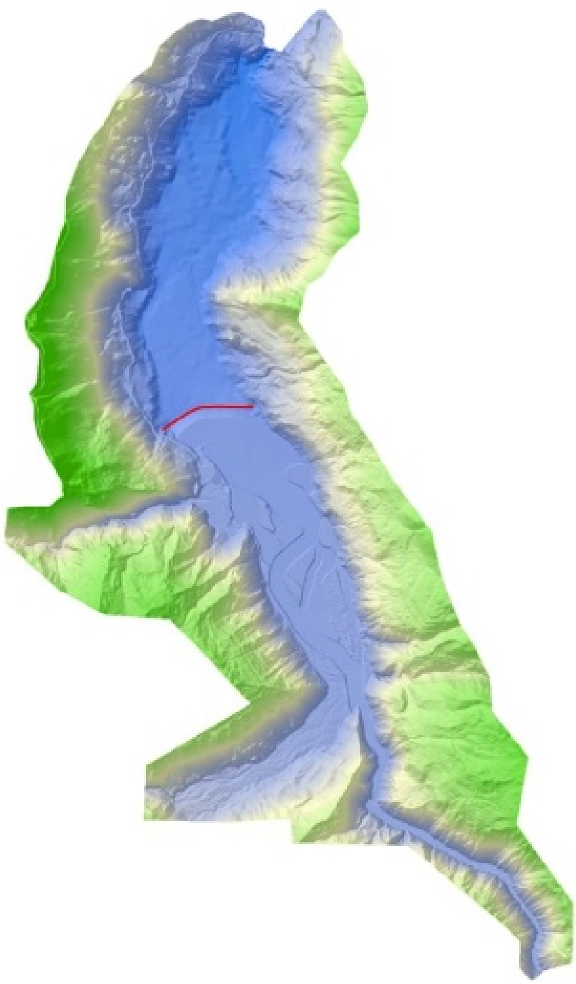
Mass Balance Model for Reservoir Sediment Erosion



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Cover: Example model results; simulated topographic surface of Lake Mills after 27 ft of drawdown on Jan,07, 2012.

Mass Balance Model for Reservoir Sediment Erosion

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Abstract

A new mass balance model was created to simulate the sediment erosion, redeposition, and downstream transport in support of the Elwha River Restoration Project, near Port Angeles, WA. This project included the incremental removal of Glines Canyon Dam and Elwha Dam from the Elwha River, the two largest dams ever removed. The mass balance model used empirically based rules and parameters to predict the amount and location of sediment erosion and redeposition within each reservoir during each increment of dam removal. The model also predicted the magnitude and timing of sediment transported past each dam.

The mass balance model was useful for project planning, both before and during project implementation. Prior to implementation, the model was used to evaluate project alternatives and to estimate environmental impacts. During implementation, the model was used to help guide the monitoring program and forecast the environmental effects from the next increment of dam removal.

Introduction

A new mass balance numerical model was created to simulate the reservoir sediment erosion associated with Elwha River Restoration Project near Port Angeles, WA. This report documents the model development and how it was applied to the Elwha River Restoration Project. The restoration project included the removal of Elwha Dam and Glines Canyon Dam, both on the Elwha River (Figure 1) (DOI 1996a, 1996b, 1996c, 2004, 2005a, and 2005b). The mass balance numerical model, and its earlier versions, were used to help plan the reservoir drawdown increments, estimate environmental impacts, and to help guide the project monitoring and provide updated forecasts during dam removal. Lake Mills, behind Glines Canyon Dam, and Lake Aldwell, behind Elwha Dam both had deltas primarily composed of coarse sediment and finer lakebed sediments (Randle et al. 2015 and Bountry et al., 2018).

The numerical model employs the conservation of mass principle and empirical rules to simulate the incremental erosion and redeposition of delta sediments and the subsequent sediment transport past each dam during the concurrent and phased removal of the two large dams. Separate models of Lake Mills and Lake Aldwell were used in series to predict the amount and timing of coarse and fine sediment erosion from both reservoirs and the volume and topography of sediment terraces remaining in each reservoir. The model described in this paper is an extension of work conducted by Randle et al. (1996) and Randle (2002). The initial idea for the numerical model was based on observations and measurements made during the 1994 Lake Mills drawdown experiment (Childers et al., 2000). The model was later refined based on the results from physical modelling conducted by Bromley (2007).

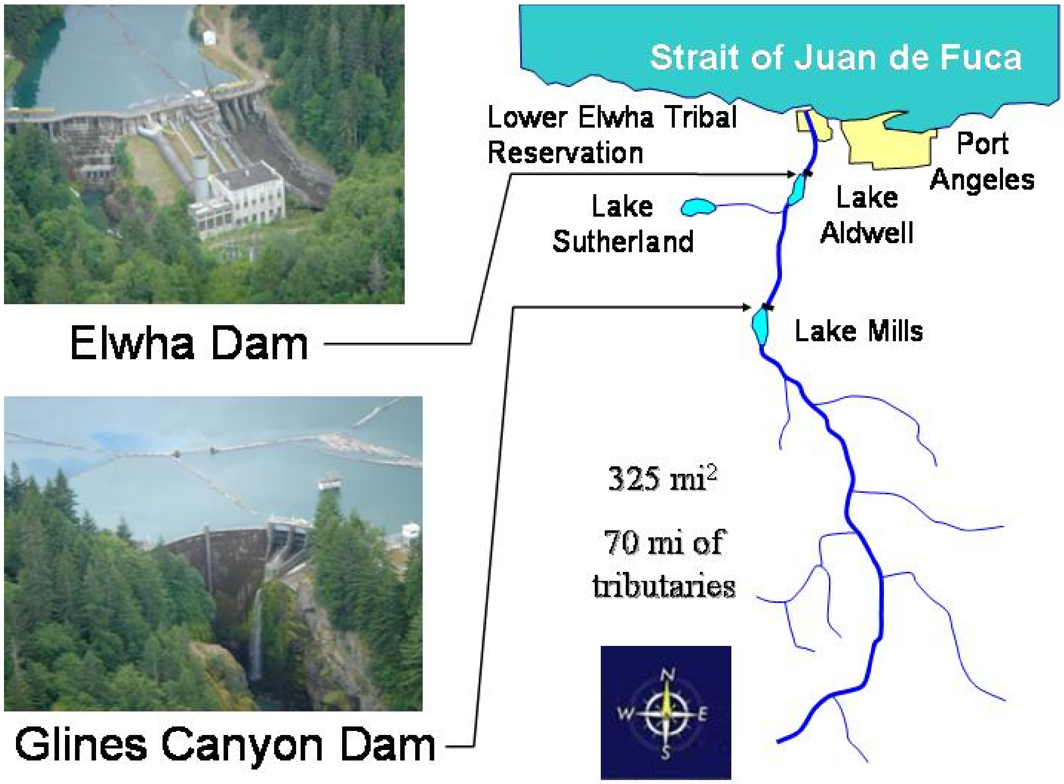


Figure 1. Elwha and Glines Canyon Dams are located on the Elwha River near Port Angeles, Washington.

Elwha Dam was completed in 1913 at river mile 5 and formed Lake Aldwell (U.S. Department of the Interior and U.S. Department of Commerce, 1994). Elwha Dam was a concrete gravity dam with an original structural height of 105 feet. Lake Aldwell had an original storage capacity of 8,100 acre-feet (Randle et al., 2015 and Bountry et al., 2018).

Glines Canyon Dam was completed in 1927 at river mile 13 and formed Lake Mills. Glines Canyon Dam was a concrete arch dam with an original structural height of 210 feet. Lake Mills had an original storage capacity of 40,500 acre-feet. Since the mid 1970's, both reservoirs were nearly always kept full and operated for the production of hydroelectric power. Neither reservoir provided flood control or water supply storage.

The concurrent removal of both Elwha Dam and Glines Canyon Dam began in September 2011. Removal of Elwha Dam was complete seven months later, by April 2012. Removal of Glines Canyon Dam was complete three years later, by September 2014 (Bountry et al., 2018).

Adaptive Management Program

An adaptive management program was implemented to reduce uncertainty and help to ensure that Elwha River Restoration Project management objectives were met and that sediment impacts were contained by mitigation facilities (e.g., downstream flood control levees, and water treatment plants) (Randle and Bountry, 2010). The adaptive management program allowed for flexible decision making based on outcomes from previous management actions and hydrology (Williams et al., 2007). Near real-time monitoring data were a necessary component to measure reservoir and river responses and comparing those responses to model predictions. The model was continually updated with actual hydrology and rates of dam removal and reservoir drawdown. When model predictions did not match the measured outcomes, then the model was updated to better represent the physics of reservoir sediment erosion.

Key monitoring activities focused on the extent and rate of reservoir sediment erosion and redeposition, downstream turbidity and suspended sediment concentration, and changes to the longitudinal river profile.

Numerical Reservoir Model Objectives and Overview

The numerical model was developed specifically for the Elwha River Restoration Project. The computer code was not written for general use and no user's manual was prepared. Additional data would be needed for model validation before the model could be suggested for general use. However, the model concepts described here could be used to develop models for other dam removal projects, assuming validation data were available. The three primary objectives of the numerical reservoir model are listed below:

1. Simulate reservoir sediment erosion, redeposition, and release of fine (clay and silt) and coarse-sized (sand and gravel) sediment over time from both reservoirs.
2. Predict the volume and spatial distribution of sediment remaining in the reservoir after dam removal.
3. Provide predictions to guide the collection and analysis of monitoring data.

In addition to the predictive capabilities, the numerical model represented a set of linked hypotheses that were tested and updated based on monitoring data. The required model inputs and the outputs helped focus and organize the monitoring data that were crucial for testing the hypotheses. Monitoring data and observations were used to test processes that were included in the model and determine the importance of any processes that were excluded from the model. In addition, the latest monitoring data from the beginning of dam removal were periodically included in input files for subsequent model simulations. These data included the actual hydrology, reservoir drawdown schedule, and erosion channel alignments.

The empirical rules of the numerical mass balance model were conceptually based on geomorphic and sediment transport principles, field measurements, and generally confirmed by physical model experiments. The numerical model tracks fine sediment (clay and silt) separately from coarse sediment (sand and gravel). Coarse sediment eroded from the exposed reservoir delta was assumed to redeposit in the receded reservoir until the reservoir pool no longer remained. Fine sediment eroded from the exposed reservoir delta was assumed to be suspended in the receded reservoir pool. A portion of this fine suspended sediment was redeposited on the lakebed while the remainder was transported past the dam.

One-dimensional hydraulic and sediment transport models available at the time of the project (e.g., HEC-RAS or SRH-1D) were not used because both vertical and lateral sediment erosion processes were important for Lake Mills and Lake Aldwell and they did not incorporate lateral sediment erosion at the time of the project. A two-dimensional hydraulic and sediment transport model (e.g., SRH-2D) was not used because of the long simulation time required for each simulation and the large number of simulations required to account for the wide range of future hydrology and dam removal schedules. In contrast, the numerical mass balance model runs relatively fast and was able to track the complex three-dimensional topography of each reservoir over time.

The numerical mass balance model consisted of three computer programs for each reservoir:

1. The pre-processing FORTRAN program was developed to determine the daily reservoir water and sediment inputs, the daily reservoir drawdown schedule, and the reservoir simulation time periods. These time periods were variable and typically ranged from days to months to account for reservoir drawdown increments, high flows, and subsequent hold periods.
2. The mass balance model was developed to simulate the sediment inflow, erosion, deposition, and subsequent downstream release and to simulate the complex topographic surfaces of the reservoir after each time period.
3. The post-processing FORTRAN program was developed to estimate the daily coarse and fine sediment release past each dam.

Model Boundary and Initial Conditions

The following model boundary conditions had to be specified:

- Daily hydrographs of upstream water discharge and coarse and fine sediment loads
- Planned reservoir drawdown schedules, which may be disrupted by periods of high flow or required hold periods

The following Initial reservoir conditions had to be specified:

- Top bathymetric and topographic surface of the reservoir sediment (below and above water), including channels along the delta surface
- Predam topographic surface of the reservoir (bottom of reservoir sediment)
- Polygons delineating planimetric areas of reservoir sediment with different grain size proportions
- Top surface of any distinguishable underlying sediment layers within a polygon
- Proportions of coarse and fine sediment within each polygon area and sediment proportions for any vertical layers

Boundary Conditions

The upstream boundary discharge hydrographs included both the measured mean-daily discharge since the beginning of dam removal and the assumed discharge hydrograph representing future conditions. The upstream boundary sediment loads were computed by the numerical model in the Pre-Processing Program as a function of the inflow discharge. The downstream boundary reservoir water surface elevations were determined by the Pre-Processing Program based on the planned dam removal schedule, inflow discharge, and reservoir drawdown requirements.

For the Elwha River Restoration Project, one of four discharge hydrographs were used to represent future conditions based on 13-year periods of historic hydrology. As dam removal progressed, the assumed future daily discharge values were replaced with the measured discharge values:

- Water years 1950 through 1963 (normal hydrology)
- Water years 1968 through 1981 (dry hydrology)
- Water years 1971 through 1984 (normal hydrology)
- Water years 1989 through 2002 (wet hydrology)

The historic hydrology (representing inflows to Lake Mills and Lake Aldwell) was based on USGS records of mean-daily discharge at the McDonald Bridge stream gage (12045500) located between Elwha and Glines Canyon Dams. Real-time discharge values were used during project implementation. The discharge values were not adjusted to account for decreases or increases in drainage area. Limited records of mean-daily discharge (1994 to 2011) were also available for the USGS gage above Lake Mills (12044900). However, these data were not used.

Initial Conditions

The initial conditions for the top surface of the reservoir sediment was based on the 2009 aerial LiDAR survey and 2010 bathymetric survey conducted prior to the beginning of dam removal (Bountry et al., 2011). During September 2010, a pilot channel was constructed along the Lake Mills delta prior to dam removal and this channel was incorporated into the initial delta topography. No pilot channel was constructed along the Lake Aldwell delta.

The numerical model assumed that the lower limit of reservoir sediment erosion was the surface of the predam reservoir. The predam reservoir surface for Lake Mills was developed from a 10-foot contour map produced from a 1921 topographic survey, conducted prior to the construction of Glines Canyon Dam. The horizontal and vertical coordinates of the predam contour map had to be adjusted to match modern datums. In addition, the predam map required some rectification so the topographic alignment of the valley walls better matched the modern LiDAR and bathymetric survey measurements.

No predam topographic map was available for Lake Aldwell, so the predam surface was initially based on the 2010 bathymetric survey conducted prior to dam removal (Bountry et al., 2011), sediment thickness estimates from a geologic investigation (Gilbert and Link, 1995), a predam map of the river channel alignment, and estimates of longitudinal channel slope and valley bottom width. Updated estimates of sediment thickness were made during dam removal as tree stumps were exposed on the predam surface and from additional thickness probe measurements.

