ELWHA RESERVOIR SEDIMENT MODELING IN A GIS FRAMEWORK

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Abstract: An empirically based, sediment-budget model was developed in a geographic information system (GIS) framework to support an adaptive sediment management program for two dam removals on the Elwha River near Port Angeles, Washington State, USA. This numerical model had the advantages of being able to handle the complex three-dimensional topography of sediment layers in a reservoir, rapidly incorporate new monitoring data, and quickly simulate multiple future scenarios in response to changing conditions. Even though the model did not simulate the detailed hydraulics, it was able to simulate the most important aspects of channel evolution through reservoir sediments during dam removal.

Model simulations were used to aid the adaptive management program by predicting the channel evolution in the reservoir and forecast the coarse (sand and gravel) and fine (silt and clay) sediment release to the downstream river channel over time under various hydrologies and dam removal schedules. The simulated three-dimensional reservoir topography could easily be visualized in GIS. The model predictions helped to guide and focus the monitoring activities while the monitoring results helped to revise and calibrate the numerical model. This combined approach of hypotheses, incorporated into the numerical model, and monitoring results increased the rate of learning compared to singular approaches of only monitoring or modeling.

INTRODUCTION

This paper describes the development and application of an empirically based, sediment-budget model for the adaptive management program associated with a project to remove two large dams on the Elwha River near Port Angeles, Washington, USA. The model accounts for the primary geomorphic processes (e.g., channel incision, lateral erosion, aggradation, and new delta formation), but not the detailed hydraulics. The model was developed in a geographic information system (GIS) framework to account for the complex three-dimensional reservoir geometries and to facilitate the display of simulated reservoir topography.

The National Park Service, with technical support from the Bureau of Reclamation, removed Elwha and Glines Canyon Dams on the Elwha River to restore anadromous fish and the natural ecosystem (Figure 1). The Elwha River dams had blocked fish migration for a century. The two dams were the largest ever removed and together (before their removal) contained 27 million yd^3 of reservoir sediment (Randle et al., 2015). These dams were concurrently removed in controlled increments over a one and three-year period, which began in September 2011.

The 105-foot high Elwha Dam was completed in 1913 at river mile 5 and formed Lake Aldwell, which had an original storage capacity of 9,100 acre-feet (U.S. Department of the Interior and U.S. Department of Commerce, 1994). The 210-foot high Glines Canyon Dam was completed in 1927 at river mile 13 and formed Lake Mills, which had an original storage capacity of 40,500

acre-feet. Both dams were constructed to produce hydroelectric power and neither reservoir provided flood control or water supply storage.

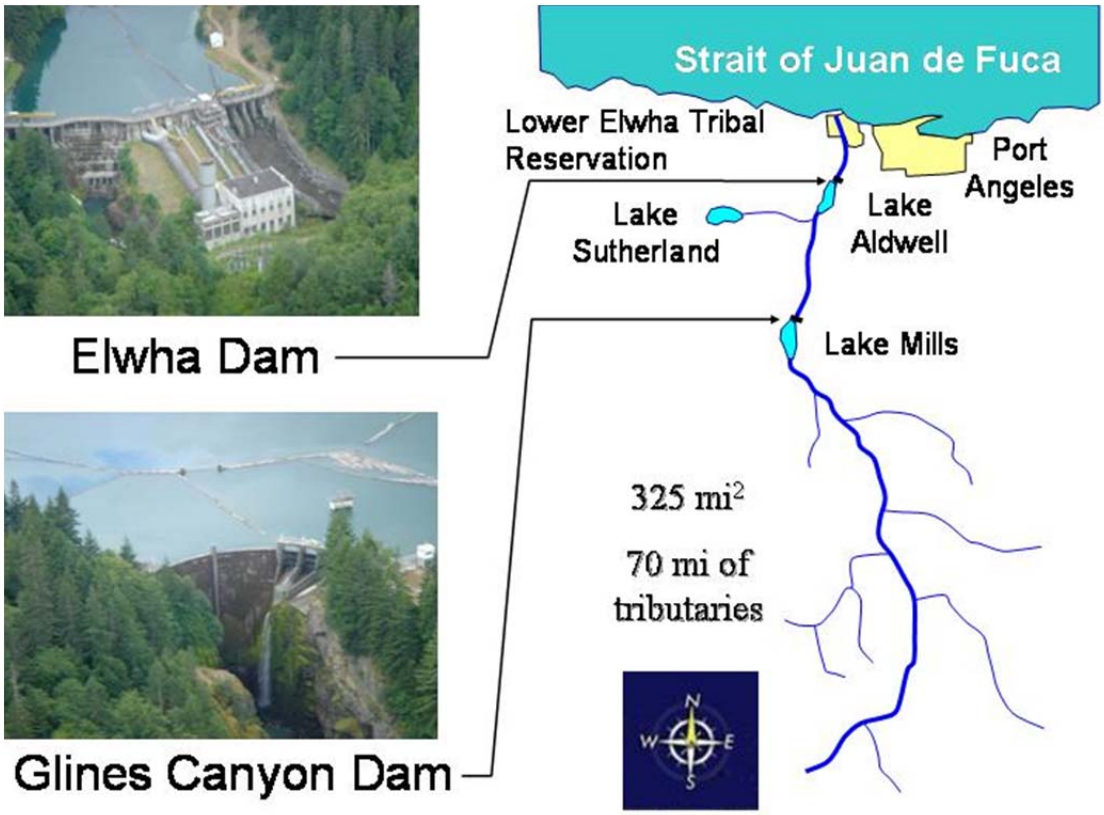

Figure 1. Elwha and Glines Canyon Dams are located on the Elwha River near Port Angeles, Washington, U.S.A.

