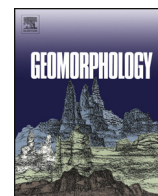




Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Large-scale dam removal on the Elwha River, Washington, USA: Erosion of reservoir sediment

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ARTICLE INFO

Article history:

Received 10 July 2014

Received in revised form 28 December 2014

Accepted 29 December 2014

Available online xxxx

Keywords:

Channel evolution

Reservoir sedimentation

Reservoir drawdown

Reservoir sediment erosion

Delta

ABSTRACT

Base-level lowering of reservoirs impounding upstream sediment supply triggers a series of channel evolution steps such as degradation, lateral erosion, and redeposition that can dramatically alter the reservoir landscape and decouple the relationship between stream power and sediment supply. Many case studies exist for small dam removals with a few years of sediment storage or dam breaches triggering instantaneous large sediment releases. However, quantitative information for a controlled drawdown initiating erosion of a large sediment deposit is rare. We investigate reservoir sediment response to the phased and concurrent drawdown of two reservoirs on the Elwha River, Washington, USA, during the largest dam removal in history by measuring changes in reservoir topography and channel morphology as a function of base-level lowering, river discharge, and cohesion.

After two years, the Elwha Dam was completely removed, and three-quarters of Glines Canyon Dam were removed. Reservoir drawdown increments of 3 to 5 m were sufficient to initiate channel degradation and delta progradation across the width of the receding reservoir, redistributing decades of accumulated delta sediment throughout the reservoir while the lake still remained. The first year of dam removal resulted in up to 5 m of incision through the Lake Aldwell delta down to the predam surface and in just over 20 m of incision through the Lake Mills delta. In contrast, delta progradation resulted in a few meters of deposition in Lake Aldwell and 2 to 10 m in Lake Mills on top of prodelta and lakebed deposits. In coarse, noncohesive sediment, a braided channel developed and widened up to tenfold across the entire width of the reservoir. The most extensive lateral erosion occurred in noncohesive deposits during multiweek hold periods coinciding with flows greater than the mean annual flow, but less than a 2-year flood peak. Channel widening in more cohesive fine sediments of the prodelta and lakebed was less than half of that in the coarse, noncohesive delta sediments. Dam removal resulted in the erosion and downstream release of 23% of the sediment in Lake Aldwell (1.12 ± 0.07 million m^3) and 37% of the sediment in Lake Mills (5.95 ± 0.12 million m^3), representing nearly four decades of sediment supply from the upstream watershed within a two-year time frame. A significant portion of the reservoir sediment is expected to remain as sediment terraces within the reservoir landscape, but additional erosion is expected after the remainder of the Glines Canyon Dam is removed and during future floods until the river reaches quasi-equilibrium. After phased dam removal, the reservoir landscape consists of a series of sediment terraces of varying heights composed of prograded coarse sediment overlying fine lakebed deposits. The predam surface is exposed along the river corridor, and abundant 1- to 3-m stumps from pre-removal forests create unique morphology where the river interacts with the predam landscape.

Published by Elsevier B.V.

1. Introduction

Conceptual models predicting the geomorphic response of reservoir sediment deposits to dam removal have been developed using geomorphic analogies of channel evolution in incising rivers (Doyle et al., 2002, 2003). Recent literature relating these models to dam removals has been limited. Most of the 1200 dams removed to date have been relatively small (<10 m) with modest sediment volumes that were less

than the decadal sediment load of the channel (e.g., Cheng and Granata, 2007; Burroughs et al., 2009; Pearson et al., 2011; Major et al., 2012; Woelfle-Erskine et al., 2012; American Rivers, 2014). Quantitative data on reservoir and downstream river response to dam removal are limited to a few cases where detailed data have been collected (Doyle et al., 2002; Pizzuto, 2002; Major et al., 2012; Tullis and Wang, 2014; Wilcox et al., 2014). The rate and extent of reservoir sediment erosion and downstream release are relatively unknown for dam removals with large sediment volumes (>10 times the annual sediment load), largely because so few have occurred. In the only recent example of a large sediment volume associated with a dam removal, the bottom

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of the 100-year old, 38-m high Condit Dam on the White Salmon River, Washington, USA, was suddenly breached on 26 October 2011 as part of the dam removal plan (Wilcox et al., 2014). This resulted in rapid draining of the relatively narrow reservoir and release of more than 60% of the estimated 1.8 million m³ of sediment within the first 15 weeks after the breach (Wilcox et al., 2014).

Predicting the magnitude and rate of reservoir sediment erosion is important for dam removal planning, particularly in cases where water users, aquatic species, infrastructure, and recreation may be affected by sediment. The rate of dam removal, and timing with respect to hydrology, can dramatically affect the rate and extent of reservoir sediment erosion and downstream release.

Removal of the Elwha and Glines Canyon Dams on the Elwha River near Port Angeles, Washington, USA (Fig. 1), provided a unique opportunity to investigate the effects of two concurrent, phased dam removals on erosion, redistribution, and release of the largest sediment

volume associated with any dam removal. Sediment deposits in the two reservoir deltas cumulatively contained nearly a century of coarse sediment supply. The delta and lakebed sediment deposits consisted of cohesive and noncohesive layers, providing an opportunity to investigate how cohesion influences erosion following dam removal. We collected data using a variety of methods to monitor reservoir sediment erosion, redistribution, and release over the first two years of dam removal. Together with complementary investigations of river channel and floodplain geomorphic change (East et al., 2015), fluvial sediment transport (Magirl et al., 2015), coastal evolution (Gelfenbaum et al., 2015), and source-to-sink sediment budget (Warrick et al., 2015) we characterize a systemwide response that is rarely monitored at this field scale. We explore the following research questions to help address a data gap in quantitative information on the extent and rate of reservoir sediment erosion associated with large dam removals: (i) in a phased dam removal with a mixed sediment regime, how do