The polygons that delineated planimetric areas of reservoir sediment with different grain size proportions were based on geologic investigations of Gilbert and Link (1995). The polygons are presented in Figure 2. The sediment volume, thicknesses, and spatial extent for each polygon are presented in Table 1 and Table 2 for Lake Aldwell and Lake Mills. Prior to dam removal, a series of drill holes through the sediments in each reservoir provided data on sediment thickness and grain size. In addition, sediment samples from hand-dug test pits and natural erosion channels provided additional size-gradation data of the delta surface. These data were used to delineate and characterize different areas of delta, pro-delta, and lakebed sediments for each reservoir. The main Lake Mills delta was delineated into upstream and downstream areas, each with three vertical layers. The other delta areas of Lake Mills (Rica Canyon, Cat Creek, and Boulder Creek) were each modeled as one vertical layer. The pro-delta area and two lakebed areas also were each modeled as one vertical layer. All planimetric areas of Lake Aldwell were modeled as one vertical layer.

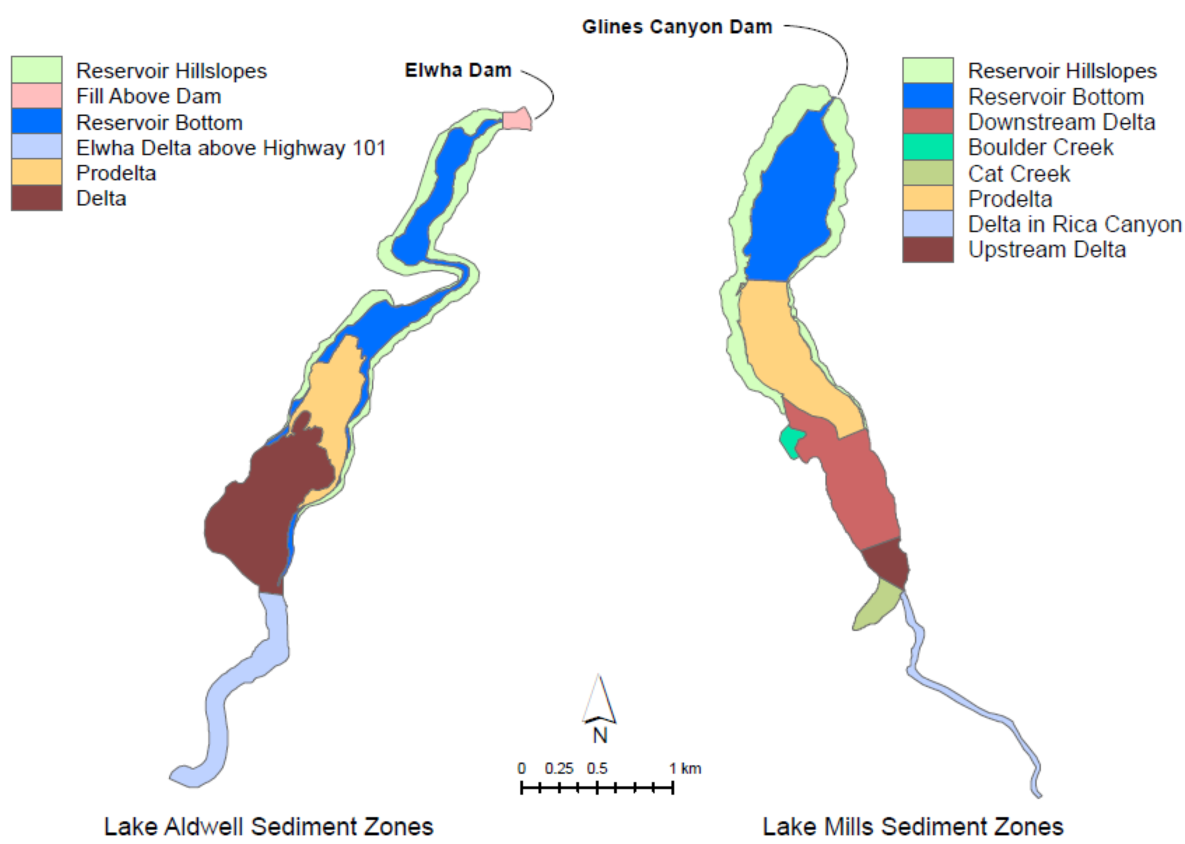


Figure 2. Reservoir sediment polygons in Lake Aldwell (left) and Lake Mills (right) based on conditions in 2010, prior to the start of dam removal (Randle, et al. 2015).

Table 1. Lake Aldwell sediment volume, thicknesses, and spatial extent (Bountry et al., 2018)

Surface	Sediment volume (10^6 yd^3)	Sediment volume (% of total)	Surface area (% of total)	Average sediment thickness (ft)	Coarse Sediment Portion
Elwha Delta Upstream Hwy 101	0.09	1%	13%	1.1	100%
Delta	3.2	51%	30%	16	51% to 90%
Pro-delta	1.1	17%	14%	11	14%
Reservoir Bottom	1.3	20%	20%	9.4	4% to 11%
Reservoir Hillslopes	0.43	7%	22%	2.9	4%
Fill Above Dam	0.24	4%	1%	27	No data
Totals	**6.4**	**100%**	**100%**		

Table 2. Lake Mills sediment volume, thicknesses, and spatial extent (Bountry et al., 2018)

Zone	Sediment volume (10^6 yd^3)	Sediment volume (% of total)	Surface area (% of total)	Average sediment thickness (ft)	Coarse Sediment Portion
Delta in Rica Canyon	1.4	7%	4%	47	95%
Upstream Delta	8.4	8%	5%	60	77% to 94%
Downstream Delta	1.6	41%	16%	64	47% to 95%
Pro-delta	5.0	24%	21%	31	11%
Reservoir Bottom	3.4	16%	25%	18	2%
Hillslope	No data		26%	No data	
Cat Creek	0.8	4%	3%	37	95%
Boulder Creek	0.23	1%	1%	28	95%
Totals	**21**	**100%**	**100%**		

The proportions of coarse and fine sediment, for each planimetric area and vertical layer, were based on composite sediment-particle-size gradations determined from the sediment sampling program (Gilbert and Link, 1995).

Simulation of Reservoir Sediment Erosion Processes

The simulation of reservoir sediment erosion model utilized a pre-processing FORTRAN program, mass balance model, and a post-processing FORTRAN program.

Pre-Processing Program

The model simulation began with the pre-processing program to determine the various simulation time periods and inputs of water discharge and sediment loads for the mass balance model (see Boundary Conditions). The pre-processing program computed the daily upstream loads of coarse and fine sediment. The pre-processing program also determined the downstream boundary reservoir water surface elevations and the simulation time periods for the mass balance model. These simulation time periods incorporated the reservoir drawdown increments and subsequent hold periods. The time periods were variable and typically ranged from days to months.

The fine and coarse sediment loads flowing into Lake Mills were computed from sediment-discharge rating curves that were calibrated to match the measured sediment deposition in Lake Mills (Randle et al., 1996).

$$Q_{Sc} = 1.915 \times 10^{-10} \times {Q_w}^{3.734} \quad \text{when } Q_w < 1{,}970 \text{ ft}^3\text{/s} \tag{1}$$

$$Q_{Sc} = 3.470 \times 10^{-06} \times {Q_w}^{2.442} \quad \text{when } Q_w \geq 1{,}970 \text{ ft}^3\text{/s} \tag{2}$$

$$Q_{Sf} = 1.748 \times 10^{-10} \times {Q_w}^{3.542} \quad \text{when } Q_w < 2{,}250 \text{ ft}^3\text{/s} \tag{3}$$

$$Q_{Sf} = 3.000 \times 10^{-10} \times {Q_w}^{3.475} \quad \text{when } Q_w \geq 2{,}250 \text{ ft}^3\text{/s} \tag{4}$$

Where Q_{Sc} is the coarse sediment load in tons/day,

Q_{Sf} is the fine sediment load in tons/day,

Q_w is the water discharge in ft^3/s, The daily predicted outputs of water discharge and fine and coarse sediment loads from Lake Mills were assumed to equal the daily inputs to Lake Aldwell. This model assumption ignored any water storage or sediment deposition along the Elwha River between the two reservoirs.

Daily reservoir water surface elevations (downstream boundary condition) were determined by the model based on the following information:

- Planed dam removal and reservoir drawdown schedule
- Daily reservoir inflow discharge
- Reservoir drawdown rate restrictions
- Reservoir drawdown increment limits
- Required reservoir hold periods after each drawdown increment and during certain time periods

After each 10 to 15 ft of reservoir drawdown, hold periods of two weeks were required before then next drawdown increment. In addition, reservoir drawdown was not permitted during certain time periods know as fish windows:

- May 1st to June 30th
- August 1st to September 15th
- November 1st to December 31st

The model assumed that dam removal could not progress when reservoir inflow exceeded certain discharge thresholds that inundated the construction work area:

- 2,300 ft^3/s for Glines Canyon Dam
- 15,000 ft^3/s for Elwha Dam

Mass Balance Model

For each simulation time period, the mass balance model computed the volumes of reservoir sediment erosion, redeposition, and transport past the dam. The model also determined the complex topographic and bathymetric surfaces of the reservoir sediment at the end of each time period.

While a reservoir pool remained, all the eroding coarse sediment, and a portion of the fine sediment, were assumed to deposit within the receded reservoir. Therefore, the volume of coarse sediment redeposition was forced to match the net upstream volume of coarse sediment erosion. The model maintained a strict sediment-mass balance between the incoming loads of coarse and find sediment, erosion of the exposed reservoir delta, redeposition within the reservoir, and transport past the dam. Sediment unit wights, or bulk densities, were specified to convert between volume and mass. Once the eroding delta had reached the dam and there was no longer a reservoir pool, and all eroding sediment was assumed to transport past the dam.

The erosion volume of the exposed reservoir delta was initially computed as a function of the reservoir-drawdown increment (D_{AMT}), longitudinal erosion slope (S_E), peak discharge, and the erosion width (W) (Figure 3). The width of the erosion channel reaches a maximum where the channel meets the receded reservoir (see Sediment Erosion and Deposition Volume Calculations). The area of wide lateral delta erosion was caused by redeposition of sediment across the width of the receded reservoir. This area was referred to as the "delta sweep" (Figure 4).

The topset slope of new delta deposition (S_T) was assumed to be less than the upstream delta erosion slope (S_E). Therefore, some sediment deposition occurs along the delta erosion channel at a deposition slope (S_D). This process was discovered at Lake Mills during the first year of dam removal and subsequently added to the model. The deposition along the delta erosion channel meant that the maximum incision depth was less than reservoir drawdown increment (D_{AMT}).

The fine sediment fraction of the erosion volume was assumed to enter the receded reservoir as suspended load. Using a sediment trap efficiency equation (Pemberton and Lara, 1971), the model calculated the portion of fine suspended sediment that settled to the reservoir bottom and the portion that transported in suspension past the dam (see Reservoir Sediment Trap Efficiency Calculations). All the sediment volume calculations, and determination of new topographic and bathymetric surfaces, were performed in the geospatial information system (GIS) model (see GIS Spatial Model).

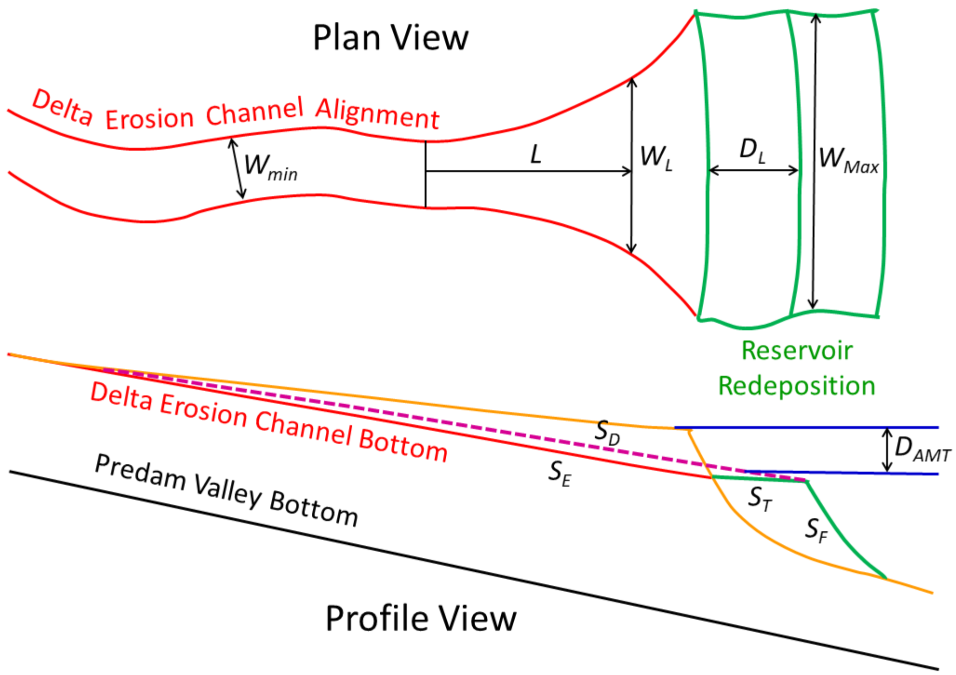


Figure 3. Plan and profile sketch of reservoir sediment erosion and redeposition volumes. The variables shown in the figure are described in the body of the paper.

Figure 4. Photographs of the delta sweep showing actual sediment erosion and redeposition at Lake Mills as of August 2011 (16 ft of spillway drawdown prior to dam removal) and a laboratory model of Lake Mills (Bromley, 2007).

Sediment Erosion and Deposition Volume Calculations

Computations of the river-erosion volume began with each reservoir drawdown increment. The downstream extent of the erosion channel was computed as the intersection of the erosion channel and the receded reservoir. At the downstream end of the delta erosion channel, the bottom elevation was initially assumed to equal the lowered reservoir-water surface elevation. From this elevation, the user specified longitudinal erosion slope (S_E) was projected upstream to the intersection with the upstream delta surface or the predam surface, whichever was encountered first. The centerline alignment of the delta erosion channel was specified by the model user. In the predictive mode, the model computed the left and right bank lines of the delta erosion channel from the specified channel centerline and the computed erosion-channel widths. In monitoring mode, the measured alignments and slope of the delta erosion channel centerline, and the alignments of the left and right banks, were specified. The use of monitoring data in the model helped to improve subsequent predictions for the remainder of the dam removal simulation.

In the predictive mode, the model computed the minimum erosion-channel width (W_{min}) as a function of the peak discharge for a given time period.

$$W_{min} = aQ_w{}^b \tag{5}$$

where W_{min} is the minimum width of the delta erosion channel (Figure 3).
The exponent b is chosen from literature (typically, $b = 0.5$) while the coefficient a is calibrated from measured erosion widths ($a = 5.95$ for English units).

