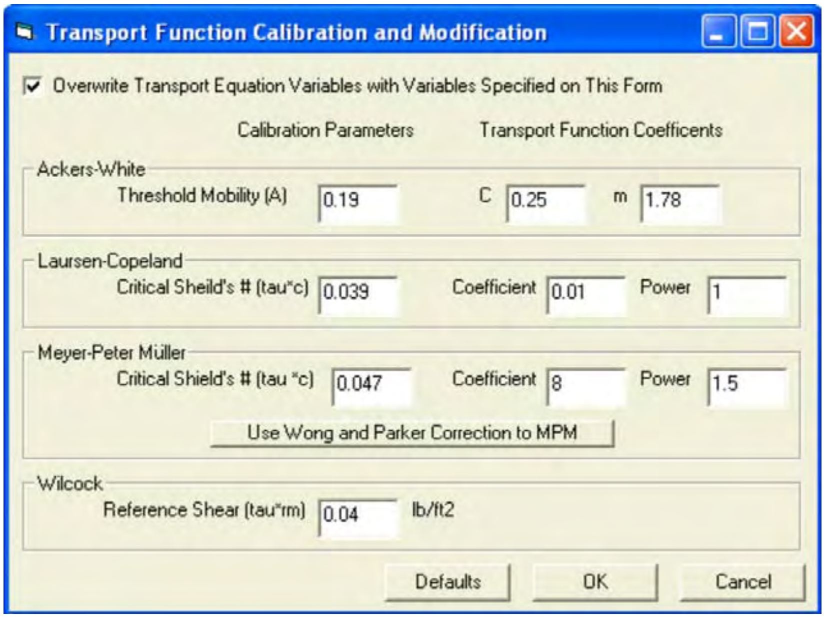

Figure 5 Transport function calibration editor in HEC-RAS with default calibration coefficients.

The default LC parameters resulted in excessive deposition, six times the observed deposition in the overall reach. The default shape was overly steep in all parts of the river. Deposition was over predicted in all areas, but was particularly egregious in the upper 10 miles of the model.