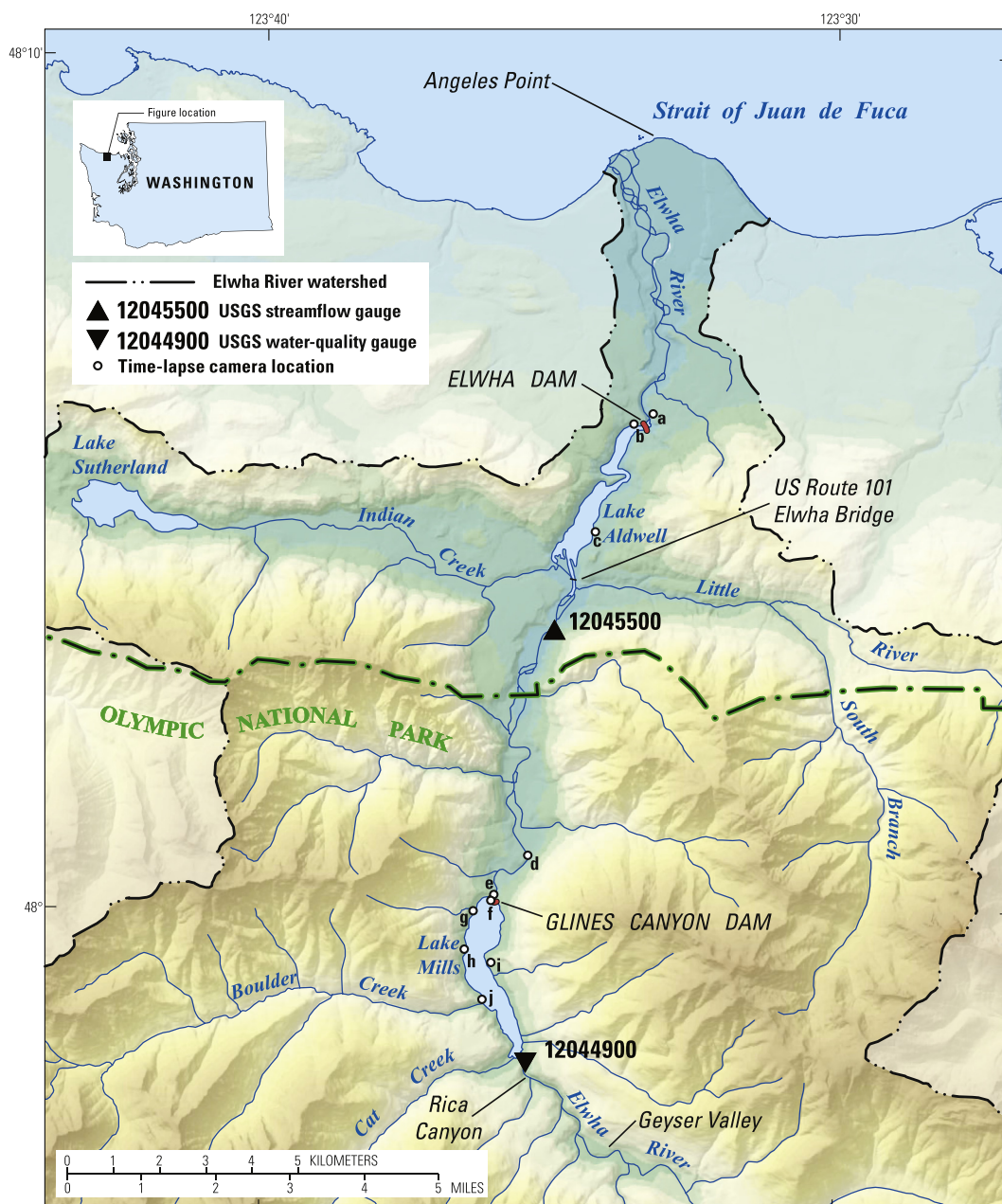


Fig. 1. Location map of the Elwha River and tributaries, Elwha Dam and Lake Aldwell, Glines Canyon Dam and Lake Mills, USGS stream gage locations, and time-lapse cameras.

river flow, reservoir drawdown schedule, and sediment cohesion control the erosion and rate of sediment export from the reservoirs? (ii) how do available conceptual models of river response to dam removal (base-level lowering) compare with findings on the Elwha? and (iii) are there new findings from the Elwha that can help refine or extend these models?

2. Glines Canyon Dam and Elwha Dam removal background

The Elwha River flows north from the heart of the Olympic Mountains for about 72 km and enters the Strait of Juan de Fuca at Angeles Point, about 10 km west of Port Angeles, WA (Fig. 1). Most of the watershed (83% of 833 km²) is within the boundaries of Olympic National Park, a UN International Biosphere Reserve and UNESCO World Heritage Site primarily managed as wilderness. Average annual precipitation in the Elwha watershed ranges from 1 m at the river mouth to 6 m on Mount Olympus near the headwaters (Duda et al., 2011). The average annual discharge is 42 m³/s and the 2-year flood peak is 400 m³/s (Curran et al., 2009). Flood peaks tend to be flashy and typically occur during the fall–winter storm season. High flows during spring snowmelt are smaller, but longer in duration. The natural river bed is composed of gravel, cobbles, boulders, and sand, with some exposed bedrock. The river alternates between narrow bedrock canyons and wider alluvial reaches for much of its length (Beechie et al., 2006; Warrick et al., 2011).

In 1992, the U.S. Congress passed the Elwha River Ecosystem and Fisheries Restoration Act, which authorized the U.S. Department of the Interior to purchase and remove the privately-constructed Elwha and Glines Canyon Dams. The Elwha Dam was completed in 1913, 7.9 km upstream from the river mouth (Fig. 2A). This 32-m-high concrete gravity dam had 30 m of head and formed Lake Aldwell, which had a storage capacity of 10 million m³ at the time of removal. Built without fish passage structures, the dam significantly impacted formerly productive salmon populations by restricting their distribution to the lowermost portion of the watershed in habitat that continued to decline in quality and quantity from the effects of the upstream dams (Wunderlich et al., 1994; Duda et al., 2008; Pess et al., 2008). Glines Canyon Dam was completed in 1927, 21 km upstream from the river mouth (Fig. 2B). This 64-m-high concrete arch dam had 59 m of head and formed Lake Mills, which had a storage capacity of 32 million m³ at the time of removal (50 million m³ when first built) (Bountry et al., 2011). Both dams were constructed to produce hydroelectric power, with both reservoirs kept full and operated as run-of-the river facilities since 1975 (Johnson, 1994; U.S. Department of Interior, 1996). Neither

reservoir provided significant flood control or water supply benefits. The two reservoirs inundated 9 km of riverine habitat, interrupted the downstream flux of sediment and organic material, and increased water temperatures (Wunderlich et al., 1994). The dams virtually eliminated bed-material sediment supply to the river reaches downstream, forming large deltas at the upstream end of each reservoir (Curran et al., 2009; Fig. 3).

The reservoir sediment management plan called for concurrent and phased removal of both dams over a two- to three-year period. This would control the sediment release, allowing the Elwha River to erode a portion of the reservoir sediments to the sea. The rate of dam removal was designed to be fast enough to affect only a few generations of fish, but slow enough that the rate of reservoir sediment erosion and redistribution kept pace with the rate of dam removal. Based on a field drawdown experiment in 1994 and a physical model study of dam removal rates, drawdown increments of 4.6 m were selected with 14-day hold periods in between. Additional hold periods of 4 to 6 weeks were incorporated during times when anadromous fish heavily utilize the Elwha River.