During the first year of dam removal, extensive lateral erosion was observed on the surface of the Lake Mills delta, which was composed of cohesionless, coarse sediment. Therefore, an additional function was included in the model to increases the minimum erosion channel width based on the number of days (during the simulation time period) when the discharge exceeded a threshold.

$$W'_{min} = [(\beta \ T_D) + 1]\, W_{min} \tag{6}$$

Where W'_{min} is the increased minimum delta erosion channel width,

β is an empirical coefficient (0.0667 / day),
T_D is the number of days where $Q_W > Q_{TH}$
Q_{TH} is the discharge threshold (e.g., average discharge for the time period)

The erosion channel width increased with distance toward the receded reservoir where it reaches a maximum (W_{max}) (Figure 3). Computed erosion widths were always constrained by the width of the reservoir valley.

$$W_L = 2cL^2 + W_{min} \tag{7}$$

where W_L is the erosion width at a downstream distance L.

c is a coefficient computed by the model so that the erosion channel width equals the reservoir deposition width at the intersection with the reservoir.

L is the longitudinal downstream distance along the erosion channel centerline and begins ($L = 0$) where the minimum erosion width (W'_{min}) begins to increase due to downstream delta deposition in the receded reservoir. The origin ($L = 0$) is at a distance upstream from the receded reservoir (L_{Max}) and is computed as a function of the local reservoir width.

$$L_{Max} = f\, W_{max} \tag{8}$$

f is a coefficient multiplier of the local reservoir width (typically between 1.0 and 3.0).

The model computed the coarse sediment volume that redeposited within the receded reservoir from the length of the new delta topset (D_L), topset and foreset delta slopes (S_T and S_F), and the deposition width across the receded reservoir (W_{max}) (Figure 3). The reservoir deposition length (D_L) was computed as a function of the delta topset width (W_{max}) and the deposition volume. The delta topset and foreset slopes were specified by the model user. A minimum delta topset length (D_{L-min}) was also specified in the event the deposition volume was insufficient to spread laterally across the entire width of the reservoir. This was the case during the first increment of Lake Mills drawdown (see Figure 4). For subsequent reservoir drawdown increments, the erosion volumes, and corresponding deposition volumes, were enough to spread across the entire reservoir width and the computed delta topset length (D_L) was greater than the minimum (D_{L-min}).

The model determined the reservoir deposition width (W_{max}) and length (D_L) by trial and error so that the coarse sediment deposition volume matched the coarse delta erosion volume to within 1 percent. If the reservoir-deposition width was less than the local reservoir width, then the user specified topset length (D_{L-min}) was applied. However, if the reservoir-deposition width equals the local reservoir width, then the model calculates the topset length (D_L) so the deposition volume matches the upstream erosion volume.

Reservoir Sediment Trap Efficiency Calculations

While a reservoir pool remained, the mass balance model computed the sediment trap efficiency to predict the portion of fine suspended sediment that deposited evenly over the reservoir bottom (between the delta and dam) and the portion that was transported past the dam.

$$V_{Df} = V_{Ef}\, P \tag{9}$$

$$V_{Tf} = V_{Ef}\ (1 - P) \tag{10}$$

Where V_{Df} is the fine sediment deposition volume,

V_{Ef} is the fine sediment erosion volume,

P is the fine sediment trap efficiency,

V_{Tf} is the fine sediment volume transported past the dam.

All the coarse sediment erosion volume was assumed to redeposit within the receded reservoir until there was no longer a reservoir pool.

$$V_{Dc} = V_{Ec} \qquad \text{and} \qquad V_{Tc} = 0 \tag{11}$$

Where V_{Dc} is the coarse sediment deposition volume,

V_{Ec} is the coarse sediment erosion volume,

V_{Tc} is the coarse sediment volume transported past the dam.

Once the delta had reached the dam and there was no longer a reservoir pool, all the eroding coarse and fine sediment were assumed to transport past the dam.

$$V_{Dc} = 0 \qquad \text{and} \qquad V_{Tc} = V_{Ec} \tag{12}$$

$$V_{Df} = 0 \qquad \text{and} \qquad V_{Tf} = V_{Ef} \tag{13}$$

While a reservoir pool remained, the fine sediment trap efficiency (P) was computed as a function of the particle fall velocity (ω), inflow discharge (Q_w), 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, °F) (Pemberton and Lara, 1971).

$$P = \left(1 - \frac{1}{e^{\left(\frac{1.005\omega A_S}{Q_W}\right)}}\right) \tag{14}$$

$$\omega = \frac{\sqrt{36.064\ d^3 + (6\ \nu)^2} - 6\ \nu}{d} \tag{15}$$

$$\nu = \frac{0.00002}{(1.0334 + 0.03672\ T + 0.0002058\ T^2)} \tag{16}$$

GIS Spatial Model

Using the previously described methods and equations, the complex topographic and bathymetric surfaces of the reservoir were simulated using customized GIS software for each time period. The spatial model consisted of a set of vector-based customizations and a series of raster-based analysis tools that were run for each time period according to the reservoir drawdown schedule. The vector-based customizations were used to determine potential erosion geometries as well as the geometry for coarse sediment deposition. Once determined, the vector geometries were fed into the raster-based analysis tools that updated an input surface raster to reflect computed sediment inflow, erosion, redeposition, and transport past the dam. All raster analyses in the spatial model were performed using a 10 ft × 10 ft cell size. The collection of raster layers in the spatial model included static baseline layers as well as layers that were generated after each time period. The following baseline raster layers were provided as user input:

- Initial top surface of the reservoir sediment (above and below water)
- Predam reservoir surface
- Polygons delineating planimetric areas of reservoir sediment
    - Top surface of any vertical layers within a polygon area
    - Proportions of coarse and fine sediment within each area and layer.

Raster layers generated after each time period are listed below:

- Reservoir sediment surface at the end of the time period
- Total reservoir sediment erosion
- Incremental coarse sediment erosion within the time period
- Cumulative coarse sediment erosion
- Incremental fine sediment erosion within the time period
- Cumulative fine sediment erosion
- Incremental coarse sediment deposition within the time period
- Cumulative coarse sediment deposition
- Incremental fine sediment deposition within the time period
- Cumulative fine sediment deposition
- Post-deposition surface

Post-Processing Program

The post-processing program used the computed sediment erosion volumes from the mass balance model (for each simulation time period) to compute the daily fine and coarse-sediment release rates passing the dam. Time-distribution factors were computed for each day of the simulation time period to allocate the daily sediment release volumes. Unit weights, or bulk densities, were specified for the fine and coarse sediment to convert the volumes to mass. In the equations below, (t_n) indicates the value at day n and t_o indicates the value at the beginning of the simulation time period.

$$V_{Tf}(t_n) = D_F(t_n)\ (1-P)V_{Ef} \tag{17}$$

$$V_{Tc}(t_n) = D_F(t_n)\ V_{Ec} \tag{18}$$

$$M_{Tf}(t_n) = V_{Tf}\ \Upsilon_f \tag{19}$$

$$M_{Tc}(t_n) = V_{Ec}\ \Upsilon_c \tag{20}$$

Where $V_{Tf}(t_n)$ is the daily volume of fine sediment transporting past the dam,

$V_{Tc}(t_n)$ is the daily volume of coarse sediment transporting past the dam,

$D_F(t_n)$ is the daily time distribution factor,

V_{Ef} is the fine sediment erosion volume for the time period,

P is the reservoir trap efficiency for fine sediment,

V_{Ec} is the coarse sediment erosion volume for the time period,

$M_{Tf}(t_n)$ is the daily mass of fine sediment transporting past the dam,

$M_{Tc}(t_n)$ is the daily mass of coarse sediment transporting past the dam,

Υ_f is the unit weight for fine sediment, and

Υ_c is the unit weight for coarse sediment.

The daily time-distribution factors were used to temporarily distribute the sediment erosion volumes over each model time period. Rather than assuming the rate of sediment erosion is constant over each model time period, the time distribution functions temporarily distribute the sediment erosion volume based on the temporal patterns of the reservoir water surface and the inflow discharge. The daily time-distribution factor (D_F) was computed as a function of the daily reservoir drawdown factor (R_F) and the daily discharge factor (Q_F). The daily factors for each simulation time period must sum to one.

$$D_F(t_n) = c_7 R_F(t_n) + (1 - c_7) Q_F(t_n) \tag{21}$$

Where $R_F(t_n)$ is the daily reservoir drawdown factor based on changes in reservoir water surface elevation,

$Q_F(t_n)$ is the daily discharge factor based on changes in reservoir inflow, and

c_7 is a user specified coefficient that weights the relative importance of $R_F(t_n)$ and $Q_F(t_n)$.

The computation of the daily reservoir drawdown factor (R_F) depends on whether the reservoir was drawing down, holding, or refilling. The daily reservoir drawdown increment (D_{INC}) and cumulative drawdown for the period (D_{AMT}) were computed from the daily water surface elevations (WSE). The change in mean-daily discharge (ΔQ_w) was also computed.

$$D_{INC}(t_n) = WSE(t_n) - WSE(t_{n-1}) \tag{22}$$

$$D_{AMT}(t_n) = WSE(t_n) - WSE(t_o) \tag{23}$$

$$\Delta Q_w(t_n) = Q_w(t_n) - Q_w(t_{n-1}) \tag{24}$$

If the reservoir was drawing down where $D_{INC}(t_n) \leq c_3$ = -0.50 ft/day, then the daily reservoir drawdown factor was exponentially weighted by the incremental amount of drawdown.

$$R_F(t_n) = \frac{0.020(c_1)^{\left(\frac{-1 D_{AMT}(t_n)}{1.5ft}\right)}}{\sum R_F(t_n)} \tag{25}$$

Where c_1 is a user-specified factor to increase the sediment concentration over time factor during continued reservoir drawdown.

If the reservoir was holding or refilling where $D_{INC}(t_n) \geq c_3$, then the daily reservoir drawdown factor was incrementally decreased each day.

$$R_F(t_n) = \frac{c_2\, R_F(t_{n-1})}{\sum R_F(t_n)} \tag{26}$$

Where c_2 is a user-specified factor to decrease the sediment concentration over time during continued reservoir holding or refilling. This coefficient was applied for a limited number of days ($IDAYS_{max}$) from the beginning of the simulation time period and set equal to one for the remaining days of the simulation period.

c_3 is a threshold for the change in reservoir water surface to distinguish between drawdown and holding or refilling.

If the reservoir inflow discharge was significantly increasing [$\Delta Q_w(t_n) >$ 1,000 ft^3/s/day] or if the inflow discharge was high [$Q_w(t_n) >$ 3,500 ft^3/s, then the daily reservoir drawdown factor was exponentially weighted by the daily discharge.

$$R_F(t_n) = \frac{R_F(t_n)(c_1)^{\left(\frac{Q_W(t_n)}{1000 ft^3/s}\right)}}{\sum R_F(t_n)} \tag{27}$$

The discharge factor was computed as a function of the discharge raised to a power.

$$Q_F(t_n) = \frac{(Q_W)^{c_4}(t_n)}{\sum(Q_F)(t_n)} \tag{28}$$

Where c_4 is user-specified exponent to for weighting the discharge.

The model computed the concentration of fine sediment (ppm) transported past the dam from the mass transport rate and the mean-daily river discharge (Q_w). A time lag was also applied to account for travel time through the reservoir. The time lag varies with each simulation time period.

$$Conc\ (t_{n+Lag}) = \frac{M_{Tf}(t_n)}{Q_W(t_n)}\left(\frac{2{,}000\ lbs/ton}{(62.4\ lbs/ft^3)(3{,}600\ s/hr)(24hr/day)}\right)1{,}000{,}000 \tag{29}$$

$$Lag = \frac{V_R}{[\overline{Q_W}(3600s/hr)(24hr/day)]} \tag{30}$$

Where $Conc\ (t_{n+Lag})$ is the fine sediment concentration released past the dam after a time lag,

Lag is the time (days) for water to flow through the reservoir,

V_R is the reservoir volume, and

$\overline{Q_W}$ is the average reservoir inflow discharge for the simulation period.

Turbidity was computed from the concentration by use of a power equation.

$$Turbidity\ (t_{n+Lag}) = c_5[conc(t_{n+Lag})]^{c_6} \tag{31}$$

Where c_5 and c_6 are a user-specified coefficient and exponent to convert concentration to turbidity.

Summary List of Model Input Parameters

Lists of model input parameters:

- Delta erosion parameters (Table 3)
- Delta deposition parameters (Table 4)
- Reservoir sediment trap efficiency parameters (Table 5)
- Daily sediment release parameters (Table 6).

Table 3. Delta erosion channel input parameters

Variable	Description	Equation or Figure
a and b	Coefficient and exponent used to compute the minimum erosion-channel width as a function of discharge.	Eq. 5
β	Coefficient to estimate the increase in minimum erosion-channel width as a function of the number of days (T_D) where discharge exceeds a threshold (Q_{TH}).	Eq. 6
Q_{TH}	Discharge threshold where the minimum erosion-channel width begins to increase.	Eq. 6
f	Coefficient used to compute the maximum erosion channel length (L_{max}) that is influenced by new delta deposition.	Eq. 8
S_E	Initial longitudinal slope of the delta erosion channel. • For Lake Mills, a steeper delta erosion slope was specified for the coarse sediments within Rica Canyon than downstream. • For Lake Aldwell, a steeper delta erosion slope was specified for the coarse river sediments upstream from the Highway 101 Bridge than downstream.	Figure 3
S_D	Finial longitudinal slope of the delta erosion channel after some deposition.	Figure 3

Table 4. Delta deposition input parameters for the receding reservoir

Variable	Description	Equation or Figure
D_L	Minimum topset length (feet).	Figure 3
S_T	Topset slope.	Figure 3
S_F	Foreset slope.	Figure 3

Table 5. Reservoir sediment trap efficiency input parameters

Variable	Description	Equation
d	Median particle size of fine sediment (d = 0.010 mm).	Eq. 15
T	Water temperature (T = 50 degrees Fahrenheit).	Eq. 16

Table 6. Post-processing model input parameters for computing the daily sediment release

Variable	Description	Equation
Υ_f	Unit weight of fine sediment (70 lbs/ft^3).	Eq. 19
Υ_c	Unit weight of coarse sediment (100 lbs/ft^3).	Eq. 20
c_1	Factor to increase the sediment concentration over time factor during continued reservoir drawdown (c_1 = 1.10).	Eq. 25 & 27
c_2	Factor to decrease the sediment concentration over time during continued reservoir holding or refilling (c_2 = 0.97).	Eq. 26
$IDAYS_{max}$	Maximum number of days, from the beginning of the simulation-time period, where the user specified value of c_2 was used. c_2 was set equal to one for the remainder of the time period ($IDAYS_{max}$ = 30 days).	Eq. 26
c_3	Threshold for the change in reservoir water surface to distinguish between drawdown and holding or refilling (c_3 = -0.50 ft/day).	Eq. 25
c_4	Exponent for weighting the discharge (c_4 = 3.50).	Eq. 28
c_5	Coefficient to convert sediment concentration to turbidity (c_5 = 0.892).	Eq. 31
c_6	Exponent to convert sediment concentration to turbidity (c_6 = 1.0044).	Eq. 31
c_7	Coefficient for weighting the relative importance of daily reservoir drawdown [$R_F(t_n)$] and discharge [$Q_F(t_n)$] factors (c_7 = 0.3333).	Eq. 21

Model Calibration

The numerical mass balance model had several calibration parameters related to reservoir delta erosion, deposition, sediment trap efficiency, and the time distribution of sediment transported past the dam. In purely predictive mode, best estimates of model parameters had to be specified for the entire simulation. As dam removal progressed and monitoring data became available, input parameters were adjusted over time to reflect the ever changing conditions of the reservoir sediment erosion.