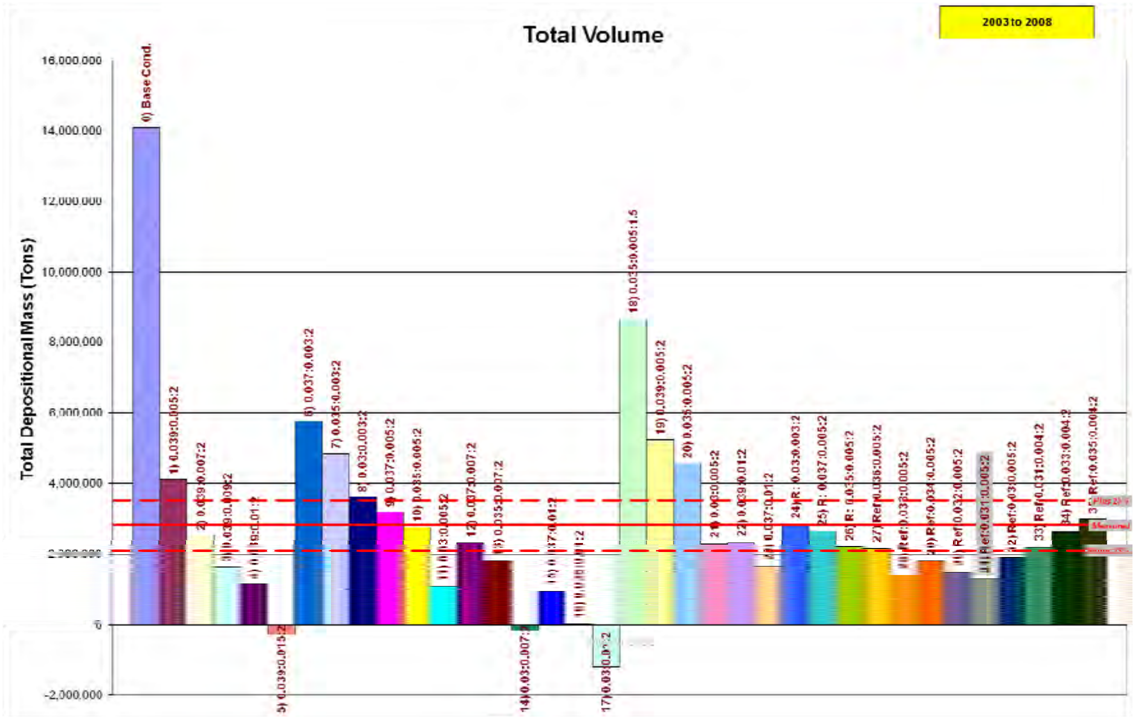

Figure 6 Preliminary results of total deposition computed over the calibration period for a several combinations of calibration parameters. Total deposition was compared to the total deposition measured from the hydrosurveys (solid red line) ± 25% (dotted red line).

Several of the more promising runs were then evaluated based on how the bed change matched observed data along the reach. There was far too much scatter in the discrete comparison of computed bed change to localized patterns of observed bed change (Figure 7) to meaningfully evaluate or differentiate the performance of the parameter adjustments. Instead the Longitudinal Cumulative Deposition output from HEC-RAS was compared to total observed sediment deposition summed from upstream to downstream (Figure 8). This is a classic method for eliminating the noise of localized bed perturbations to evaluating the longitudinal calibration trends. This allowed the quality of the calibration 'fit' to be compared not only to the total simulated deposition but also the 'shape' of the depositional curve. The range of LC parameters evaluated during calibration was as follows:

Critical Shield's #:	0.020 to 0.045
Coefficient:	0.002 to 0.020
Power:	0.7 to 2.0

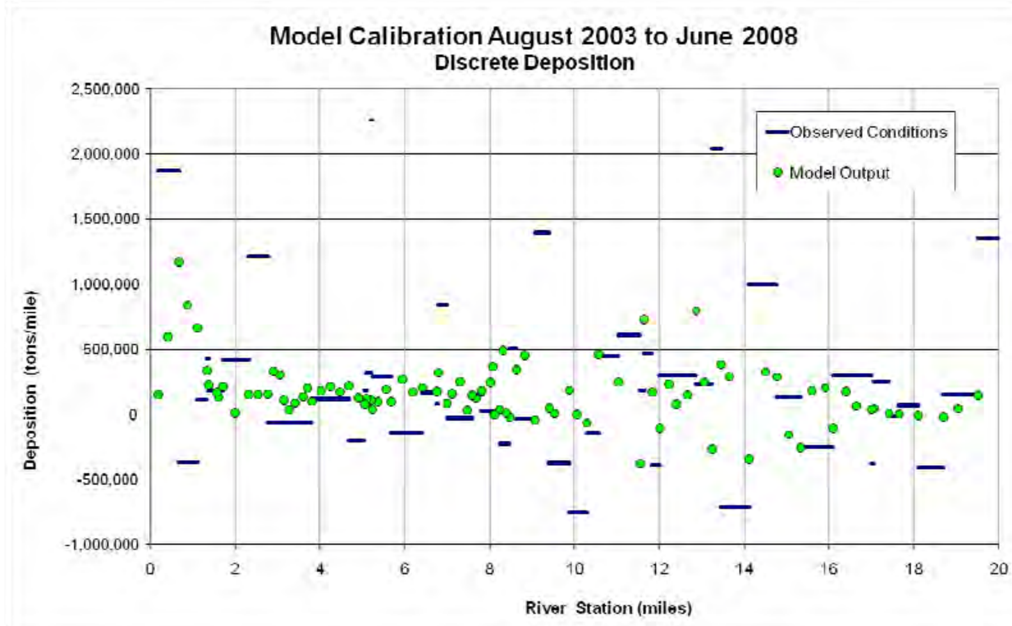

Figure 7 Simulated bed change over the calibration period compared to bed change measured from hydrosurveys. Both computed and observed deposition values are divided by the length of the representative control volume and presented in mass/distance to get rid of scale distortions. It is still very difficult to evaluate the longitudinal fit of calibration parameters with this method.