The sediment management objective was to erode as much as possible of the sediment that would eventually erode during dam removal and to redistribute a portion of the sediment along the valley margins to form a series of varying-height sediment terraces. Because a dam removal sediment-management plan had never been implemented at this scale—and owing to uncertainty associated with timing and magnitude of erosion, deposition, and transport processes and the natural variation in hydrology—the sediment management plan adaptively modified hold periods during the project (Randle and Bountry, 2010). This ensured that the rate of dam removal was slow enough so that reservoir sediment erosion and transport through the downstream river channel maintained the following conditions: (i) 100-year peak flood stage did not increase more than 0.5 m in the middle reach of the Elwha River (between the two reservoirs) and did not increase more than 0.8 m in the lower reach below the Elwha Dam; and (ii) sediment concentration did not exceed 40,000 nephelometric turbidity units, which was the design capacity of the downstream water treatment plant, constructed as part of the overall project.

3. Methods

To analyze reservoir sediment evolution in response to drawdown, it was necessary to reconstruct conditions at the time of dam construction (predam), capture conditions at the start of dam removal (pre-removal),

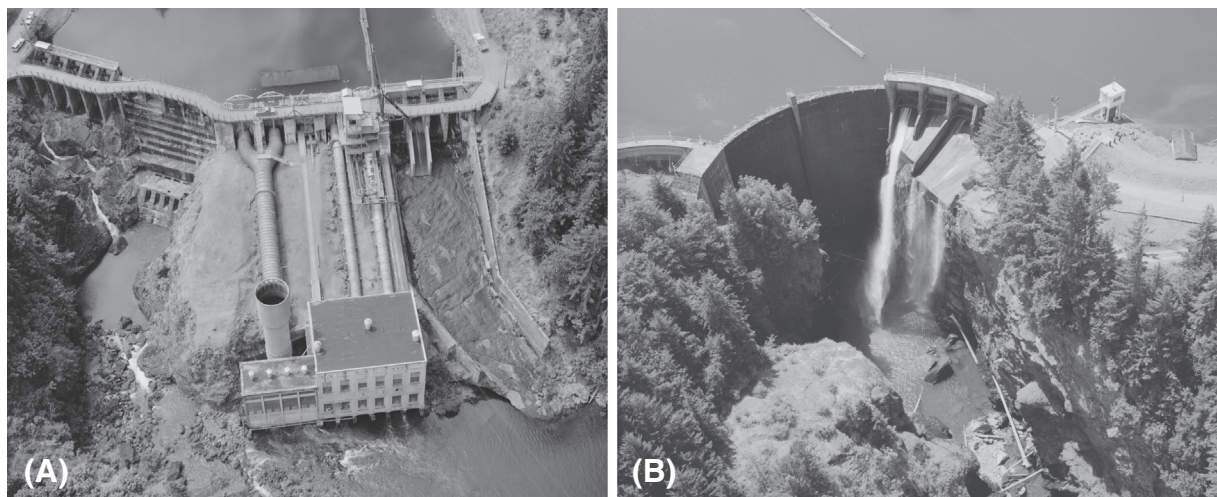


Fig. 2. Pre-project aerial photographs (1995) looking upstream at Elwha Dam forming Lake Aldwell (A) and Glines Canyon Dam forming Lake Mills (B). Photographs by Jet Lowe, National Park Service.

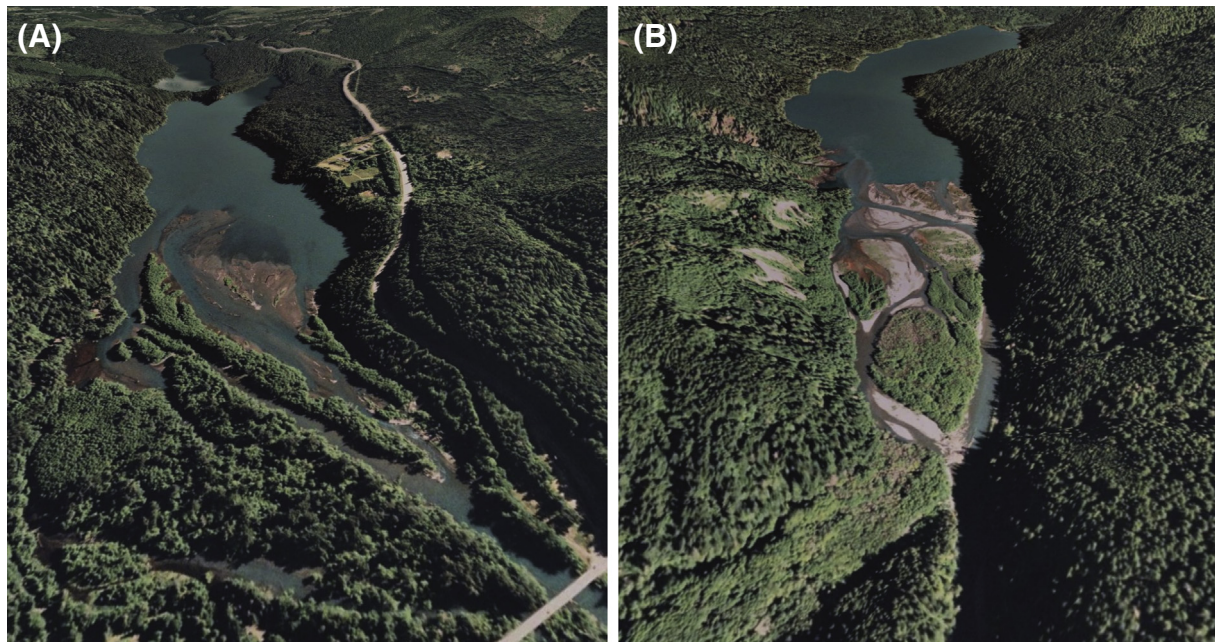


Fig. 3. Pre-project aerial photographs (2009) looking downstream along Lake Aldwell delta (A) and Lake Mills delta (B).

and regularly monitor the response of reservoir reaches during dam removal to reservoir drawdown and river hydrology. Data collection during dam removal included river discharge, reservoir and dam crest elevations, time-lapse imagery, water-surface elevation recorders, terrestrial and bathymetric surveys, structure-from-motion (SfM)-based photogrammetry, aerial and terrestrial light detection and ranging (LiDAR) surveys (USGS, 2012; Watershed Sciences, 2012; Woolpert, 2013), sediment grain size analyses, and field observations. Analyses included measurements of vertical channel incision, lateral erosion, downvalley progradation of the reservoir deltas, and subaerial and subaqueous deposition of reservoir sediments. Uncertainty computations for topographic surfaces and for volume and mass calculations are documented in a supplemental data section.