The parameters related to delta erosion and redeposition can be reasonably estimated or directly measured and calibration is not necessary. The delta channel erosion widths, lengths of the delta erosion sweep, and longitudinal erosion slopes were calibrated separately for Lake Mills and Lake Aldwell. The model was calibrated with data from the early part of dam removal and reservoir drawdown. The alignment of the delta erosion channels evolved with time and were determined based on measurements and professional judgment. The median grain size for fine sediment deposition was calibrated to a value of 0.01 mm, which represents fine silt.

The parameters related to the daily time distribution of sediment transport past the dam require calibration and professional judgement. Post processing model parameters were calibrated to match the pattern and magnitude of turbidity measured downstream from Elwha Dam from the first part of dam removal. Additional and more rigorous calibration could have performed for the post processing parameters (coefficients c_1 through c_7), however these parameters only affect the daily time distribution within a model time period and not the sediment erosion volumes for that time period.

Longitudinal Delta Slopes

The model user must specify the longitudinal slopes of the channel eroding the exposed delta surface in response to reservoir drawdown (Figure 3). This includes the initial erosion slope (S_E) and subsequent deposition slope (S_D). The delta erosion slopes of the model are user specified in the predictive mode. These could have been estimated using a transport function, but were initially estimated based on measured results from the 1994 Lake Mills drawdown experiment (Childers, et al., 2000).

For Lake Mills, the delta slope was assumed to be steeper within Rica Canyon (above the former reservoir pool area) than within the reservoir pool area. The slope within Rica Canyon was assumed to be 0.088 for the duration of the model. This slope was steep enough to limit erosion in Rica Canyon during the early simulation time periods based on river stage measurements from the USGS gage at the mouth of Rica Canyon (Figure 5). Measurements indicate the erosion near Rica Canyon was initially limited during low flow periods by large cobbles and wood.

Field measurements show that episodic erosion occurred during high flows combined with reservoir drawdown (Randle, et al., 2015). Some channel armoring occurred along the upstream portions of both the Lake Mills and Lake Aldwell deltas, which resulted in delayed erosion. However, continued reservoir drawdown and periodic high flows eroded these armor layers. Sand was the predominate gain size of the deltas and erosion slopes were sometimes less steep than the predam channel which was composed of cobbles and boulders. A one-dimensional sediment transport model would be needed to more fully simulate the complex relationships between discharge, grain size, and knickpoint erosion induced by reservoir drawdown. The mass balance model relies on empirical measurements of the erosion slope and how they change over time as the incising channels encounter finer sediment particles at deeper depths.

The measured water surface elevation at the mouth of Rica Canyon and the downstream distance to the delta front was used to compute the channel erosion slope for several model time periods. The slope of the Lake Mills delta erosion channel downstream from Rica Canyon varied from 0.005 to 0.017 during dam removal. After dam removal, the erosion slope was assumed to match the predam channel slope, 0.007 based on the average slope along the Elwha river reach between Glines Canyon Dam and the USGS gage at McDonald Bridge. The maximum slope of 0.017 was comparable to the measured river slope of the Elwha River within the first river mile downstream from Glines Canyon Dam. Selected longitudinal profiles, simulated for Lake Mills, are presented in Figure 6 along with a measured profile from February 2012.

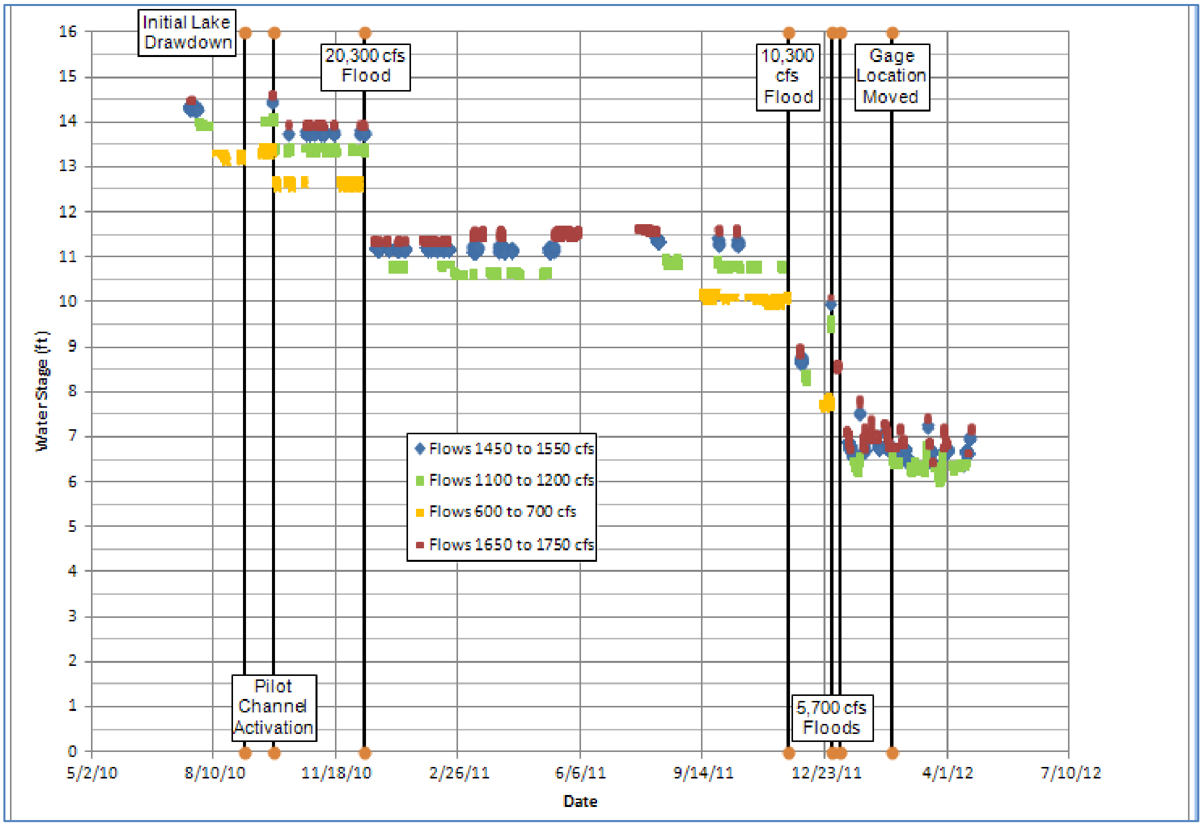


Figure 5. Time series of measured Elwha River stage, corresponding to selected discharge ranges. The decreases in river stage over time indicate when the channel bed eroded. Measured river stage was from the USGS gage above Lake Mills (at the mouth of Rica Canyon). Total channel incision during the first two years of dam removal was about 7 to 8 ft and occurred incrementally after excavation of the pilot channel (minor), during December 2010 flood, and during November and December 2011 floods.

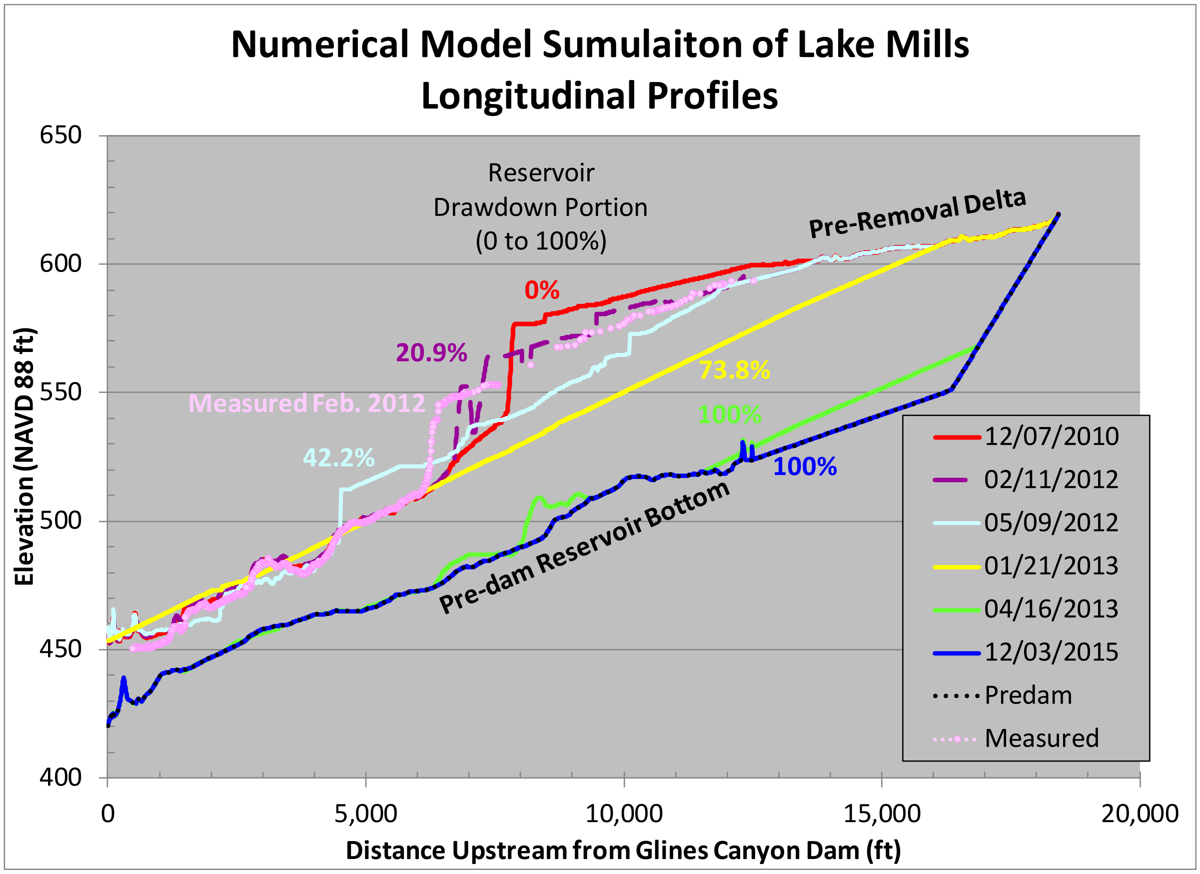


Figure 6. Selected simulated longitudinal profiles of Lake Mills sediment erosion and redeposition during and after dam removal. A measured profile from February 2012 is presented for comparison.

For Lake Aldwell, the delta erosion channel slope was assumed to be steeper upstream from the Highway 101 Bridge (upstream extend of former reservoir pool) than downstream. The slope upstream of Highway 101 was assumed to be 0.0113 for the initial model runs to limit upstream incision until a flood occurred during the fish window from November to December 2011. Prior to the flood, actual upstream erosion was limited due to a large log jam that formed a hydraulic grade control for the upstream river channel. During the November 2011 flood, the log jam was mostly washed out and the channel incised about 5 to 6 ft near the Highway 101 Bridge. After this flood, the upstream erosion channel slope was set to 0.0059.

The erosion slope for Lake Aldwell delta was computed from measurements of Elwha River stage at the Highway 101 Bridge and modeled longitudinal channel distance to the delta front. The delta erosion channel slope was initially set at 0.0040 based on measurements from the October 2011 survey. Following the November and December 2011 floods, the slope varied from 0.0017 to 0.0062, gradually steepening over time (Table 7). Figure 7 shows the various simulated longitudinal slopes of Lake Aldwell over time. The erosion channel slope temporarily flattened when the upstream end of the reservoir pool receded to the constricted reach located along the middle of the former reservoir (locally referred to as the gooseneck). The gooseneck constriction caused an upstream backwater and flatter slope until the reservoir was drawn down past the constriction and the river adjusted to a steeper channel. Specific to Lake Aldwell, the upper portion of the erosion channel (station 9,000 to 15,000 ft in Figure 7) eroded down to the predam terrace where numerous tree stumps were present. The predam map indicates that the Elwha River channel was along the left (west) side of the valley and not yet accessed by the delta erosion channel. Because the model limits erosion to the predam surface, the upstream point used to compute slope was shifted to a new location as shown in Figure 7 at about station 9,000 ft.