In July 2010, reservoir sedimentation in both lakes was estimated to be 27 million yd^3 (Randle et al., 2015), which was 35 percent of the original storage capacity. Most of the coarse reservoir sediment (sand and gravel) had deposited as a large delta in Lake Mills (the upstream reservoir). The thickest delta deposit, measured from drill holes in 1999 and 1994, was 70.5 feet in Lake Mills and 42.6 feet in Lake Aldwell (Gilbert and Link, 1995).

In preparation for dam removal, new facilities were constructed for water quality and flood protection. The quantitative sediment effects of dam removal were initially predicted for an environmental impact statement (U.S. Department of the Interior, 1996) based on measured sediment erosion during the 1994 Lake Mills drawdown experiment (Childers et al., 2000), sediment and topographic surveys of the reservoir, a numerical sediment-budget model, and numerical modeling of the downstream river channel (Randle et al., 1996). Later, a laboratory model was utilized to evaluate the extent and rate of reservoir sediment erosion as a function of the dam removal rate (Bromley, 2007). Prior to the beginning of dam removal, the empirically-based sediment-budget model (initially developed by Randle et al., 1996) was updated and re-written in a GIS framework. The model described in this paper was used to provide up-to-date predictions based on dynamic reservoir sediment conditions, hydrology, and updated dam removal schedules. The model simulated the reservoir channel evolution, amount and timing of

coarse (sand and gravel) and fine (silt and clay) sediment erosion and release from both reservoirs and the volume and future topography of sediment remaining in the reservoirs.

An adaptive management program was designed to ensure that Elwha River Restoration Project management objectives were met and that sediment impacts were contained by mitigation facilities (Randle and Bountry, 2010 and Bountry, 2015 these proceedings). Key monitoring activities focused on the extent and rate of vertical and lateral erosion of the exposed reservoir sediment, downstream water quality impacts associated with release of fine sediment from the reservoirs, downstream aggradation from the release of coarse reservoir sediment, and forecasting the sediment release through the reservoirs with numerical modeling. Measured sediment effects were compared with predictions, so that adjustments in the dam removal schedule (or other corrective actions) could be taken when necessary.

The empirically-based, sediment-budget modeling approach was used, rather than a one- or two-dimensional (1D or 2D) sediment transport model. A 1D model could not simulate important lateral erosion and delta progradation processes. A 2D model would have required many days or weeks of computer time to simulate the necessary range of hydrologies and changing dam removal schedules and there would have been difficulty automatically adjusting the 2D model mesh with continued sediment terrace bank erosion. The sediment-budget model runs relatively fast and was able to track the complex three-dimensional topography of each reservoir over time.

DAM REMOVAL AND SEDIMENT MANAGEMENT PLAN

The dam removal and sediment management plan was to concurrently remove both dams in controlled increments and allow the Elwha River to incise and erode a portion of the reservoir sediments downstream to the Strait of Juan de Fuca (U.S. Department of the Interior, 1996). The model incorporated reservoir drawdown increments of 5 to 15 feet at a maximum allowable rate of 3 feet per 49 hours. After each reservoir drawdown increment, the remaining reservoir pool was held at relatively constant levels for two weeks to two months to induce lateral erosion of the exposed sediments. The longer reservoir hold periods were known as “fish windows” and corresponded to important fish migration periods: May 1 to June 30, Aug. 1 to Sep. 15, and Nov. 1 to Dec. 31.

Because of the anticipated large sediment release, several water quality and flood protection facilities were designed and constructed to mitigate impacts. Water treatment plants, new wells, and a new surface water intake were constructed to protect existing water users from high suspended sediment concentrations. Some new levees were constructed and the heights of existing levees were increased to protect property and infrastructure from possible increases in flood stage that could result from coarse sediment aggradation in the downstream river channel.

NUMERICAL MODEL OBJECTIVES AND OVERVIEW

The primary numerical model objectives are: (1) simulate the reservoir sediment erosion, re-deposition, and release of fine and coarse-sized sediment over time from both reservoirs; (2) predict the portion of sediment retained within the reservoir after dam removal; and (3) provide a framework to guide the collection and synthesis of monitoring data.

The empirical rules of the numerical sediment-budget model are based on geomorphic and sediment transport principals and field measurements. The model tracks fine sediment separately from coarse sediment. As the reservoir is drawn down, the river is assumed to erode a primary channel through the exposed reservoir sediments. The coarse sediment that is eroded during this process is assumed to redeposit in the receded reservoir so long as the reservoir exists. Fine sediment that is eroded during this process is assumed to become suspended in the receded reservoir. A portion of this fine suspended sediment is assumed to re-deposit on the lakebed while the remainder is assumed to transport past the dam. After the reservoir has been drained, eroding coarse and fine sediments are assumed to be transported past the dam.

The numerical sediment-budget model consists of three computer programs for each reservoir:

1. The pre-processing FORTRAN program determines the daily reservoir water and sediment inputs, the daily reservoir drawdown schedule, and the GIS model time steps. These GIS model time steps are variable, but typically range from one to two months and include a given reservoir drawdown increment and subsequent hold times, which may be extended due to high flows or fish windows.
2. The GIS model simulates the channel evolution through the complex topographic surfaces of the reservoir sediment terraces for each model time step.
3. The post-processing FORTRAN program computes the daily coarse and fine sediment loads and concentrations released past each dam based on the output from the GIS model.