3.1. Predam reservoir topography

The Lake Mills predam valley bottom topography was developed primarily from a 1921 survey denoting elevation with 3.0-m contours between elevations of 134 and 183 m in the mean sea level datum (Thebo et al., 1926). Lake Aldwell predam data were limited to a 1913 topographic sketch lacking elevation information. In Lake Aldwell, valley bottom elevations were estimated by applying the average measured valley slope after exposure of the predam surface (0.0064) through predam outcrops in the former Lake Aldwell and by using a measured slope of 0.0054 for the river segment inundated by the reservoir upstream of the lake. To simulate the predam channel, valley bottom elevations were lowered by 1 m within the estimated 1913 predam channel footprint. We developed predam contours along Lake Aldwell hillslopes within the reservoir by subtracting sediment thickness of exposed hillslope deposits from ground elevations at the top of deposits measured with aerial LiDAR. To derive sediment thickness, we probed 387 locations over two-thirds of the newly exposed hillslope area after drawdown began, and for the remaining one-third of steep hillslopes adjacent to the valley bottom we used 1989 sediment thickness contours from Hosey and Associates (1990).

3.2. Pre-removal reservoir topography and sediment characteristics

Pre-removal reservoir topography was developed from bathymetric and topographic survey data collected with real-time kinematic (RTK)

global positioning system (GPS) instruments and single-beam acoustic fathometers in July 2010 (Bountry et al., 2011), combined with aerial LiDAR data from 2009 and 2012, to create a pre-removal surface. Sediment volume and thickness at the start of dam removal (pre-removal) were computed for both reservoirs by differencing concurrent pre-removal and predam rasters within the full pool areas and upstream river segments affected by reservoir sedimentation.

Spatially variable pre-removal reservoir sediment gradation was documented in drill-hole data, probing data, visual field inspections, and 1989 sediment investigations (Hosey and Associates, 1990; Gilbert and Link, 1995). To characterize cohesiveness of lakebed mud deposits that were hypothesized to affect lateral erosion rates, we collected six samples of fine sediment in Lake Mills and one sample from Lake Aldwell in February 2014. Samples were bagged and analyzed for size-gradation and Atterberg Limits (Analytical Resources, Inc., 2014).

The percentage of fine (silt and clay < 0.062 mm) and coarse (sand, gravel, and cobble > 0.062 mm) sediment in reservoir deposits was partitioned into zones based on gradation data to allow computation of fine and coarse fractions eroded and released during dam removal (Gilbert and Link, 1995). Sediment zones with different ratios of coarse and fine sediment were defined for the delta upstream of the full reservoir pool, the delta topset and foreset (area of rapidly settling sediment), the prodelta (area of active delta growth in the transition zone between the delta and bottomset deposit), reservoir bottom (areas of fine-grained sediment deposition by turbidity currents or nonstratified flow), and hillslope (also fine-grained deposits). The Lake Mills delta was also partitioned vertically. Sediment gradation of the Lake Mills hillslope was not included in the 1994 study, but field inspection of the exposed surface and incision by tributary streams post-dam removal confirmed that it was the same composition as the reservoir bottom. Sediment zones were designed to represent average grain size distributions for different regions of the reservoirs, broadly representing field conditions based on available data but considerably simplified from actual delta stratigraphy. Because there was continued sedimentation and substantial delta growth between 1994 and 2010, we modified the 1994 Lake Mills sediment polygons to account for the new sediment areas. In Lake Aldwell, we extended the sediment polygons to reflect findings from the newly exposed landscape following dam removal that revealed additional reservoir sedimentation areas in the upstream river segment

and in the western delta, which were previously mapped as fluvial landforms and predam terraces (Gilbert and Link, 1995).

3.3. River discharge, reservoir drawdown, and dam elevation

River discharge was measured at U.S. Geological Survey (USGS) gaging station 12045500 (Elwha River at McDonald Bridge, Rkm 13.5). Although small tributaries enter the Elwha River within the area of former Lake Mills and the downstream river, the gage provided a reasonable approximation of discharge for the entire project area throughout dam removal. We measured water surface elevations just upstream of the Elwha and Glines Canyon Dams during their removal with gages recording water surface elevation at 15-minute intervals. Dam crest and surface water elevations were also recorded by the contractor on a daily basis during dam removal periods.

3.4. Time-lapse cameras

Time-lapse photography was utilized to document changes in reservoir sediment redistribution in real time (see Fig. 1). On-line cameras uploaded imagery to a website every 30 min and were available to the public. Off-line cameras took photographs twice per day and were downloaded about once every month.

3.5. LiDAR and aerial SfM-based photogrammetry surveys

LiDAR flights conducted in April 2009 and October 2012 provided elevations of exposed reservoir sediment for comparison to predam and pre-removal topography. Continuous highly overlapping vertical aerial imagery with 10–15 cm pixel resolution was collected beginning at weekly to monthly intervals beginning 19 March 2012 along the Elwha River from the mouth to the upstream end of Geyser Valley (Rkm 31) (upstream from Lake Mills) using a novel imaging system developed for this project, based on a 12-megapixel Canon D10 camera. Image acquisition continued through the study period at an average frequency of every 20 days, depending on weather and the rate of reservoir sediment erosion. Targeted acquisition rates were every two weeks after the onset of fall rains and through spring snow melt, and monthly during the receding flow period from June through October, with several event–response flights allotted for response to storms or drawdown-related river changes. The minimum and maximum durations between aerial images were 5 and 52 days, respectively. Flights were generally conducted at similar flows. Images were processed with Agisoft's Photoscan photogrammetric software to produce orthoimagery and digital elevation models (DEMs).

Vertical and horizontal controls for aerial imagery were established through a ground control point (GCP) network that grew from a handful of points extracted from previous aerial imagery and LiDAR data to a network of about 150 points surveyed with RTK GPS. The resulting orthoimagery and DEMs generally have a horizontal accuracy of ± 0.1 to 0.25 m, and DEMs have a vertical accuracy of ± 0.25 to 0.5 m (depending on ground control point density) with increasing accuracy as control improved.

3.6. Erosion, redistribution, and release of reservoir sediment

We measured delta progradation, lateral and vertical sediment erosions, eroded and redistributed reservoir sediment volumes, and the sizes of sediment being mobilized by the new river throughout the first two years of dam removal using field survey equipment, orthoimagery and DEMs, and repeat time-lapse photography.

3.6.1. Delta progradation

We measured the delta front location and topset slope using RTK surveys, time-lapse photography, and aerial imagery. We measured the delta foreset slope using bathymetric surveys while a lake still

remained in October 2011, February 2012, and May 2012 for Lake Aldwell and Lake Mills, and additionally in September 2012 for Lake Mills.

3.6.2. Vertical and lateral erosion of newly formed river channel

We measured longitudinal water-surface elevation profiles along the newly formed channel through the exposed reservoir deltas to document timing and magnitude of vertical incision. This also allowed us to track the upstream progression of knickpoints associated with incision following base-level lowering. To measure lateral erosion, we mapped channel banklines upstream from the receding reservoir. In the first year of dam removal through September 2012, measurements were made using either navigation or survey-grade GPS along with a laser rangefinder. After October 2012, LiDAR and SfM-derived surfaces were the primary source of elevation data to compute lateral and vertical erosions. No bathymetric data were collected through the fluvial portion of the reservoir reaches during the study because of hazardous survey conditions.