Table 7. Specified Lake Aldwell model erosion slope through lower reservoir

Date	Lake Aldwell W.S. Elevation (ft)	Erosion Slope
Mar 2012	155.8	0.0017
Apr 2012	151.8	0.0023
May 2012	136.8	0.0038
July 2012	120.8	0.0051
July 2012	103.2	0.0062

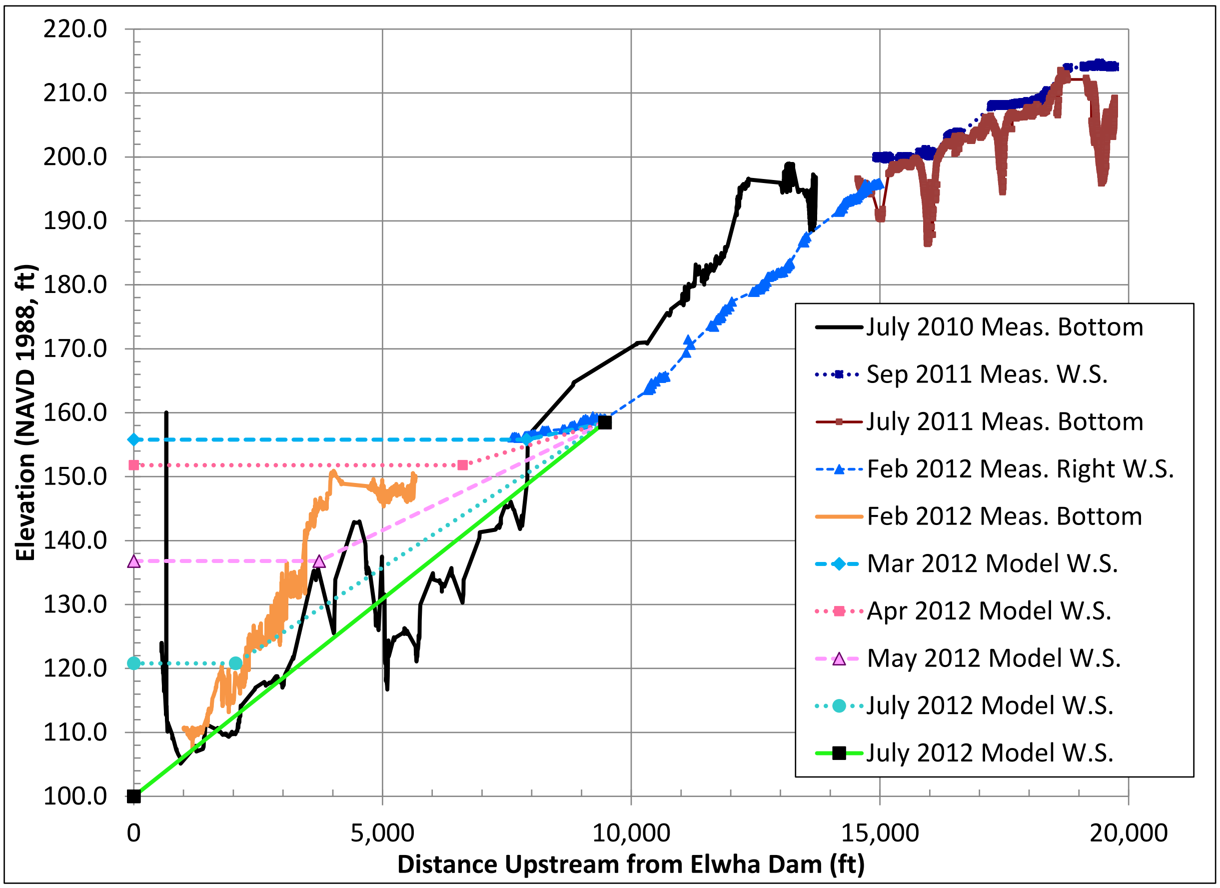


Figure 7. Comparison of surveyed and modeled profiles of Lake Aldwell for the period from February 2012 through end of dam removal.

The delta topset slope was assumed to be 0.0008 for Lake Aldwell and 0.0050 for Lake Mills based on measured data from October 2011. The delta foreset slope was assumed to be 0.020 for Lake Aldwell and 0.032 for Lake Mills also based on measured data from October 2011. The foreset slope was steeper in Lake Mills because the delta sediments were much coarser than in Lake Aldwell.

Delta Erosion Channel Centerline

In the predictive mode, the centerline alignment of the erosion channel was specified and the erosion width was computed by the model. In the monitoring mode, the alignments and slopes of the erosion channel along both banks were specified. In the predictive model, the centerline alignment was delineated in GIS and based on available measurements in Lake Aldwell and Lake Mills (field surveys and photogrammetry) and on professional judgement. Historic alignments of the delta erosion channel, left and right banks, were measured from field surveys and photogrammetry.

Future migration of the erosion channel alignment was based on past migration and professional judgment. For Lake Mills, the future channel alignment was assumed to migrate over time as a result of floods and reservoir drawdown to gradually match the alignment of the predam river channel measured in 1921 (Figure 8). For Lake Aldwell, the predicted alignments were much more confined by cohesive sediment terraces, tree stumps, and canyon walls (Figure 9).

Delta Erosion Channel Width

The model can either compute the erosion channel width and the left and right bank alignments from the user-supplied channel centerline or the model can utilize measured bank erosion alignments along the exposed delta surface.

In predictive model, the model uses a regime equation and a time function to calculate the channel erosion width along the upstream portion of the delta (Eq. 5 and Eq. 6). In Lake Mills, the upstream most erosion width computed by the model was generally constrained by the walls of Rica Canyon. From the mouth of Rica Canyon, the erosion width was increased at a linear rate with distance downstream to match the computed erosion width. For Lake Aldwell, the upstream most erosion width was generally not limited, so a transition reach was not needed. For both reservoirs, the model computes that the erosion width will increase at a parabolic rate as the exposed delta channel intersects the receded reservoir (Figure 3, Eq. 7 and Eq. 8).

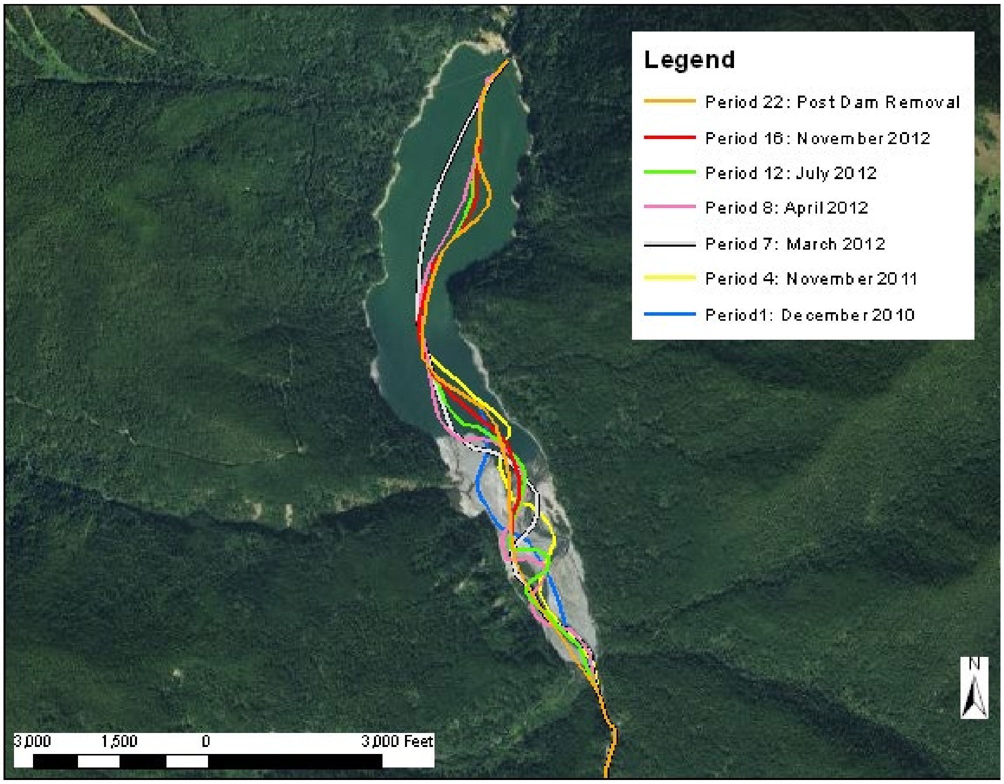


Figure 8. Example of Lake Mills measured (pre-April 2012) and estimated (post-April 2012) erosion channel centerlines used by the model.

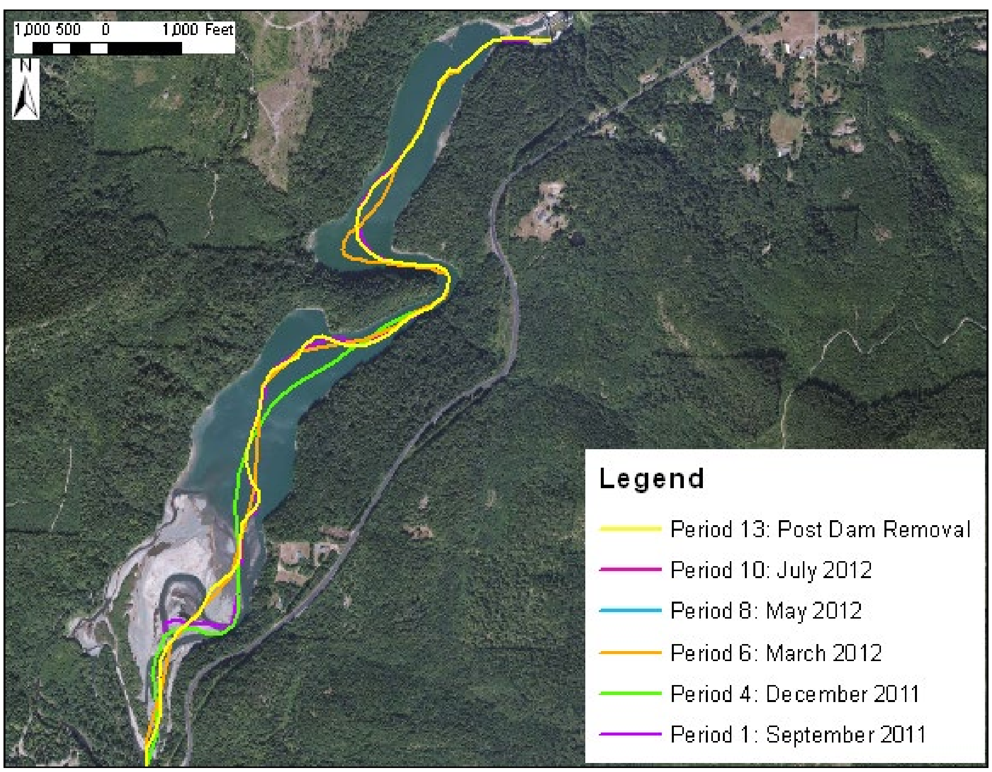


Figure 9. Example of Lake Aldwell measured (Pre-April 2012) and estimated (post-April 2012) erosion channel centerlines used by the model.

For both Lake Mills and Lake Aldwell, the exponent *b* in Eq. 5 was assumed to be a constant value of 0.5, which is commonly assumed (Soar and Thorne, 2001). The coefficient, *a*, was calibrated at a typical alluvial section of the delta channel based on measured widths following floods during the reservoir drawdown period. The coefficient, *a*, depends on the cohesive properties of the reservoir sediment terraces. Values of coefficient, *a*, are highest for non-cohesive sediments and lowest for cohesive sediments The upper layers of the delta were primarily composed of coarse and non-cohesive sediments (sand and gravel) while the underlying sediment layers were composed of finer sediments with at least some cohesion. The lakebed sediments were typically fine with some cohesion. Therefore, the values of coefficient, *a*, were varied during the model simulation, depending on cohesive properties of the sediment being eroded.

For Lake Mills the coefficient, *a*, in Eq. 5 was initially calibrated to be 2.7 based on an erosion channel measurement of 380 ft following a 20,300 ft^3/s flood in December 2010 (Figure 10). However, the buried logs and roots from red alder trees likely provided some cohesion to the initial delta surface (Randle et al., 2015). By May 2012, the delta had incised tens of feet (incised below tree roots) and the width of lateral erosion had increased significantly. A new calibration for coefficient, *a*, yielded a value of 5.95, which was used for the rest of the model simulations.

Figure 10. Measurement point used on Lake Mills to calibrate the discharge versus width equation for the delta channel. Photograph taken July 12, 2011 by Heidi Hugunin of National Park Service.

Sedimentation in Lake Aldwell (downstream reservoir) tended to be composed of finer particles (53% fine sediment) and tended to be more cohesive than the sedimentation of Lake Mills (44% fine sediment). Therefore, values of coefficient, *a*, were smaller for Lake Aldwell than for Lake Mills.

For Lake Aldwell, the coefficient, *a*, was initially calibrated using data during the initial 18 ft drawdown in June 2011. The coefficient, *a*, was calibrated to be 2.3 near photo point 6 shown in Figure 11 following a high flow of 6,750 ft^3/s with a width of 185 ft. The remaining measurement locations were not utilized because of dynamic channel migration and delta erosion and deposition. By May 2012 the delta had incised several feet and the width of lateral erosion had increased significantly. A new calibration for coefficient, *a*, yielded a value of 4.3, which was used for the rest of the model simulations.

Figure 11. Oblique aerial photograph of points along the eroding Lake Aldwell delta channel during the initial reservoir drawdown, prior to the start of dam removal. Photograph courtesy of Richard Bauman from the Elwha Project Office.

For upper layers of the Lake Mills delta, the lateral erosion of cohesionless coarse sediment was even more extensive than predicted by the regime equation (Eq. 5). Therefore, the model employed an additional function (Eq. 6) to increases the erosion channel width based on the number of days that discharge exceeds a threshold discharge. The average discharge for the simulation period was used as the discharge threshold and a value of 0.0667 was used for the coefficient β. This means that the width of the erosion channel increased by 6.67 percent each day that the discharge exceeded the average for the simulation period. After the first few months of dam removal, lateral erosion of the initial Lake Mills delta was only constrained by the valley walls.

Length of Delta Sweep

The maximum length of the delta sweep (L_{max}) (Figure 3 and Eq. 8) was initially estimated to be equal to one local reservoir width based on 2011 aerial photography and field inspection following the initial 15 to 18 ft of drawdown at each reservoir prior to the start of dam removal. This value was used for the entire Lake Aldwell simulation. For Lake Mills, the maximum length of the delta sweep was equivalent to the width available for reservoir sediment deposition (Figure 4). Because the pre-dam removal delta had extended farther downstream along the left (west) side of the reservoir, the area available for deposition was limited to the right (east) side. However, once the reservoir delta had pro-graded downstream of the pre-dam removal delta, the upstream starting point of the delta sweep was held constant and the length of the delta sweep was allowed to increase to a maximum of three reservoir widths and then held constant. This assumption was based on new aerial photography from April 7, 2012 that indicated the length of delta sweep had exceeded one reservoir width (Figure 12).