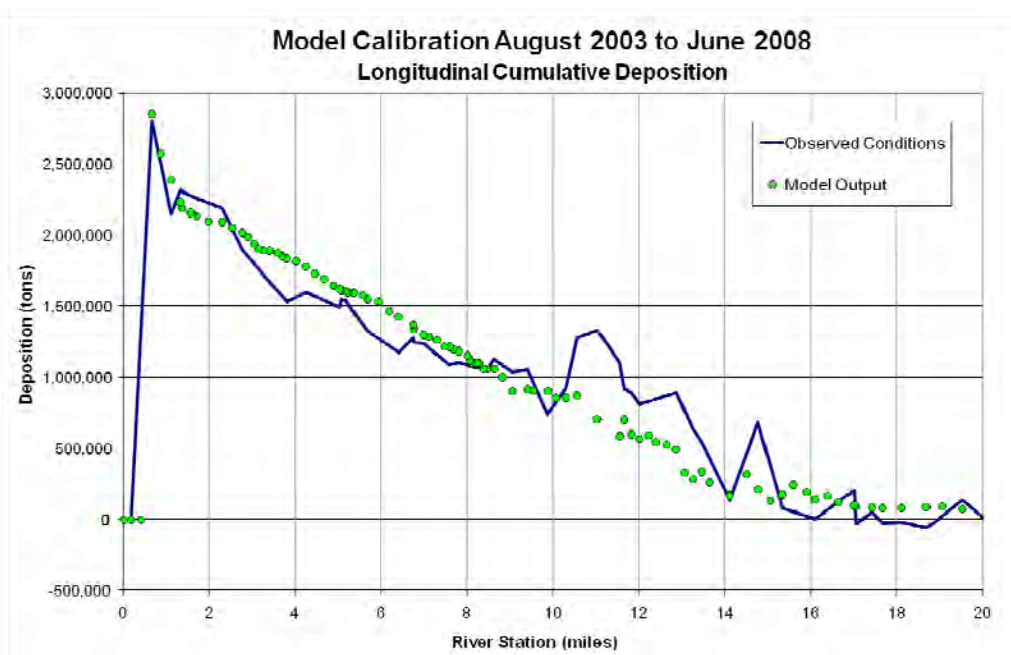

Figure 8: Longitudinal cumulative deposition display of simulated and measured deposition. Observed and simulated bed changes are summed from the upstream to downstream end of the reach. This plot can be used to evaluate the calibration on the criteria of total deposited mass and the longitudinal trends of the deposition or the "shape" of the curve.

Throughout the calibration process, model results were compared to all 4 hydrosurvey datasets though priority was given to the longest time period (August 2003 to June 2008). The August 2003 to April 2006 comparison of the final model exhibited the correct shape and a reasonable estimation of magnitude; the comparison was unfortunately limited to the lower 10 miles of the reach due to the extents of the 2006 hydrosurvey. The December 2006 hydrosurvey dataset was collected following an extremely high sediment event in November 2006 and proved particularly troublesome for calibration. The model would consistently deposit material in a short timeframe during the event while evidence indicated that the total deposition related to the event took up to two month to make their way through the reach. This can be attributed to the simple continuity approach that HEC-RAS uses to route sediment. To capture the actual process a more robust advection-dispersion method would have to be used. This is one of the reasons that HEC-RAS is considered far more appropriate for long term sediment studies than for event modeling.

As long term trends are the primary goal of the study, calibration adjustments to accurately model the temporal aspect of a rare sedimentation event was given lower priority. The long term calibration, 2003 to 2008, spanned the November 2006 event and accurately captured the overall sedimentation trends in the lower 20 miles of the Cowlitz River.

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