3.6.3. Change in reservoir sediment volume and mass

We analyzed reservoir sediment erosion, redistribution (deposition), and export volumes from both reservoirs by differencing the pre-removal surface and SfM- or LiDAR-derived topographic surfaces from intervals during the study period where surveys were conducted at similar discharges. This allowed us to identify and quantify distribution and magnitude of erosion and deposition. The volume of reservoir sediment released to the downstream channel was measured as the net reduction in total volume of reservoir sediment between differenced surfaces.

We computed differences in reservoir sediment volume at the end of years 1 (fall 2012) and 2 (fall 2013) for Lake Aldwell and Lake Mills by differencing the pre-removal surface with LiDAR and SfM rasters. These measurements reflect water surface elevations only and make the implicit assumption that river volume is not a significant factor in volume calculations. We derived the volume of exported fine (silt and clay) versus coarse (sand, gravel, and cobble) sediment by calculating the volume eroded from different zones in the pre-removal surfaces which were derived from the pre-removal reservoir sediment gradation mapping of Gilbert and Link (1995).

We also computed the differences in reservoir sediment volume for 25 periods in Lake Mills, representing changes after each dam removal increment and high flow period. In year 1, reservoir sediment erosion and redistribution were computed in a GIS framework based on field measurements of channel incision and lateral erosion above the receding reservoir. In the receding reservoir, bathymetric surveys were conducted to measure the delta progradation consisting primarily of sand-, gravel-, and cobble-sized sediment. Bathymetry of the receding reservoirs was surveyed from motorized boats using RTK GPS, and a single-beam acoustic fathometer.

A trap efficiency equation was used to compute the amount of eroded fine sediment transported past Glines Canyon Dam for each increment (Randle et al., 2012). Suspended sediment measurements within the receding reservoirs were not available. Reservoir sediment trap efficiency (P) was 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 , m/s) was computed as a function of the sediment particle size (d , m) and the water viscosity (ν , m²/s), computed as a function of water temperature (T , °C):

$$P = \left(1 - \frac{1}{e^{\left(\frac{1.005 \omega A_s}{Q \omega} \right)}} \right) \quad (1)$$

$$\omega = (0.09290) \frac{\sqrt{1273 d^3 + (64.58 \nu)^2} - 64.58 \nu}{d} \quad (2)$$

$$\nu = \frac{1.858 \times 10^{-6}}{(1.0334 + 0.03672 T + 0.0002058 T^2)} \quad (3)$$

For purposes of comparing to downstream sediment load data (Magirl et al., 2015; Warrick et al., 2015), bulk density values of 1.13 g/cm³ for fine sediment fraction (silt and clay) and 1.71 g/cm³ for coarse sediment fraction (sand, gravel, and cobble) were utilized to convert measured volume to mass. Conversion values were derived from available literature (ASCE, 2008), limited pre-removal data (Gilbert and Link, 1995; Childers et al., 2000; Mussman et al., 2008), and extensive bulk density data collected in July and September 2013 (Wing, 2014).

4. Results

Results are presented for Lake Aldwell and Lake Mills during the first two years of dam removal and early drawdown periods prior to dam removal. We describe the channel response and sediment erosion during the initial phases of early drawdown and pilot channel construction and during subsequent drawdowns and hold periods throughout the first two years of dam removal.

4.1. Lake Aldwell results

Prior to removal of the Elwha Dam, the total sediment volume within Lake Aldwell was 4.9 million m³ ± 1.4 million m³, of which 54% was fine (silt and clay) and 46% was coarse (sand, gravel, and cobble) (Table 1). The upper portion of the delta extended 0.7 km upstream from the full reservoir pool. The main delta and prodelta were 2.2 km long and located within a wide valley, 4 to 8 times the average channel width. This valley comprises the upstream reservoir segment. A narrow bedrock canyon separates the upstream and downstream reservoir segments. The downstream reservoir segment, located between the bedrock canyon and the Elwha Dam, has a valley width of 2 to 3 times the average channel width, ending at the Elwha Dam in another narrow canyon. The delta contained about one-half of the reservoir sediment with a maximum thickness of 6 to 8 m at the downstream end (Fig. 4). The upstream half of the delta was coarser, containing 90% sand and gravel with dense vegetation on the surface present since at least the 1990s. The downstream half of the delta was submerged and unvegetated and was composed of 50% coarse sediment (sand with small amounts of gravel) and 50% silt and clay. The prodelta, reservoir bottom, and hillslopes (formerly inundated by reservoir) contained the remaining sediment, ranging in average thickness from 0.9 to 3.4 m, and almost entirely composed of silt and clay (Table 2; see Figs. 4, 5).

The removal of the Elwha Dam was completed in 8 months (Fig. 6). Seven reservoir drawdown periods occurred between June 2011 and April 2012, with the first drawdown occurring prior to the start of dam removal (Table 3). Channel degradation and widening occurred after each base-level lowering. Aggradation occurred because of delta progradation while a lake still remained and after the Elwha Dam was

removed, when coarse sediment from Lake Mills was transported downstream through the former Lake Aldwell.

4.1.1. Delta front progradation

During each reservoir drawdown increment, eroded coarse sediment redeposited as the delta prograded into the receded reservoir. The first few drawdowns resulted in relatively small volumes of sediment erosion and redeposition. By the third drawdown, reservoir storage capacity was reduced to less than one-third, dramatically reducing accommodation space. Delta progradation deposited 0.5 to 1 m of coarse sediment (with some silt) on top of the pre-removal prodelta and lakebed in the upstream portion of the reservoir (Fig. 7). During the fourth drawdown, delta progradation resulted in 1 to 5 m of deposition from the narrow canyon separating the upstream and downstream reservoir downstream to the former dam site. During the fifth drawdown, delta progradation reached the dam, after which fine and coarse sediments were transported past the former Elwha Dam site.

4.1.2. Knickpoint migration, degradation, and aggradation along channel profile

Except for the upstream-most segment of the delta containing large log jams and a cobble bed, knickpoint migration and channel degradation occurred through the Lake Aldwell reservoir delta sediment after each reservoir drawdown regardless of flow magnitude. The delta had two active channels at the start of drawdown, one flowing along the left side and one with large log jams along the far right side. The first drawdown in June 2011 represented only 20% of the total drawdown, but resulted in the far right channel incising through over half of the delta deposit. The right channel became the dominant flow path and formed a meander bend that progressively eroded delta sediment along the outside edge (Fig. 8). After the drawdown, snowmelt flows peaked at twice the average annual flow (85 m³/s). A cutoff channel formed along the far right edge of the delta, capturing the flow that was previously through the meander bend, which was nearly 2.5 times longer and half the slope of the cutoff channel.