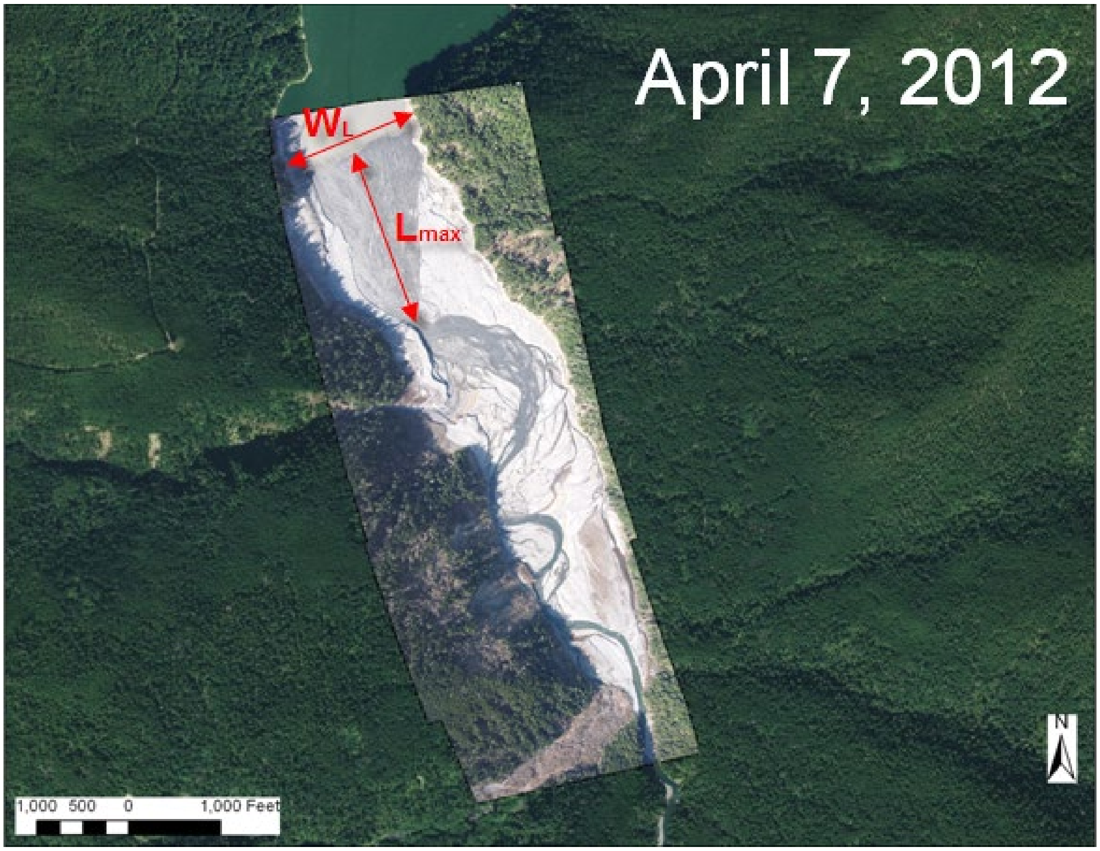


Figure 12. Aerial photograph of Lake Mills (April 2012) showing length and width of delta sweep. Aerial photograph generated by Andy Ritchie of the Elwha Project Office.

Reservoir Sediment Trap Efficiency

The reservoir sediment trap efficiency computation utilized by the model requires an estimate of the median grain size. Initially, the median grain size for fine sediment was estimated at 0.016 mm (break between fine and medium-sized silt) to represent the typical fine-sized sediment in the reservoir deltas. Based on initial turbidity data downstream of Elwha Dam from the first three months of dam removal (September to December 2011), the median grain size was reduced to 0.010 mm to decrease sediment trap efficiency and increase the amount of sediment being released from the reservoir. The temperature was assumed to be a constant 50 degrees Fahrenheit based on the average temperature measured at the reservoir staff gage locations.

Compaction of Fine Sediment

The simulation of fine sediment compaction over time was considered for the lakebed utilizing the method reported by Strand and Pemberton (1982) and Randle et al. (2006).

$$W_T = W_o + 0.4343\ K\left[\frac{T}{T-1} ln(T) - 1\right]$$

Where W_T is the average unit weight or bulk density after *T* years,

W_o is the initial unit weight (70 lbs/ft^3 for silt),
K is a constant based on the type of reservoir operation and sediment size (1.8 for silt with moderate to considerable reservoir drawdown), and
T is time in years.

Significant sediment compaction would result where fine sediments were present. Model calibration with the first set of reservoir survey data from October 2011 (one month into dam removal) indicated that model predictions more closely matched measured data if fine sediment compaction was not simulated. Fine lakebed sediments may have compacted after they were buried by the pro-grading coarse delta. However, fine sediment compaction was never simulated for Lake Mills nor Lake Aldwell.

Post-Processing Model Parameters

The coefficients c_1 and c_2 (Eq. 25, Eq. 26, and Eq. 27) control the daily rate at which the fine sediment erosion volume (for the model time period) is released from the reservoir. These two coefficients were calibrated to 1.10 and 0.97, respectively, to match the pattern of measured turbidity at the USGS gage (12046260) at the surface water intake and downstream from Elwha Dam (Figure 13 and Figure 14). The period of measured data used for calibration was September to December 2011.

The coefficient c_3 was used by the model to distinguish when the reservoir was being drawn down, holding, or refilling due to floods (Eq. 25). A value of -0.05 ft/day was used for c_3 and was not changed during the model simulation.

The exponent, c_4, was used to weight discharges within a model time period in order to compute the daily discharge factors (Eq. 28). This exponent was initially set equal to 1.00 which meant the daily discharges factors were the same every day during the simulation time period. Later, the exponent, c_4, was set equal to a value of 3.50 which significantly weighted the daily discharge factor toward the days with the highest discharge. This change was made after realizing that viable discharge within a model time period did have a significant effect on the time distribution of reservoir sediment erosion.

Coefficient c_5 and exponent c_6 were used to convert computed sediment concentration to turbidity (Eq. 31). Measured turbidity was recorded at the USGS gage below Elwha Dam in a Formazin Nephelometric Unit (FNU) (Figure 14). FNU is a measurement of turbidity commonly used in Europe and is similar to a Nephelometric Turbidity Unit (NTU). The difference is based on the wavelength of light used to make the measurement. Turbidity is a measurement of the light-absorbing and light-scattering properties of a liquid. In simplified terms, NTUs were measured with a white light, while FNUs were measured with an infrared light (or.water.usgs.gov/grapher/fnu.html).

Initially, a value of 0.6 was being used for coefficient, c_5, and a value of 1 was used for exponent, c_6, which reduced the formula to a linear equation. This correlation was based on measured turbidity data versus model predictions from August 2011 through April 2012 (Figure 14). The model predicted major trends of increasing or decreasing turbidity well. The largest differences between model predictions and measurements occurred during early calibration when the cofferdam at Elwha Dam breached and material was released into the downstream river channel. The mass balance model does not have the ability to simulate the breach of cofferdams. Later the value of coefficient, c_5, was set to 0.892 and the exponent, c_6, was set to 1.0044.

Coefficient, c_7, (Eq. 21) was set to a value of 0.3333, which meant that the combined daily time distribution factor was computed using a one-third weighting of the daily drawdown factor and a two-thirds weighting of the daily discharge factor.

Figure 13. USGS gage (12046260) at the surface water intake provided real-time turbidity and river stage for the Elwha Water Treatment Plant at approximately river mile 3.5.

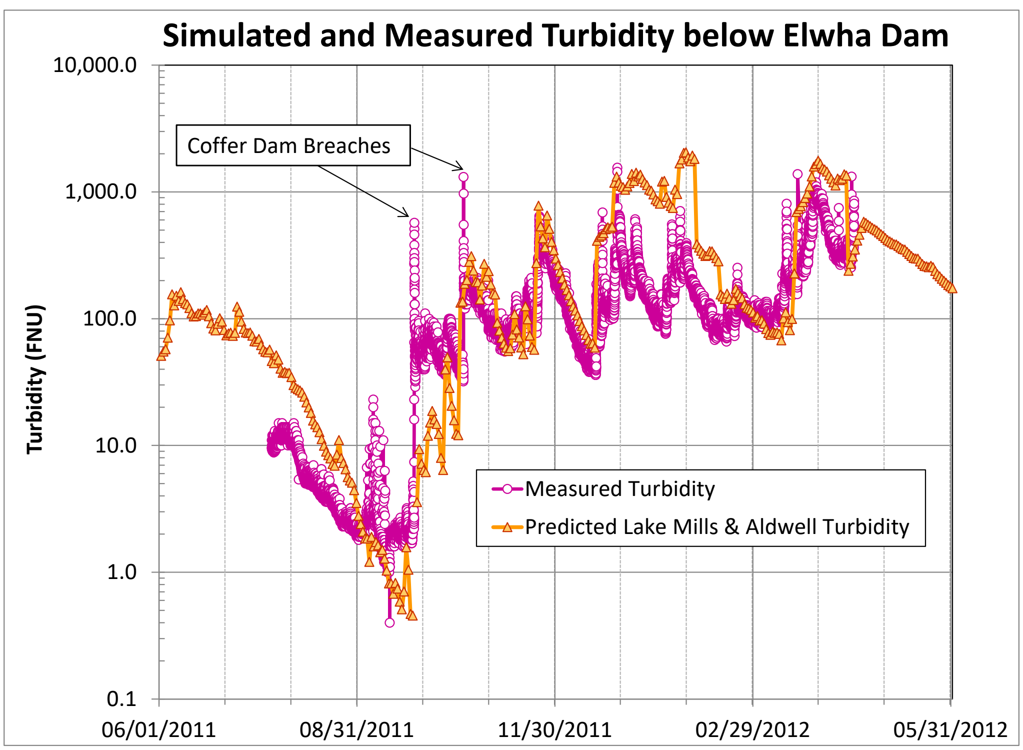


Figure 14. Comparison of measured and predicted Elwha River turbidity below Elwha Dam (includes the effects from both reservoirs).

Example Model Results

Example model simulation results are presented that incorporate the calibration of model parameters based on measurements from the first 8 months of dam removal. The example simulation results include a combination of early monitoring measurements and predictions of sediment erosion from Lake Mills and Lake Aldwell during the complete and concurrent removal of both dams and three floods following dam removal. The assumed hydrology of the simulations was based on the historical flow records from water years 1950 through 1968, except that the actual flows were used since the beginning of reservoir drawdown (October 2010) through mid-April 2012. The actual reservoir sediment erosion results are described by Bountry et al. (2018).

By April 2012, Elwha Dam had been removed enough so that riverine conditions existed through the former Lake Aldwell. Model simulations predicted that riverine conditions would have existed through Lake Mills by October 2012 when Glines Canyon Dam would have been removed down to elevation 480 feet (1988 NAVD). Once riverine conditions exist through the former reservoir, the model predicts that coarse sediment will begin being transported past the remaining dam. Based on the hydrology assumptions, the model predicted that Glines Canyon Dam would have been completely removed (down to elevation 400 feet, 1988 NAVD) by April 2013. In reality, Glines Canyon Dam removal was completed by September 2014 (Bountry et al., 2018).

Model simulation results of the Lake Mills topography and bathymetry are presented graphically (Figure 15 through Figure 35). The initial conditions topography and bathymetry are presented in Figure 15. The reservoir was initially drawn down 14 feet during September 2010 to allow excavation of a pilot channel along the delta surface (Bountry et al., 2018). Model simulation for December 2010 with 14 feet of reservoir drawdown are presented in Figure 16. Lake Mills refilled and model simulation for June 2011 are presented in Figure 17. Model simulation results are presented for the following reservoir drawdowns through October 2012:

- 13 ft by September 2011 (Figure 18)
- 27 ft by November 2011 and January 2012 (Figure 19 and Figure 20)
- 39 ft by February 2012 (Figure 21)
- 56 ft by March 2012 (Figure 22)
- 70 ft by April 2012 (Figure 23)
- 79 ft by May 2012 (Figure 24 and Figure 25)
- 94 ft by July 2012 (Figure 26)
- 102 ft by August 2012 (Figure 27)

- 109 ft by October 2012 (Figure 28)

By the end of October 2012, the receding reservoir pool had been completely drained or filled with sediment eroded from upstream. Model simulation results are presented for the following continued amounts of dam removal through April 2013:

- 118 ft by January 2013 (Figure 29)
- 138 ft by January 2013 (Figure 30)
- 160 ft by March 2013 (Figure 31)
- 187 ft by April 2013 (Figure 32)

The model predicted that the dam would have been completely removed by January 2014. In reality, the concrete arch dam was completely removed by September 2014. Model simulation results are presented for the following periods after dam removal through November 2016:

- January 2014 (Figure 33)
- December 2015 (Figure 34)
- November 2016 (Figure 35)

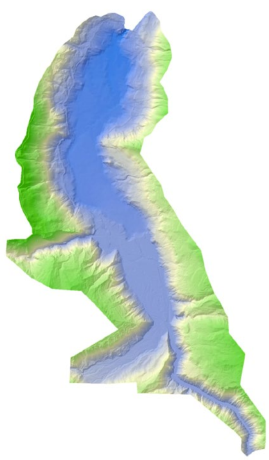


Figure 15. Lake Mills initial conditions on 2010-Oct-17.

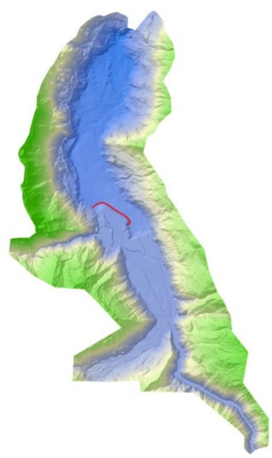


Figure 16. Lake Mills simulation after 14 ft of drawdown on 2010-Dec-10.

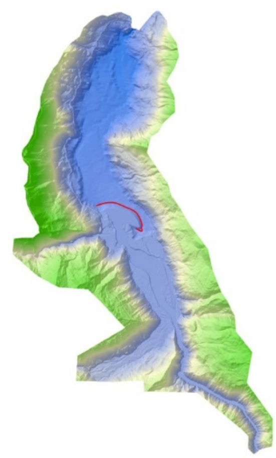
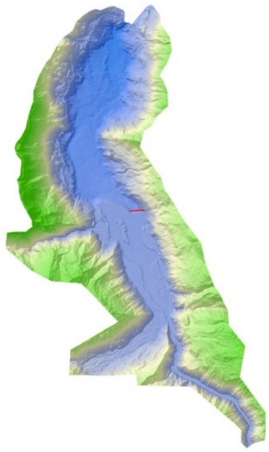
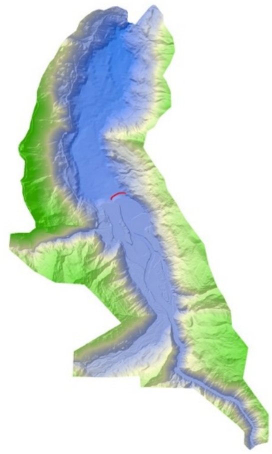
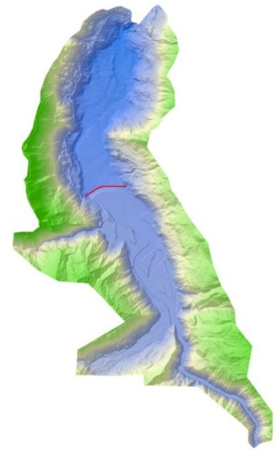
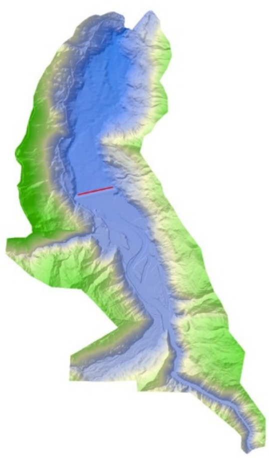
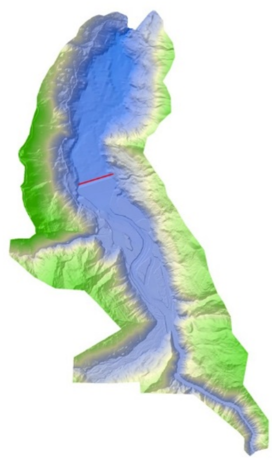
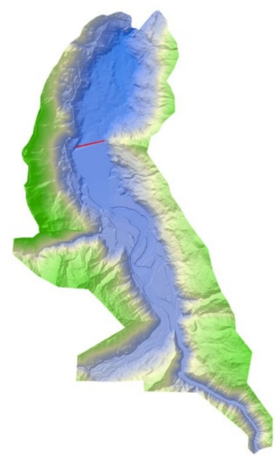


Figure 17. Lake Mills simulation after refilling on 2011-Jun-08.