MODEL BOUNDARY AND INITIAL CONDITIONS

The upstream model boundary conditions include hydrographs of water discharge and sediment load and the dam removal schedule. The initial conditions consist of the reservoir bathymetry and percentages of coarse and fine sediment for various sub-areas of the reservoir.

A range of historic discharge hydrographs (13-year periods) were used to simulate future conditions: (*i*) water years 1950 through 1963 (normal hydrology), (*ii*) water years 1969 through 1991(dry hydrology), (*iii*) water years 1971 through 1994 (normal hydrology), and (*iv*) water years 1999 through 2002 (wet hydrology). As dam removal progressed, each hydrology was updated with the measured discharge values. Discharge was measured at the McDonald Bridge stream gage (12045500), located between Glines Canyon Dam and Lake Aldwell. The fine and coarse sediment loads from the upstream watershed were computed from sediment-discharge rating curves (Randle et al., 1996).

The future reservoir drawdown schedules (a downstream boundary condition) were determined by the model based on the following information: (*i*) contractor's proposed construction schedule, (*ii*) reservoir inflow discharge, (*iii*) reservoir drawdown rate restrictions, (*iv*) reservoir drawdown increment limits, (*v*) overtopping flow work restrictions, and (*vi*) required reservoir hold periods, including fish windows.

Initial reservoir model conditions consisted of the reservoir bathymetry (measured in July 2010 by Bountry et al., 2011), coarse and fine sediment percentages, and initial alignment of river channels on the delta. A pilot channel was constructed on the Lake Mills delta during September

2010 and was incorporated into the initial topographic conditions. The predam reservoir topography was used by the model to represent the lower limit of reservoir sediment erosion. For Lake Mills, the predam topography was based on a 1921, 10-foot contour map. The Lake Aldwell predam topography had to be estimated from drill holes and thickness probes, and later by incorporating exposed pre-dam topography (Gilbert and Link, 1995; Randle et al, 2015). Percentages of coarse and fine sediment were specified for reservoir polygon areas defined by Gilbert and Link (1995). Single sediment layers were typically specified, but three vertical sediment layers were specified for the Lake Mills delta.

SIMULATION OF RESERVOIR CHANNEL EVOLUTION

For each model time step, the GIS spatial model computes a sediment balance between the upstream sediment-supply volume, the river-erosion volume of the exposed sediment, and the corresponding reservoir-deposition volume. The river-erosion volume is a function of the reservoir-drawdown increment, longitudinal erosion slope, peak discharge, and the river erosion width along the upstream portion of the delta and where the river meets the receded reservoir (Figure 2 and Figure 3). So long as a reservoir remains between the delta and the remaining dam, the coarse sediment fraction of the river erosion volume is assumed to re-deposit as a new delta in the receded reservoir on top of the fine lakebed sediment. The model is able to account for compaction of the underlying fine sediment. During each increment of reservoir drawdown, the delta front extends farther downstream into the receded reservoir causing some aggradation along the upstream erosion channel (Figure 2 profile view).

The fine sediment fraction of the river-erosion volume is assumed to enter the reservoir as suspended sediment. Using a sediment trap efficiency equation (Pemberton and Lara, 1971), the model calculates the portion of fine suspended sediment that will settle to the reservoir bottom and the portion that will be transported in suspension past the dam. Once the delta has prograded all the way downstream to the remaining dam, the reservoir pool no longer exists, and all eroded sediments are released past the dam.

For future simulations, the GIS spatial model uses the concepts illustrated in Figure 2 to simulate erosion and deposition of the complex topographic surfaces to ensure separate volume balances for coarse and fine sediments. The spatial model consists of a set of vector-based customizations and a series of raster-based analysis tools that are run at each time step according to the reservoir drawdown schedule. The vector-based customizations are used to determine potential erosion and deposition geometries. The vector geometries are fed into the raster-based analysis tools that update an input surface raster (10 ft × 10 ft) to reflect the sediment inflow, erosion, deposition, and downstream release.

The delta erosion, topset, and foreset slopes (S_T, S_T, and S_F) are specified by the model user while geometric dimensions of delta length, upstream channel width and channel width where it meets the lake (D_L, W_{min}, and W_L) are computed by the model. The volume calculations are linked where the river erosion channel meets the receded reservoir. At this location, the computed river erosion width equals the reservoir deposition width (W_{max}). Aggradation in the erosion channel is linked to the length of new delta deposition. Therefore, the model uses an iterative approach to achieve the volume balance for coarse sediment.