During the second drawdown, the left delta channel dewatered and became perched about 2 m above the incised right delta channel. Bank heights along the right channel were up to 3.5 m along the delta. Knickpoints from the second and third drawdowns migrated upstream along the right channel and stalled near two large log jams at the transition to the coarsest portion of the delta with cobble-sized sediment along the channel bed. An eight-week hold period followed the third drawdown, during which two winter flood peaks 6 to 7 times the average annual flow occurred (292 and 260 m³/s). During the first flood, the log jams and cobble bed eroded and the knickpoint progressed farther upstream, beyond the full reservoir pool. During these floods, the river along the original delta also incised to a predam surface containing numerous large stumps up to 3 m in diameter.

By the fourth drawdown, the river had reached the predam surface along most of the original delta, and incision through the predam surface slowed to tenths of a meter during each high flow. Channel degradation from drawdowns five, six, and seven occurred quickly through the 2 to 3 m of fine sediment of the prodelta and bottomset areas, and redeposited delta sediments. By September 2012, two distinct slopes had evolved in the longitudinal channel profile through the former Lake Aldwell. The upstream river slope closely matched the estimated predam valley slope of 0.006. The bedrock constriction at the dam site and large boulders left in the channel formed a backwater with a slope of just 0.001 for 1 km upstream from the former dam site. Above that, the river partially incised through prograded delta sediment, achieving a slope of 0.004, before steepening at the upstream channel along predam surfaces.

After drawdown four, degradation was limited to the downstream reservoir segment. By November 2012, channel evolution throughout the former Lake Aldwell switched from degradation to aggradation, as sediment released from Lake Mills moved downstream. About 1 to

Table 1

Summary of reservoir sedimentation volumes in July 2010—uncertainty is rounded to one significant figure when the leading digit is greater than two, and the second digit is greater than five, and is otherwise two significant figures, following uncertainty principles discussed in Taylor (1997).

June 2010 reservoir sedimentation	Lake Aldwell	Lake Mills	Totals
Total sedimentation volume (10 ⁶ m ³)	4.9 ± 1.4	16.1 ± 2.4	21 ± 3
Fine sedimentation volume (10 ⁶ m ³)	2.6 ± 1.1	7.0 ± 1.4	9.7 ± 1.8
Coarse sedimentation volume (10 ⁶ m ³)	2.3 ± 0.9	9.0 ± 1.9	11.3 ± 2.1
Total reservoir sediment mass (10 ⁶ t)	6.8 ± 2.3	23 ± 6	30 ± 6
Fine sediment mass (10 ⁶ t)	3.0 ± 1.4	8.0 ± 2.5	11 ± 3
Coarse sediment mass (10 ⁶ t)	3.9 ± 1.8	15 ± 5	19 ± 5

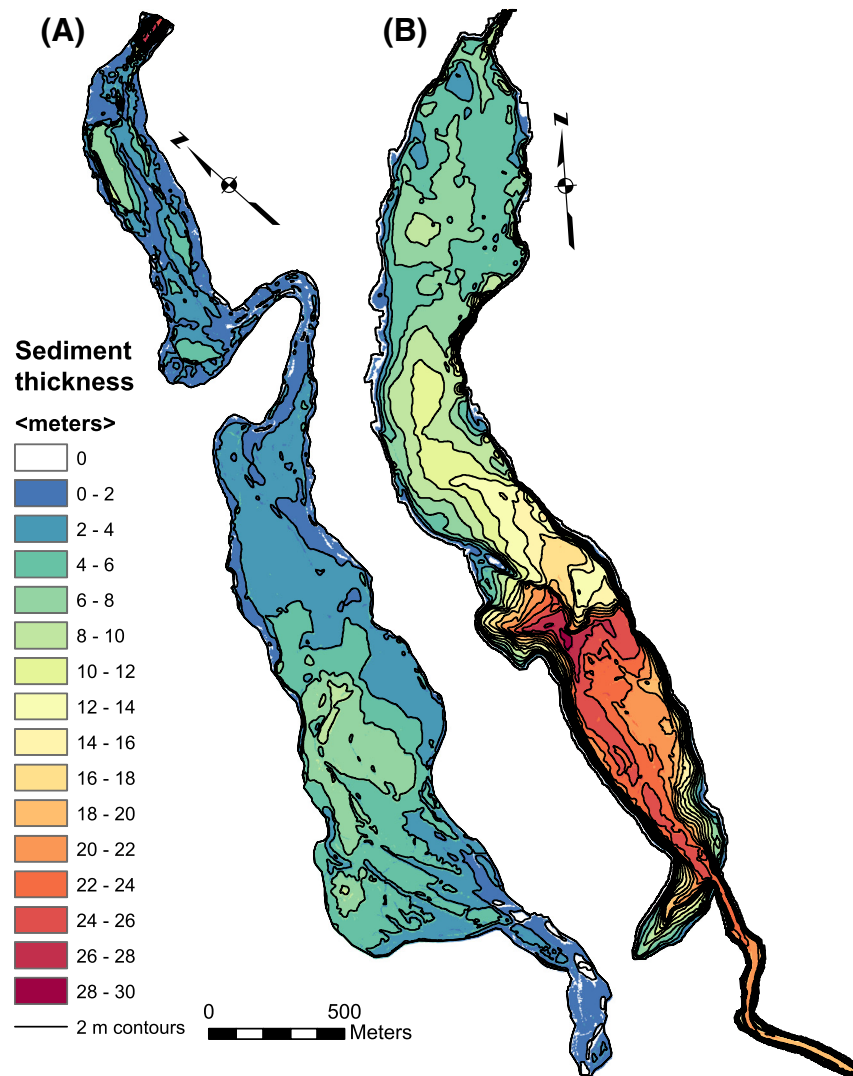


Fig. 4. Reservoir sediment thickness (m) and 2-m contour lines of Lake Aldwell (A) and Lake Mills (B) in 2010, prior to the start of dam removal on the Elwha River, Washington.

1.5 m of aggradation occurred along the former delta in November 2012 through December 2012. By January 2013, the river had incised back through the aggradation in the upper reservoir. By September 2013, the river had downcut 0.5 to 1 m below the predam surfaces along the delta and prodelta. The channel aggraded 1 to 3 m along the lower half of the former Lake Aldwell, so that slope became steeper to more closely match the upstream channel slope. Degradation through the steeper channel in the lower delta had not yet occurred as of September

2013 and the average channel slope remained about 0.005. A backwater with a flatter slope of 0.001 continued for 0.3 km upstream from the bedrock constriction and boulders near the former dam site.

4.1.3. Channel widening

The average channel width through the former Lake Aldwell from May to September 2012 was 66 m, increasing to 77 m in the second year. Along the channel, the width varied considerably, with a standard deviation ranging from 30 to 50 m over 17 time intervals following the loss of Lake Aldwell to September 2013.