 Figure 18. Lake Mills simulation after 13 ft of drawdown on 2011-Sep-27.	 Figure 19. Lake Mills simulation after 27 ft of drawdown on 2011-Nov-06.	 Figure 20. Lake Mills simulation after 27 ft of drawdown on 2012-Jan-07.
 Figure 21. Lake Mills simulation after 39 ft of drawdown on 2012-Feb-11.	 Figure 22. Lake Mills simulation after 56 ft of drawdown on 2012-Mar-19.	 Figure 23. Lake Mills simulation after 70 ft of drawdown on 2012-Apr-13.

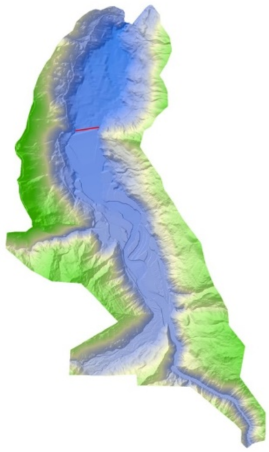


Figure 24. Lake Mills simulation after 79 ft of drawdown on 2012-May-09.

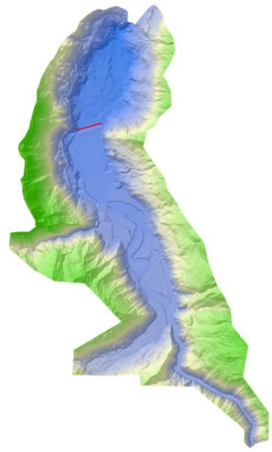


Figure 25. Lake Mills simulation after 79 ft of drawdown on 2012-Jul-02.

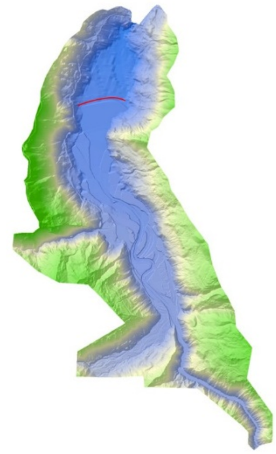


Figure 26. Lake Mills simulation after 94 ft of drawdown on 2012-Jul-26.

Figure 27. Lake Mills simulation after 102 ft of drawdown on 2012-Aug-14.

Figure 28. Lake Mills simulation after 109 ft of drawdown on 2012-Oct-07.

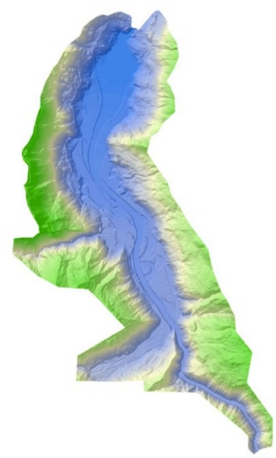


Figure 29. Lake Mills simulation after 118 ft of dam removal on 2012-Nov-10.

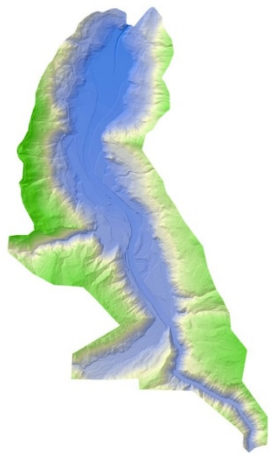


Figure 30. Lake Mills simulation after 138 ft of dam removal on 2013-Jan-21.

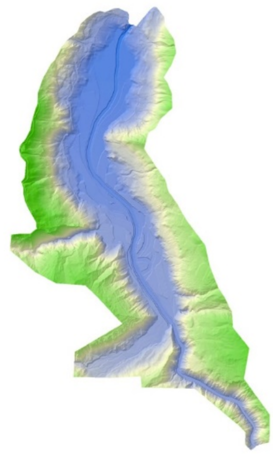


Figure 31. Lake Mills simulation after 160 ft of dam removal on 2013-Mar-01.

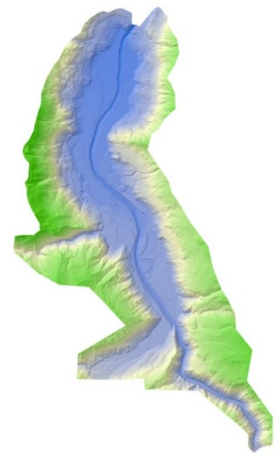


Figure 32. Lake Mills simulation after 187 ft of dam removal on 2013-Apr-16.

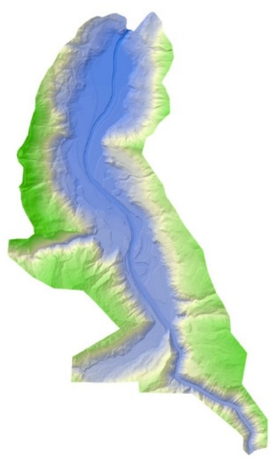


Figure 33. Lake Mills simulation on 2014-Jan-20 after complete dam removal.

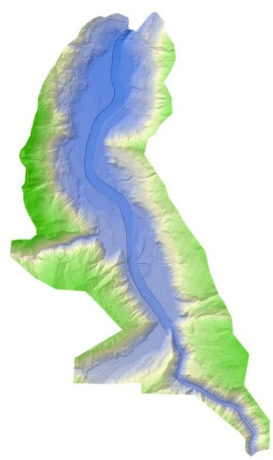


Figure 34. Lake Mills simulation on 2014-Jan-20 after complete dam removal.

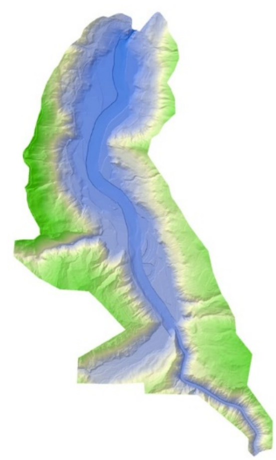


Figure 34. Lake Mills simulation on 2016-Nov-08 after complete dam removal.

A summary comparison of initial and final reservoir topography is presented in Figure 36 for Lake Mills and in Figure 37 for Lake Aldwell. Grey areas in the images represent locations where the reservoir sediments have been eroded down to the estimated predam surface. Colored areas represent areas of remaining or redeposited reservoir sedimentation. The darker the color shade, the thicker the predicted reservoir sediment terrace thickness.

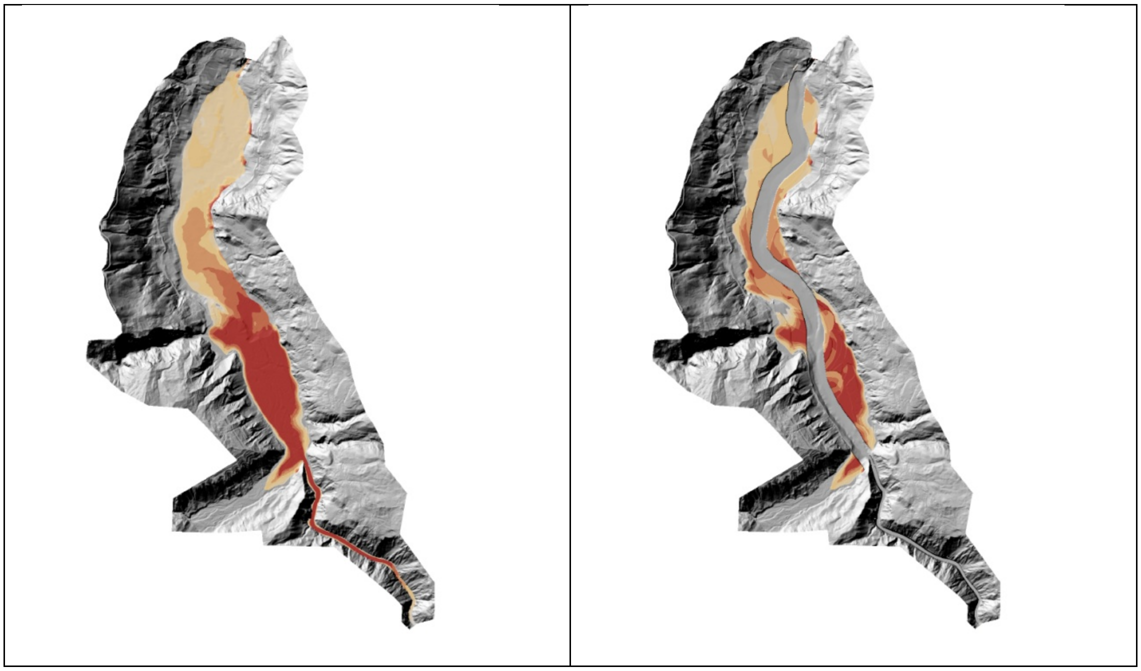


Figure 35. Example comparison of Lake Mills simulated topographic surface and sediment thickness for initial (pre-dam removal) and final (post-dam conditions.

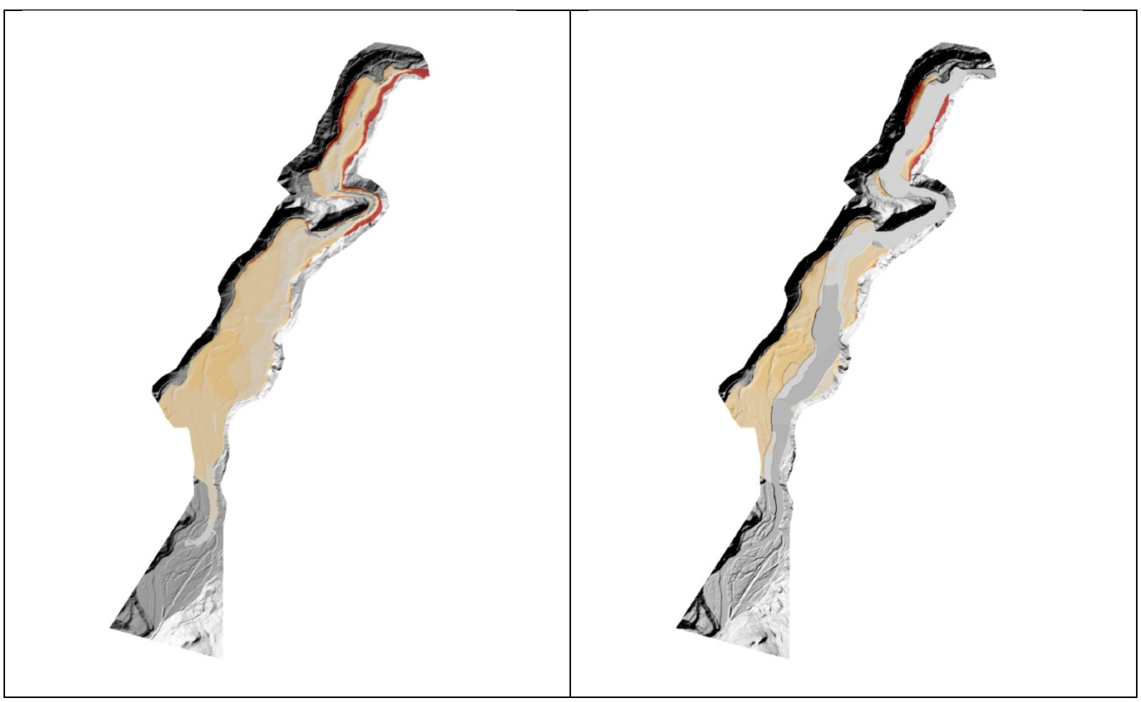


Figure 36. Example comparison of Lake Aldwell simulated topographic surface and sediment thickness for initial (pre-dam removal) and final (post-dam conditions.

Combined Lake Mills and Lake Aldwell example model results for coarse and fine sediment release past Elwha Dam are presented in Figure 38 and Figure 39. The two highest peak sediment loads and concentrations for coarse and fine sediment coincided with the following high flows:

- The first high flow following the removal of Glines Canyon Dam was simulated to occur in mid-January 2014 at 9,150 ft^3/s for the assumed hydrology.
- The first large flood since the end of dam removal was simulated to occur in early November 2016 at 19,100 ft^3/s for the assumed hydrology.

The next highest peak sediment load loads or concentrations for coarse and fine sediment coincided with the following high flows:

- The first high flow following the loss of Lake Mills when coarse sediment was being actively transported past the dam. This was simulated to occur in mid-October 2012 at 3,710 ft^3/s.
- First snowmelt following complete removal of Glines Canyon Dam. This was simulated to occur during April through May 2013.

The model correctly predicted that coarse sediment would not be released past either dam until the pro-grading delta had reached the dam and filled the remaining reservoir area. About 50% of the total sediment (coarse and fine) was predicted to be transported past the dam within three years after dam removal (2016). The remaining reservoir sediments were predicted to either not erode or be eroded and redistributed within the reservoir as newly formed terraces. In reality, 72% of the sediments had eroded from Lake Mills by the end of water year 2017 (Bountry et al., 2018).

The model correctly predicted that the release of fine sediment from each reservoir would coincide with episodes of reservoir drawdown and high flows. While at least some reservoir pool remained, some of the eroding fine sediment redeposited within the receded reservoir while the remainder was transported past the dam. The magnitudes of fine and coarse sediment release tended to increase as dam removal continued. After dam removal, the highest magnitudes of fine and coarse sediment release coincided with successively higher flows. After dam removal, the model assumed that successively greater flood peaks would be needed to cause additional reservoir sediment erosion. In reality, some reservoir sediment erosion continued between floods, but the sediment transport rates diminished over time for the same discharge (Bountry et al., 2018). In fact, successively greater flood peaks were required to cause significant reservoir erosion.