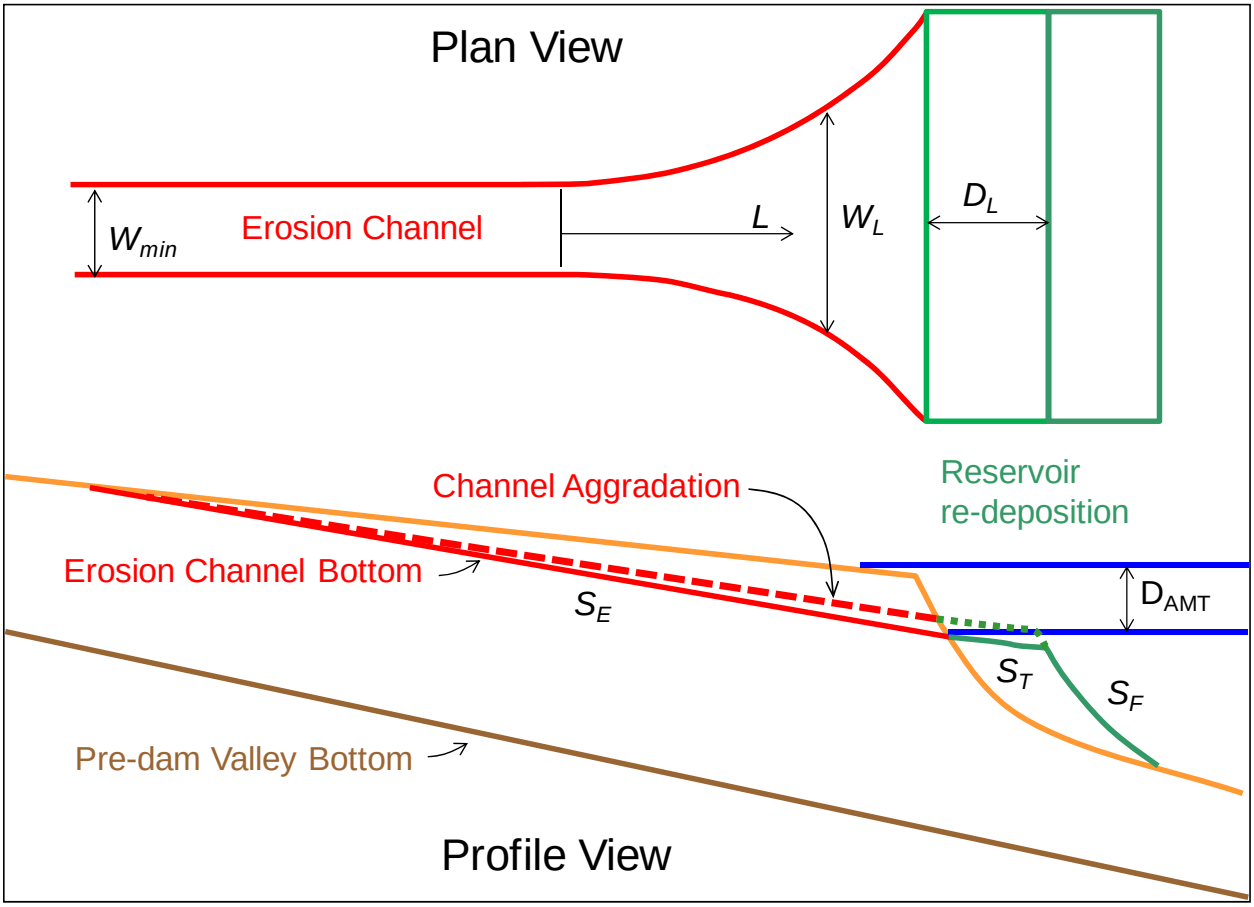

Figure 2. Plan and profile sketch of reservoir sediment erosion and re-deposition. The variables shown in the figure are described in the body of the paper.

Figure 3. Photographs of sediment erosion and re-deposition at Lake Mills (A) as observed in August 2011 (16 feet of spillway drawdown prior to dam removal) and (B) in a laboratory model of Lake Mills conducted by Bromley (2007).

The model computes the sediment erosion volume using the topography at the beginning of the time step, the delta erosion slope (S_E) corrected for aggradation, and the channel erosion widths (Figure 2 plan view). The model computes the coarse, reservoir deposition volume using the delta topset slope (S_T) adjusted for aggradation, foreset slope (S_F), the deposition width across the receded reservoir (W_{max}), and the reservoir bathymetry at the beginning of the time step. After the Lake Mills delta prograded all the way to Glines Canyon Dam, there was a year-long hold period in order to reduce the rate of reservoir sediment erosion and downstream release. For this long hold period, the model exponentially decreased the channel erosion slope over time.

$$S_E(t_n) = S_E e^{(-7.57\text{E}-04\ T_Q)} \tag{1}$$

Where T_Q is the cumulative number of days since the delta reached the dam (10/23/2013) where the discharge was greater than a transport threshold (2,000 ft^3/s).

The reservoir drawdown increments in Lake Aldwell and Lake Mills nearly always eroded enough coarse sediment to deposit a new delta across the entire width of the receded reservoir. For this common case, the model computed the downstream length of the new delta topset (D_L). For the few cases where the erosion volume was not sufficient to deposit a new delta across the entire reservoir width, a default topset length wa9s specified and the model computed the delta deposition width (which is also equal to the maximum erosion width).