Channel width varied by sediment properties of terrace banks and by discharge. The widest and most active areas of lateral erosion occurred along the delta (where at least half of the terrace banks were comprised of coarse and noncohesive sediment), just downstream of the delta where the river crossed the 1913 channel alignment with few tree stumps and in the backwater area of the lower reservoir. For example, during June 2011, the right delta channel migrated 200 m, about 40% of the total deposit width, during flows that were 4 to 5 times the average annual discharge (162 and 191 m³/s) (see Fig. 7). Channel erosion width doubled during storms in November 2011. Localized channel widening occurred during flows equal to and up to 4 times the average annual flow in January 2012, spring snowmelt in 2012 and 2013, and winter high flow peaks in 2012–2013. The morphology of the wider channel was generally braided with multiple

Table 2
Lake Aldwell sediment volume calculations.

Surface	Sediment volume (% of total)	Sediment volume (10 ⁶ m ³)	Average sediment thickness (m)	Surface area (% of total)
Elwha delta above Highway 101	1%	0.071	0.32	13%
Delta	51%	2.5	5.0	30%
Prodelta	17%	0.81	3.4	14%
Reservoir bottom	20%	0.98	2.9	20%
Reservoir				22%
Hillslopes	7%	0.33	0.90	
Fill above dam	4%	0.18	8.1	1%
Totals	100%	4.9		100%

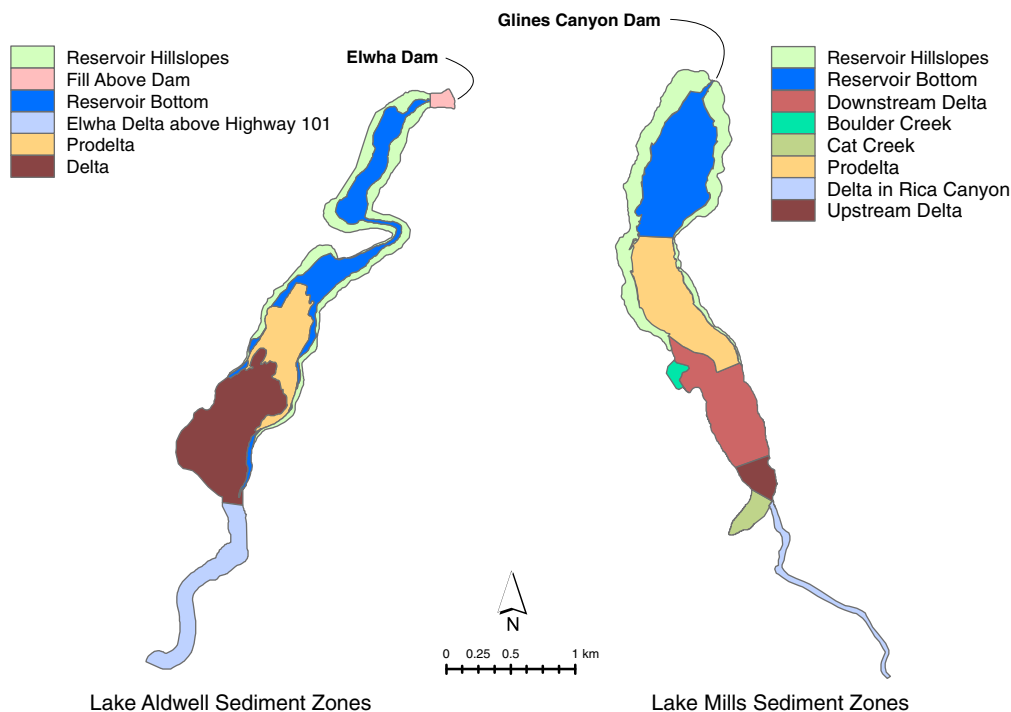


Fig. 5. Reservoir sediment zones in Lake Aldwell (left) and Lake Mills (right) based on conditions in 2010, prior to the start of dam removal on the Elwha River, Washington. Modified from Gilbert and Link (1995).

mid-channel and longitudinal bars. Where channel alignment was along the predam surface, large, well-preserved tree stumps with intact root systems provided roughness and accumulated coarse woody debris during periods of high flow. The largest cedar stumps also acted like jetties along the bank, locally limiting lateral erosion.

The channel was narrower through bedrock-confined segments and where it ran along more cohesive terrace banks or the prodelta that had up to 2-m-high banks composed of lakebed muds. Although narrow, the

channel still contained numerous mid-channel sediment bars. Fine sediment in the delta and bottomset deposits was primarily composed of silt and fine sand, with nonplastic characterization from laboratory testing that would indicate low cohesion. However, the deposits contained ubiquitous amounts of woody material (large logs to small twigs), leaves, and 10 to 20% clay that contributed to cohesiveness. Bulk density also increased with depth in the delta deposits such that older bottom layers were more cohesive than upper layers (Gilbert and Link, 1995).

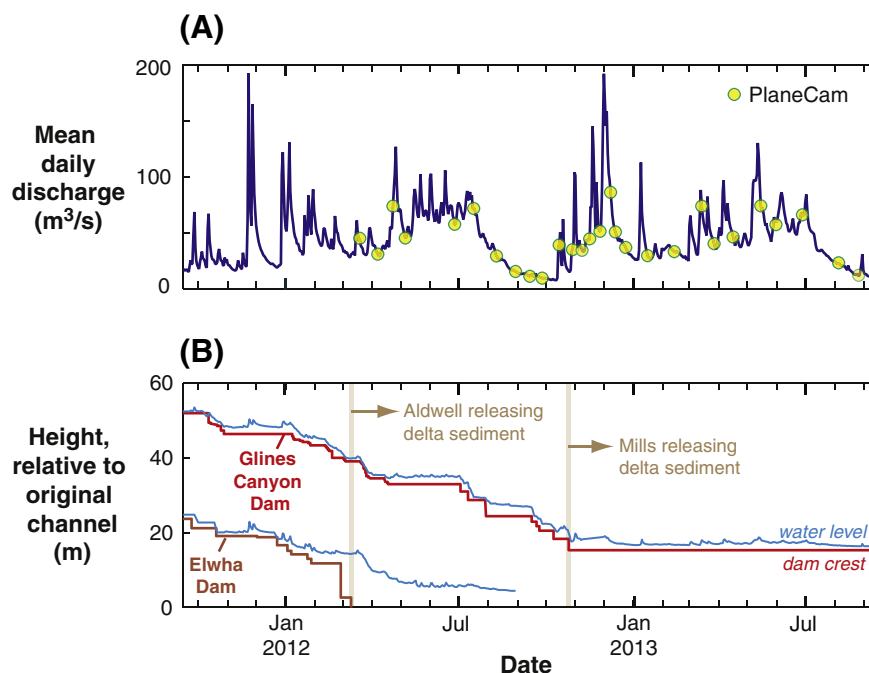


Fig. 6. Timeline of dam deconstruction and monitoring activities for the Elwha River reservoirs near Port Angeles, Washington. (A) River discharge (recorded by the USGS streamflow gage 12045500) and dates of aerial photography data collection. (B) Dam deconstruction as shown by heights of remaining dam crests and water surface levels recorded behind dam structures.