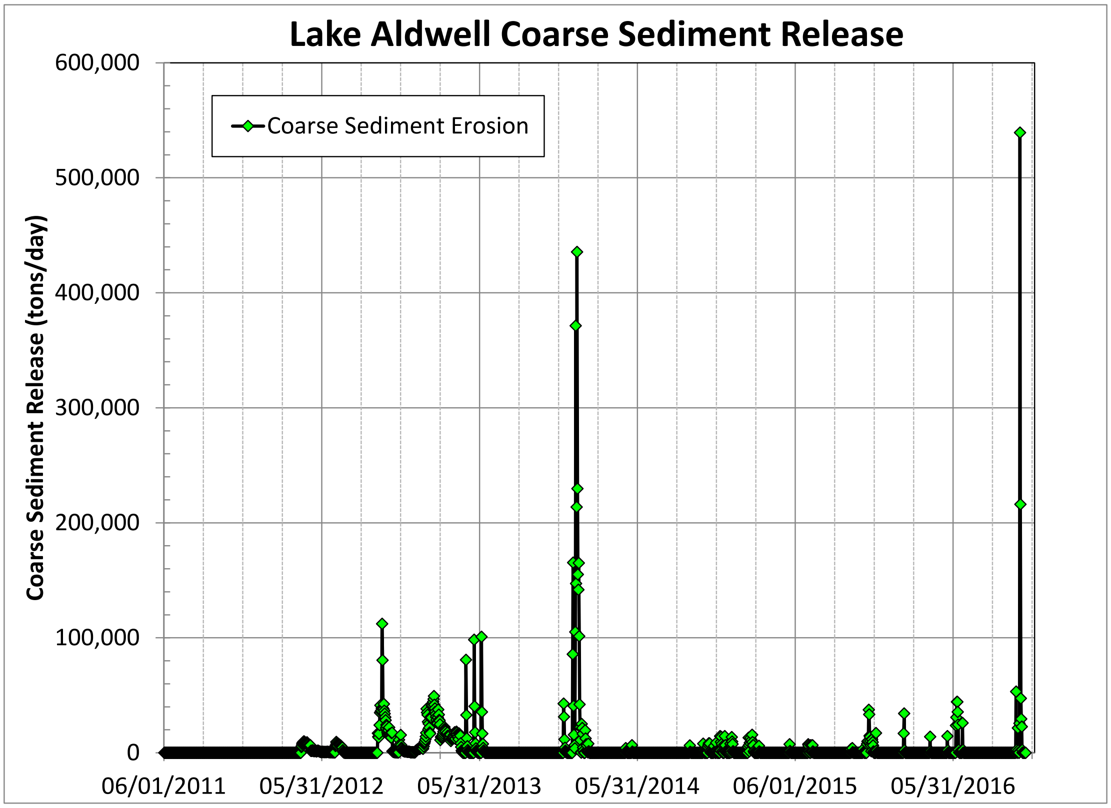


Figure 37. Example model results for coarse-sediment release below Elwha Dam from Lake Mills and Lake Aldwell.

Turbidities were predicted to exceed 20 FNUs (a threshold for operating the water treatment plant) below Elwha Dam slightly more than 40% of the days during the model simulation. Turbidities were predicted to exceed 1,000 FNU about 12% of the time and exceed 10,000 FNU less than 0.5 % of the time. The highest predicted turbidities exceed 10,000 FNU's for only a few days. In reality, the 20 FNU/FBU threshold was exceeded nearly 100% of the time the first two years of dam removal but reduced to only 23% during water year 2017. The highest threshold of 1,000 FNU/FBU was exceeded 19% during water year 2013, but only 0 to 2% in subsequent years (Bountry et al., 2018).

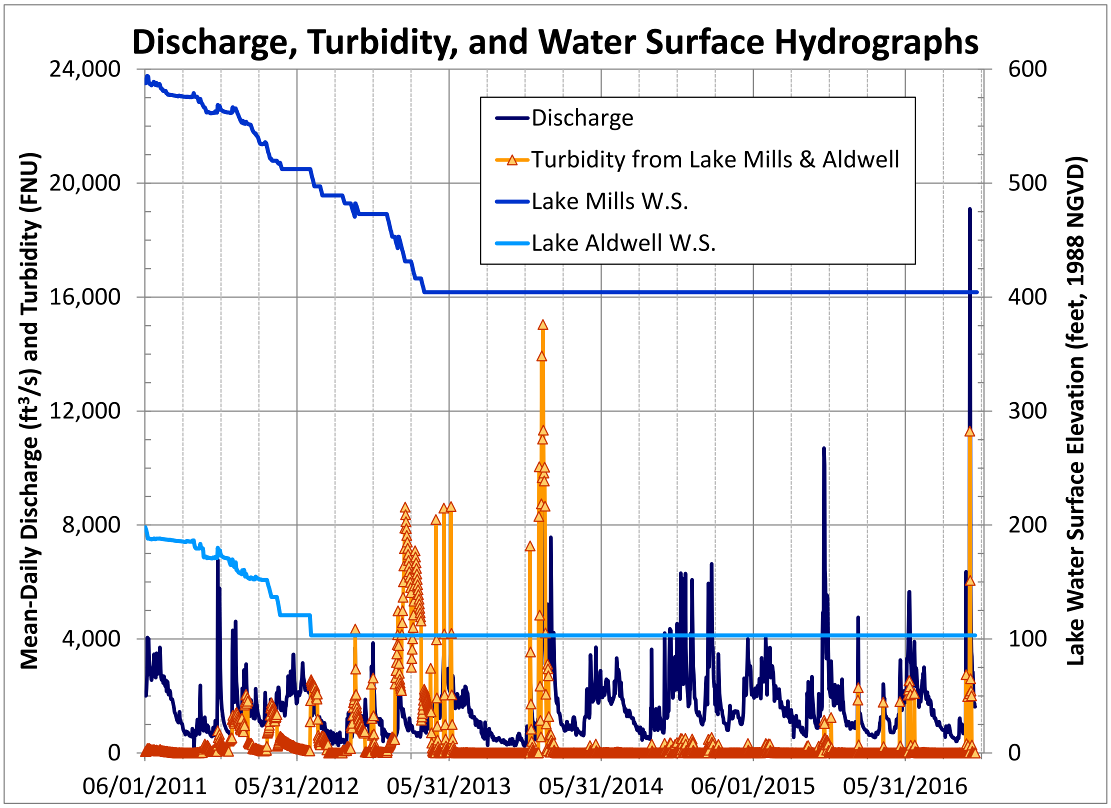


Figure 38. Example model results for fine-sediment release below Elwha Dam from Lake Mills and Lake Aldwell.

Conclusions

The mass balance model was a useful tool to simulate the reservoir sediment erosion and redeposition processes, and the subsequent sediment release during the concurrent removal of Glines Canyon Dam and Elwha Dam. Simulations of the mass balance model were much faster than a two-dimensional hydrodynamic model so a wide range of hydrologies and dam removal schedules could be simulated. Although the mass balance model did not simulate fluid mechanics, the most important aspects of sediment erosion, redeposition, and downstream release were simulated. Now that both dams have been removed, simulation of the reservoir sediment erosion using a processes-based model would provide an interesting comparison with the mass balance model.

Proper use of the model required experience with sediment transport and geomorphic processes. Because the model was empirically based, input parameters needed to be based on monitoring results, such as the 1994 Lake Mills drawdown experiment. Initial model predictions contained large uncertainties, but the accuracy improved as more and more monitoring data were incorporated into model inputs or used in subsequent calibrations. Even with uncertainties, the model results were found to be conceptually correct. Model results were most sensitive to the channel erosion slopes and coefficients used to predict the erosion widths. Model input parameters, used in post processing, only affected the daily distribution of the sediment erosion volume from a given model time period.

The model was useful as a predictive tool for project planning both before and during project implementation. The model was used to evaluate impacts from alternative schedules of incremental reservoir drawdown and hold periods. Uncertainty in hydrology and model input parameters was evaluated by simulating a wide range reasonable scenarios. During project implementation, the model helped guide the monitoring program by providing sediment-related hypotheses and quantitative predictions. Monitoring data were then used to test these hypotheses and predictions. When monitoring results agreed with model predictions there was confidence in proceeding with the next increments of dam removal and reservoir drawdown. When monitoring results differed from model predictions, there were opportunities to determine why and either recalibrate the model or modify algorithms.

The topographic and bathymetric patterns predicted by the model matched observations during the monitoring program. However, the model under-predicted the extent of lateral erosion and the total volume of sediment eroded from Lake Mills. Had more time been available, at least part of this under-prediction could have been corrected by adjusting the three input parameters related to lateral erosion. More time and budget would have been needed to reverify all calibrated input parameters to fully assess model uncertainty.

The simulated release of fine sediment from both reservoirs matched measurements reasonably well during the first year of dam removal because most all of the eroded fine sediment came from Lake Aldwell. The upper layers of the Lake Mills delta were composed primarily of coarse sediment and a significant reservoir pool remained to trap the small amounts of fine sediment that did erode. During subsequent years of dam removal, fine sediment was being eroded from both reservoirs and calibration was quite difficult, especially without continuous turbidity or concentration measurements at a river location between the two reservoirs.

The model correctly predicted that the greatest release of fine sediment from each reservoir would coincide with episodes of reservoir drawdown and high flows. While a reservoir pool remained, some of the eroding fine sediment redeposited in the receding reservoir while the remainder was released downstream. The magnitudes of fine and coarse sediment release tended to increase as more of each dam was removed.

After dam removal, the highest measured magnitudes of sediment erosion coincided with high flows, but there was a decrease in sediment concentration or turbidity over time corresponding to the same discharge magnitude. The model correctly predicted this trend of decreasing sediment loads. However, the model incorrectly predicted that very little sediment would erode between high flows.

References

Bountry, J.A.; Ferrari, R.; Wille, K.; and Randle, T.J. (2011). 2010 Survey Report for Lake Mills and Lake Aldwell on the Elwha River, Washington, SRH-2010-23, U.S. Department of the Interior, Bureau of Reclamation, Denver, CO, June 2011.

Bountry, J.; Randle, T.J.; Ritchie, A.C. (2018). *Adaptive Sediment Management Program Final Report for the Elwha River Restoration Project*, Technical Report SRH-2018-13, U.S. Department of the Interior, Bureau of Reclamation, Geolgoical Survey, National Park Service, Denver, CO, February 2018.

Bromley, J.C. (2007). “The morphodynamics of sediment movement through a reservoir during dam removal,” thesis submitted to the University of Nottingham to the degree of Doctor of Philosophy.

Childers, D., Kresch, D.L., Gustafson, A.S., Randle, T.J., Melena, J.T., and Cluer, B. (2000). “Hydrologic Data Collected During the 1994 Lake Mills Drawdown Experiment, Elwha River, Washington,” *Water-Resources Investigations Report 99-4215*, U.S. Geological Survey, Tacoma, Washington, 115 pages.

Gilbert, J. and Link, R. (1995). “Alluvium Distribution in Lake Mills, Glines Canyon Project and Lake Aldwell, Elwha Project, Washington,” *Elwha Technical Series PN-95-4*, U.S. Bureau of Reclamation, Pacific Northwest Region, Boise, ID, 60 pages.

Pemberton, E.L. and Lara, J.M. (1971). “A Procedure to Determine Sediment Deposition in a Settling Basin,” U.S. Bureau of Reclamation, Sedimentation Investigations Technical Guide Series, Section E. Intake Works and Desilting Basins, Part 2. Setting Basins, Sedimentation Section, Denver, CO, 8 pages.

Randle, T.J.; Young, C.A.; Melena, J.T.; Ouellette, E.M. (1996). “Sediment Analysis and Modeling of the River Erosion Alternative,” *Elwha Technical Series PN-95-9*, U.S. Department of the Interior, Bureau of Reclamation, Boise, Idaho, 138 pages.

Randle, T.J. (2002). Memorandum to Brian Winter, Olympic Elwha Project Team Leader, Elwha River Restoration Project, Olympic National Park, National Park Service. Application of the report entitled: "Sediment Analysis and Modeling of the River Erosion Alternative," Elwha Technical Series PN-95-9, Randle, Young, Melena, and Ouellette, U.S. Bureau of Reclamation, October 1996.

Randle, T.J. and Bountry, J.A. (2010). "Elwha River Restoration: Sediment Adaptive Management," 9th Federal Interagency Sedimentation Conference, Las Vegas, Nevada, June 27 - July 1, 2010.

Randle, T.J., C.T. Yang, and J. Daraio (2006). "Chapter 2, Erosion and Reservoir Sedimentation" in *Erosion and Sedimentation Manual*, U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado. https://www.usbr.gov/tsc/techreferences/mands/mands-pdfs/Erosion%20and%20Sedimentation%20Manual.pdf

Randle, T.J., Bountry, J.A., Ritchie, A.C., Wille, K.B (2015). "Large-scale dam removal on the Elwha River, Washington, USA: erosion of reservoir sediment," *Journal of Geomorphology,* Volume 246, 1 October 2015, Pages 709-728.

Soar, P.J. and Thorne, C.R. (2001). *Channel Restoration Design for Meandering Rivers*, U.S. Army Corps of Engineers, Costal Hydraulics Laboratory, ERDC/CHL CR-01-1, Vicksburg, Mississippi.

Strand, R.I. and E.L. Pemberton (1982). *Reservoir Sedimentation*. Technical Guideline for Bureau of Reclamation, Sedimentation and River Hydraulics Group, Hydrology Branch, Division of Planning Technical Services, Engineering and Research Center, Denver, Colorado. https://www.usbr.gov/tsc/techreferences/reservoir/ReservoirSedimentationTechGuide10_1982.pdf

U.S. Department of the Interior (DOI), 1996a. Elwha River Ecosystem Restoration Implementation, Draft Environmental Impact, National Park Service, Olympic National Park, WA, April 1996.

U.S. Department of the Interior (DOI), 1996b. Elwha River Ecosystem Restoration Implementation, Final Environmental Impact, National Park Service, Olympic National Park, WA, November 1996.

U.S. Department of the Interior (DOI), 1996c. Record of Decision, Final Environmental Impact Statement, Elwha River Ecosystem Restoration Implementation. December 1996.

U.S. Department of the Interior (DOI), 2004. Elwha River Ecosystem Restoration Implementation, Draft Supplement to the Final Environmental Impact Statement, National Park Service, Olympic National Park, WA, December 2004.

U.S. Department of the Interior (DOI), 2005a. Elwha River Ecosystem Restoration Implementation, Final Supplement to the Final Environmental Impact Statement, National Park Service, Olympic National Park, WA, July 2005.

U.S. Department of the Interior (DOI), 2005b. *Record of Decision, Elwha River Ecosystem Restoration Implementation, Final Supplement to the Final Environmental Impact Statement*, National Park Service, Olympic National Park, WA, November 2005.

Williams, B. K., R. C. Szaro, and C. D. Shapiro. (2007). *Adaptive Management: The U.S. Department of the Interior Technical Guide*. Adaptive Management Working Group, U.S. Department of the Interior, Washington, DC.