<u>Sediment Erosion Volume Calculations</u> For future simulations, the model computes the minimum erosion-channel width (W_{min}), for each time step, as a function of the peak discharge (Q_{max}) and a time-adjustment factor (T_A), which was developed from monitoring observations.

$$W_{min} = \left[a{Q_{max}}^b\right]T_A \tag{2}$$

The coefficient a is calibrated from measured erosion widths and the exponent b is chosen from literature (typically 0.5). The time-adjustment factor (T_A) is based on the number of days (N_D) (during the model time step) where the mean-daily discharge equals or exceeds the mean discharge (for the model time step) and is also above a user-specified threshold. An empirically determined coefficient (α) is also used in Eq. 3.

$$1 \leq T_A = (\alpha N_D + 1) \qquad \alpha = \frac{2/3}{10} = 0.0667 \tag{3}$$

The minimum erosion width is assumed to increase as the river erosion channel approaches the receded reservoir where the channel laterally migrates to deposit sediments.

$$W_L = 2cL^2 + W_{min} \tag{4}$$

where W_L is the erosion width as the river approaches the receded reservoir, L is the longitudinal distance along the erosion channel centerline (Figure 2), and c is a coefficient computed by the model so that the erosion channel width equals the reservoir deposition width where the erosion channel meets the reservoir. The total length of channel (L_{max}) where the erosion width increases is specified by the model user as a function of the local reservoir width.

$$L_{max} = f\ W_{max} \tag{5}$$

Computation of the river-erosion volume begins with the reservoir drawdown increment. The downstream extent of the erosion channel is computed as the intersection of the erosion channel and the receded reservoir. Initially, the channel bottom elevation at the downstream end is assumed to equal the lowered reservoir-water surface elevation. From this elevation, the user specified longitudinal erosion slope is projected upstream to the intersection with the upstream sediment surface or the predam surface, whichever is encountered first. The aggradation volume in the sediment erosion channel is computed after the new delta length (D_L) is computed.

The erosion channel centerline is specified by the model user. The left and right banks of the river erosion channel are determined from the channel centerline and the computed erosion-channel widths. Alternatively, when measured bank-line data are available from the monitoring program, they can be used as an input feature in place of the computed erosion-channel widths in conjunction with the user-specified centerline. This was of particular value when the actual erosion width was non-uniform along substantial portions of the channel length.

Reservoir Sediment Trap Efficiency Calculations The reservoir sediment trap efficiency (P) is computed as a function of the sediment particle fall velocity (ω), inflow discharge (Q), and surface area of the remaining reservoir (A_s) (Pemberton and Lara, 1971). The sediment particle fall velocity (ω) is a function of the median fine sediment particle size (d, ft) and the water viscosity (ν, ft^2/s), which is a function of water temperature (T, ^{o}C).

$$P = \left(1 - \frac{1}{e^{\left(\frac{1.005\omega A_S}{Q}\right)}}\right) \tag{6}$$

$$\omega = \frac{\sqrt{36.064\ d^3 + (6\ \nu)^2} - 6\ \nu}{d} \tag{7}$$

$$\nu = \frac{0.00002}{(1.0334 + 0.03672\ T + 0.0002059\ T^2)} \tag{8}$$

Daily Reservoir Sediment Release Calculations The post-processing FORTRAN program uses the fine and coarse-sediment erosion volumes (computed by the GIS model for each simulation time period) to compute the daily fine and coarse sediment-release rates past each dam. A daily factor (D_F) is computed to distribute the sediment release volumes from the longer GIS model time step. Initially, each daily factor (D'_F) is computed as the weighted sum of the daily reservoir drawdown factor (R_F) and the daily discharge factor (Q_F) (Eq. 9). The daily factors within each GIS model time step are then adjusted to sum to 1 (Eq. 10). In the equations below, t_n indicates the value at day n and t_o indicates the value at the beginning of the time step. Model coefficients and exponents are described in Table 1, Table 2 and Table 3.

$$D'_F(t_n) = c_7 R_F + (1 - c_7) Q_F(t_n) \tag{9}$$

$$D_F(t_n) = \frac{D'_F(t_n)}{\sum_{n=1}^{m} D'_F(t_n)} \tag{10}$$

The computation of the daily reservoir drawdown factor (R_F) depends on whether the reservoir is drawing down, holding, or refilling. The daily reservoir drawdown increment (D_{INC}) (Eq. 11) and the cumulative drawdown increment since the beginning of the GIS model time step (D_{AMT}) (Eq. 12) are computed from the daily water surface elevations (WSE). The daily change in mean-daily discharge (ΔQ_w) (Eq. 13) is also computed to determine if the discharge is increasing.

$$D_{INC}(t_n) = WSE(t_n) - WSE(t_{n-1}) \tag{11}$$

$$D_{AMT}(t_n) = WSE(t_n) - WSE(t_o) \tag{12}$$

$$\Delta Q_w(t_n) = Q_w(t_n) - Q_w(t_{n-1}) \tag{13}$$

If the reservoir is drawing down, $D_{INC}(t_n) < c_3$, then

$$R_F(t_n) = 0.020\ c_1^{\left(\frac{-1\{D_{AMT}(t_n)\}}{1.5ft}\right)} \tag{14}$$

If the reservoir is holding, $D_{INC}(t_n) \geq c_3$, then

$$R_F(t_n) = c_2\ R_F(t_{n-1}); \tag{15}$$

If the reservoir inflow discharge is increasing, $\Delta Q_w(t_n) \geq 1{,}000$ ft^3/s, or the inflow is high, $Q_w(t_n) > 3{,}500$ ft^3/s, then

$$R_F(t_n) = 0.020\ c_1^{\left(\frac{Q_W(t_n)}{1{,}000ft^3/s}\right)} \tag{16}$$

Initially, the daily discharge factor (Q'_F) is computed as a function of the mean daily discharge (Eq. 17).

$$Q'_F(t_n) = (Q_w)^{c_4}(t_n) \tag{17}$$

$$Q_F(t_n) = \frac{Q'_F(t_n)}{\sum_{n=1}^{m} Q'_F(t_n)} \tag{19}$$

The model computes the concentration of fine sediment (ppm) being transported past the dam from the sediment trap efficiency (P), erosion volume (V_F), unit weight of sediment (γ), and the mean-daily river discharge (Q_w). A time lag is also applied to account for travel time through the reservoir.

$$Conc = \frac{(1-P)V_F\,\gamma}{Q_w}\left(\frac{2{,}000lbs/ton}{(62.4lbs/ft^3)(3{,}600s/hr)(24hrs/day)}\right)1{,}000{,}000 \tag{19}$$

Turbidity is computed from the concentration by use of a power equation, but the coefficient and exponent were found to vary over time under changing sediment conditions.

$$Turbidity = c_5\ (Conc)^{c_6} \tag{20}$$

MODEL CALIBRATION

Although there are many model calibration parameters, the coefficients and exponents appeared to be very reasonable. Compaction of fine reservoir sediment was considered, but not used. The median grain size for fine sediment was calibrated to a value of 0.01 mm, which represents fine silt. The delta channel erosion widths, lengths of delta erosion affected by deposition, and longitudinal erosion slopes were calibrated separately for Lake Mills and Lake Aldwell. The erosion channel centerline of the exposed delta is a user input. Measured past channel alignments were delineated in GIS. Future channel migration of the erosion channel alignment is based on past migration, geologic controls within the reservoir landscape, whether the channel was eroding into non-cohesive (coarse) or cohesive (fine) sediment, and professional judgment. Post processing model parameters were calibrated to match the pattern and magnitude of measured turbidity downstream from Elwha Dam. Summary lists of model input parameters are presented in Table 1 for river erosion, Table 2 for new delta deposition, and Table 3 for daily sediment release past the dam.

Table 1. Summary list of model input parameters for river erosion.

Variable	Description
a and b	Coefficient ($2.3 < a < 6$) and exponent (typically b = 0.5) used to compute the minimum erosion-channel width as a function of discharge (Eq. 2).
α	Coefficient used to compute the time-adjustment factor ($T_A = 0.0667$) (Eq. 3).
c	Coefficient used to compute the erosion-channel width near the receded reservoir. This coefficient is calculated by the model (Eq. 4).
f	Multiplier used to compute the maximum channel length (L_{max}) upstream from the receded reservoir where the erosion width is influenced by new delta deposition ($1 < f < 3$) (Eq. 5).
S_E	Longitudinal slope of the river erosion channel ($0.003 < S_E < 0.011$).

Table 2. Summary list of model input parameters for new delta deposition.

Variable	Description
D_L	Default topset length ($D_L = 200$ feet)
S_T	Topset slope ($S_T = 0.0009$ for Lake Aldwell and 0.0050 for Lake Mills)
S_F	Foreset slope ($S_F = 0.020$ for Lake Aldwell and 0.032 for Lake Mills)
Reservoir sediment trap efficiency parameters:	
d	Median particle size of fine sediment ($d = 0.010$ mm) (Eq. 7)
T	Water temperature ($T = 50$ degrees Fahrenheit) (Eq. 8)

Table 3. Summary list of model input parameters for daily sediment release.

Variable	Description
c_1	Sediment concentration time factor for continued reservoir drawdown ($c_1 = 1.10$) (Eq. 14 and 16)
c_2	Sediment concentration time factor for continued reservoir holding or refilling (if $t_n \leq 30$ days, then $c_2 = 0.97$; if $t_n > 30$ days, then $c_2 = 1$) (Eq. 15)
c_3	Threshold to distinguish between reservoir drawdown and holding or refilling ($c_3 = -0.50$ ft/day) (Eq. 14 and 15)
c_4	Exponent for weighting the discharge ($c_4 = 3.50$) (Eq. 17)
c_5	Coefficient to convert sediment concentration to turbidity ($c_5 = 0.992$) (Eq. 20)
c_6	Exponent to convert sediment concentration to turbidity ($c_6 = 1.0044$) (Eq. 20)
c_7	Weighting factor to compute the daily factor (D'_F) ($c_7 = 0.333$) (Eq. 9)

EXAMPLE MODEL RESULTS AND DISCUSSION

The reservoir sediment erosion model has been applied numerous times during concurrent dam removal to simulate a range of hydrologies and proposed dam removal schedules (Bountry et al., 2015 these proceedings). An example simulation, performed in April 2012, is provided using the historical flow records from water years 1950 through 1968, except that the actual flows were used for the period October 2010 through April 2012. Simulated hydro-graphs of reservoir water surface elevation, discharge, and turbidity are presented in Figure 4.

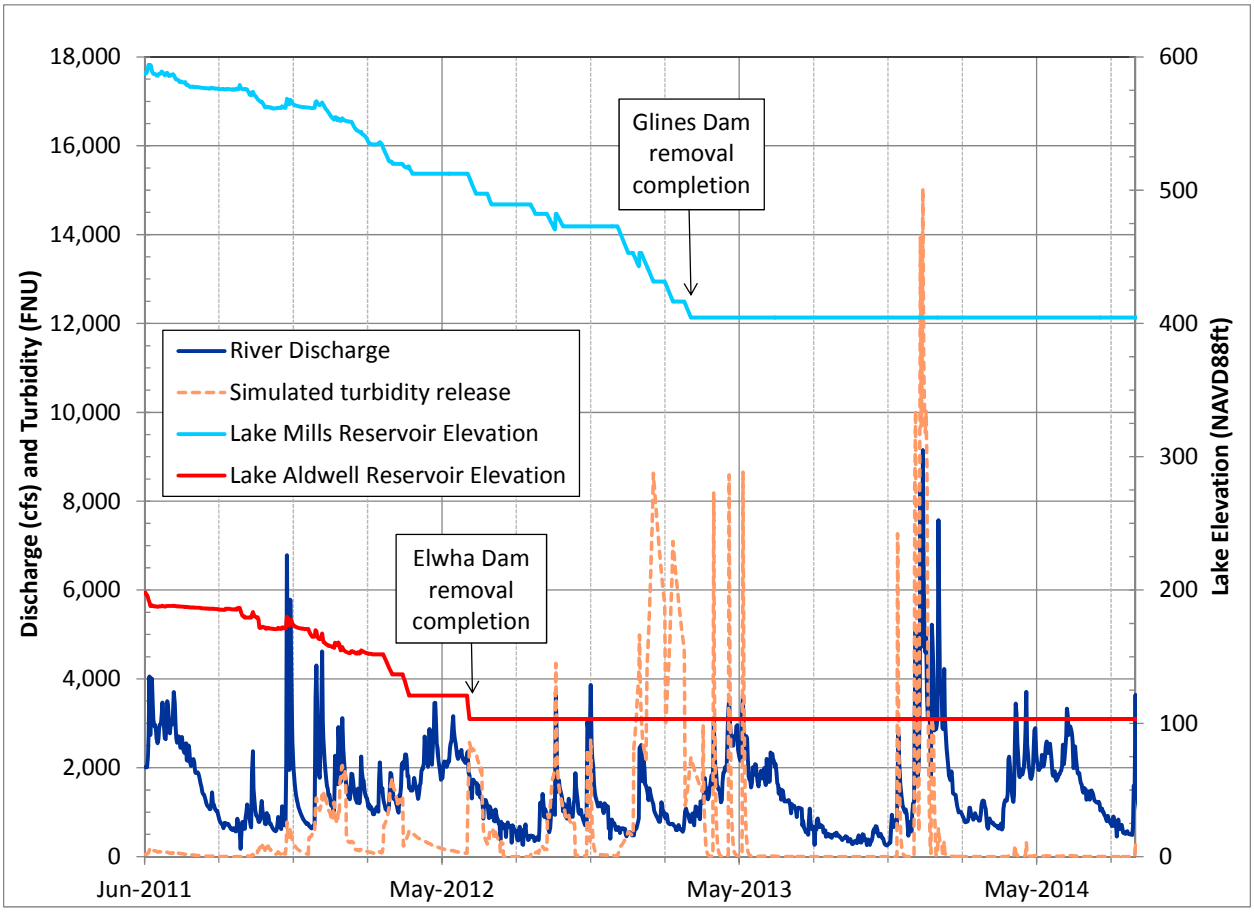

Figure 4. Example simulation of fine-sediment release from Lake Mills and Lake Aldwell.

The simulated reservoir sediment thickness before and after dam removal is presented in Figure 5 for Lake Mills and in Figure 6 for Lake Aldwell. Colored areas represent reservoir sediment terraces. The darker color red corresponds to the areas of thickest sediment while the gray areas represent areas where the sediments have been eroded down to the estimated predam surface.

For this example simulation, 50% of total reservoir sediment would be transported past the dam, 10 years after dam removal. About half of the sediment was measured to erode from the reservoirs by the end of 2014. The model correctly predicted the time when the eroding reservoir delta would reach the dam and the correct order of magnitude of downstream

turbidities. The model incorrectly assumed that the channel incision from a given reservoir drawdown increment would completely occur during a one- to two-month time step.

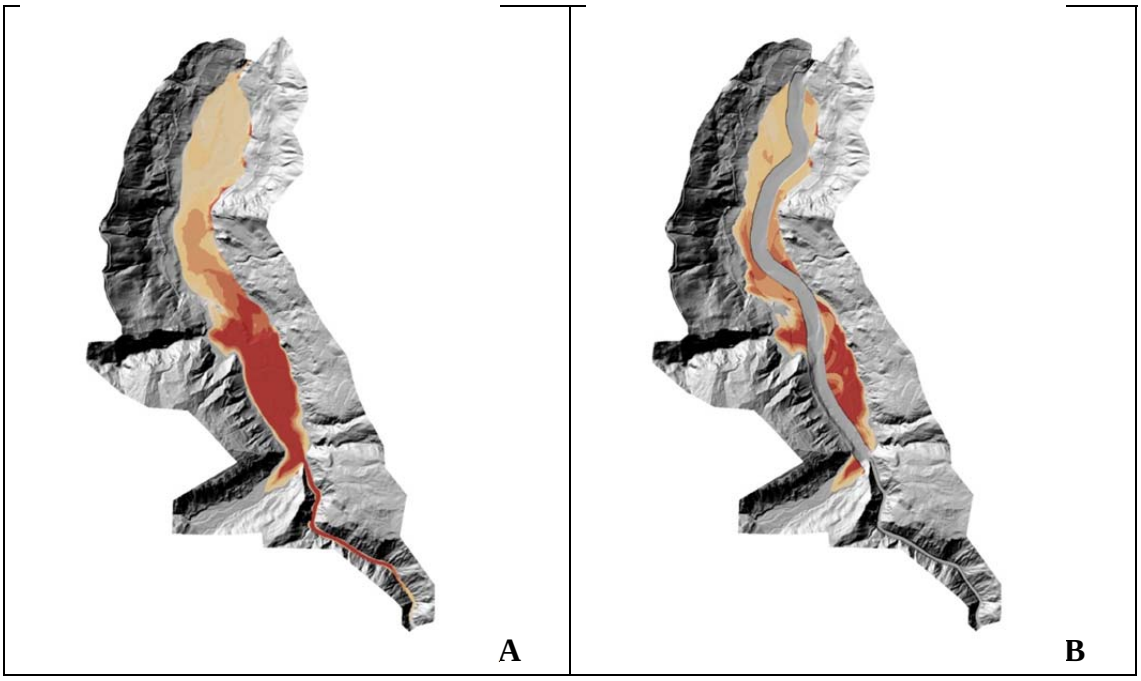

Figure 5. Example simulation of Lake Mills sediment thickness before (A) and after dam removal (B).

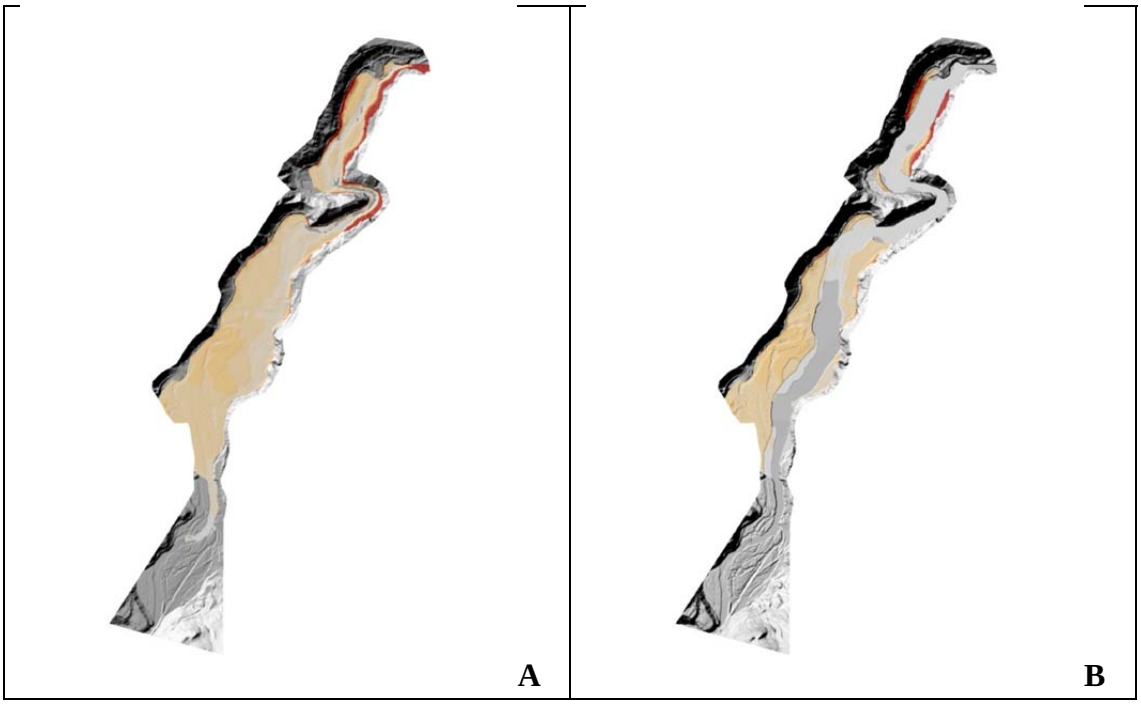

Figure 6. Example simulation of Lake Aldwell sediment thickness before (A) and after dam removal (B).

Actual knickpoint migration proved to be much slower, especially in Lake Mills. However, the actual reservoir erosion width, slope, and alignment could be updated as dam removal progressed, along with the hydrology and dam removal schedule, so that simulations of future scenarios were increasingly more accurate. The simulated volume of sediment erosion was most influenced by erosion channel width and slope. The daily patterns of sediment concentration and turbidity released downstream were most influenced by the coefficients c_1, c_2, c_3, c_4, and c_7.

Future model simulations were used in the decision to hold Glines Canyon Dam removal activities for the second year of project implementation. Actual river discharges were a bit different than the four historic hydrologies. Actual peak discharges were less than the 2-year flood peak during the first three years of project implementation, but mean discharge was above average. The dam removal contractor could work faster, and during higher river discharge, than assumed in the initial model simulations.

CONCLUSIONS

The reservoir sediment erosion model is able to simulate the channel incision, lateral erosion, and redeposition of sediment during phased dam removal. Model application requires the user to specify numerous parameters. All the physically-based model input variables are based on direct field measurements or calibrated using field measurements. Coefficients c_1 through c_7 (Table 3) are based on professional judgment, but are generally close to 1. The model was able to simulate the most important channel evolution processes and was able to simulate a large number of future scenarios of concurrent dam removal during project implementation.

In addition to the predictive capabilities, the numerical model represented a set of linked hypotheses that could be tested and updated based on monitoring data. The testing of these hypotheses with monitoring results increased the rate of learning compared to singular approaches of modeling or monitoring alone. The required model inputs and the outputs help focus and organize the monitoring data that were crucial for testing the hypotheses. The model was updated throughout the project as new information became available on dam removal schedules and monitoring on the rate and extent of sediment erosion.

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