Table 3
Lake Aldwell drawdown results from June 2011 to September 2012.

	Drawdown increment (m) and portion of total (%)	Peak flows (m ³ /s)	Mean flow (m ³ /s)	Average channel slope	Total sediment erosion (year 1)	Reservoir capacity (relative to 2010)	Phased drawdown dates (elapsed time)	Hold period after drawdown completion
1	4.3 (18%)	162	55	0.0027	2%	61%	June 2 to 11, 2011	16 weeks
2	2.1 (26%)	191	32	0.0043	3%	47%	Sept 26 to Oct 1, 2011 (4 months)	2 weeks
3	2.6 (37%)	111	25	0.0048	18%	32%	October 19, 2011 (4 1/2 months)	8 weeks
4	4.6 (60%)	292	47	0.0054	40%	10%	December 19, 2011 to February 3, 2012 (7 to 8 months)	6 week hold with 1.2 m drawdown during flow reduction
5	4.6 (79%)	163	36	0.0049	10%	<5%	March 20 to April 2, 2012 (10 months)	2 weeks
6	3.6 (93%)	58	62	0.0051	26%	0%	April 13 to May 5, 2012 (10 1/2 months)	Gradual drawdown throughout period until lake was lost
7	1.7 (100%)	137	52	0.0048	small, not measured	0%	May 5 to Sept 15, 2012	Minor drawdown during flow reduction

The shape of the Elwha sediment particles of all sizes is generally plate-like or spear-shaped, which may contribute to compaction and resistance to erosion (Childers et al., 2000).

4.1.4. Sediment exported past Elwha Dam

By the end of the study period, a little over two years after the start of reservoir drawdown, only 23% of Lake Aldwell sediment had been

exported past the Elwha Dam, and a large portion of the delta remained in place (see Fig. 7; Table 4). Of the sediment eroded and released from Lake Aldwell during the first two years of dam removal (1.12 ± 0.07 million m³), 83% of the erosion occurred during the first year and 17% occurred during the second year. The release of fine sediment from Lake Aldwell caused temporary increases in downstream turbidity and thin lenses of fine sediment on downstream gravel bars, while sand and gravel transported past the Elwha Dam deposited in low-velocity areas such as downstream pools and eddies, but did not cause reach-scale aggradation in the downstream river (East et al., 2015).

4.2. Lake Mills sediment erosion

Prior to dam removal in 2010, reservoir sediment accumulation in Lake Mills was 3.2 times more than in Lake Aldwell, and sediment thickness was also about 3 times greater, reflecting differences in reservoir size and proximity to the sediment source (upstream watershed). Lake Mills contained 16.1 million m³ (± 2.4 million m³) of sediment with a thickness of 28 to 30 m comprised of 44% fine sediment (silt and clay) and 56% coarse sediment (two-thirds sand and one-third gravel, cobble, and boulder) (Gilbert and Link, 1995; see Fig. 4; see Table 1). In 2010, more than half of the sediment was stored in the delta that filled a portion of the reservoir and extended upstream, beyond the full reservoir pool, into a narrow bedrock canyon and upstream tributaries (Table 5; see Fig. 5). The delta sediments were inversely graded with the coarsest sediment on top and the finest sediment on the bottom (Gilbert and Link, 1995). Sediment was also found to be coarser upstream and finer downstream.

Lake Mills was drawn down 42 m in 10 phased increments between June 2011 and October 2012, which is three-fourths of the total planned drawdown of 58 m (see Fig. 6). The dam removal and reservoir hold periods between these increments ranged from 2 to 10 weeks long (Table 6). Dam removal was suspended from 1 November 2012 through 14 September 2013 as an adaptive management response to problems with the downstream Elwha Water Treatment Plant. More details of river evolution phases during June 2011 to September 2013 are provided below, along with an overview of the delta pilot channel construction prior to dam removal that initiated the first round of erosion.

4.2.1. Delta pilot channel

Prior to dam removal, two channels were present on the far left and right sides of the Lake Mills delta. To encourage lateral erosion and reduce the risk of leaving high unstable sediment deposits, a narrow pilot channel (340 m long, 15 m wide, and 2 m deep) was excavated along the center, upstream portion of the Lake Mills delta in September 2010 (Fig. 9A). A forest of red alder trees growing on the delta deposits

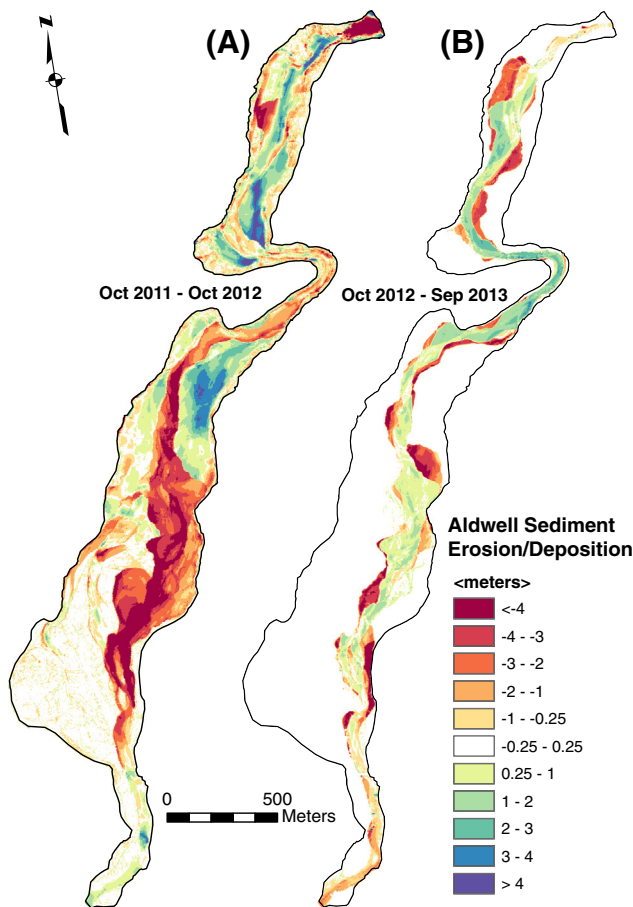


Fig. 7. Sediment erosion and deposition thickness (m) in Lake Aldwell after one year of dam removal in September 2012 (A) and after two years of dam removal in September 2013 (B) as computed using bathymetric survey, LiDAR, and structure-from-motion (SfM)-based photogrammetry data.

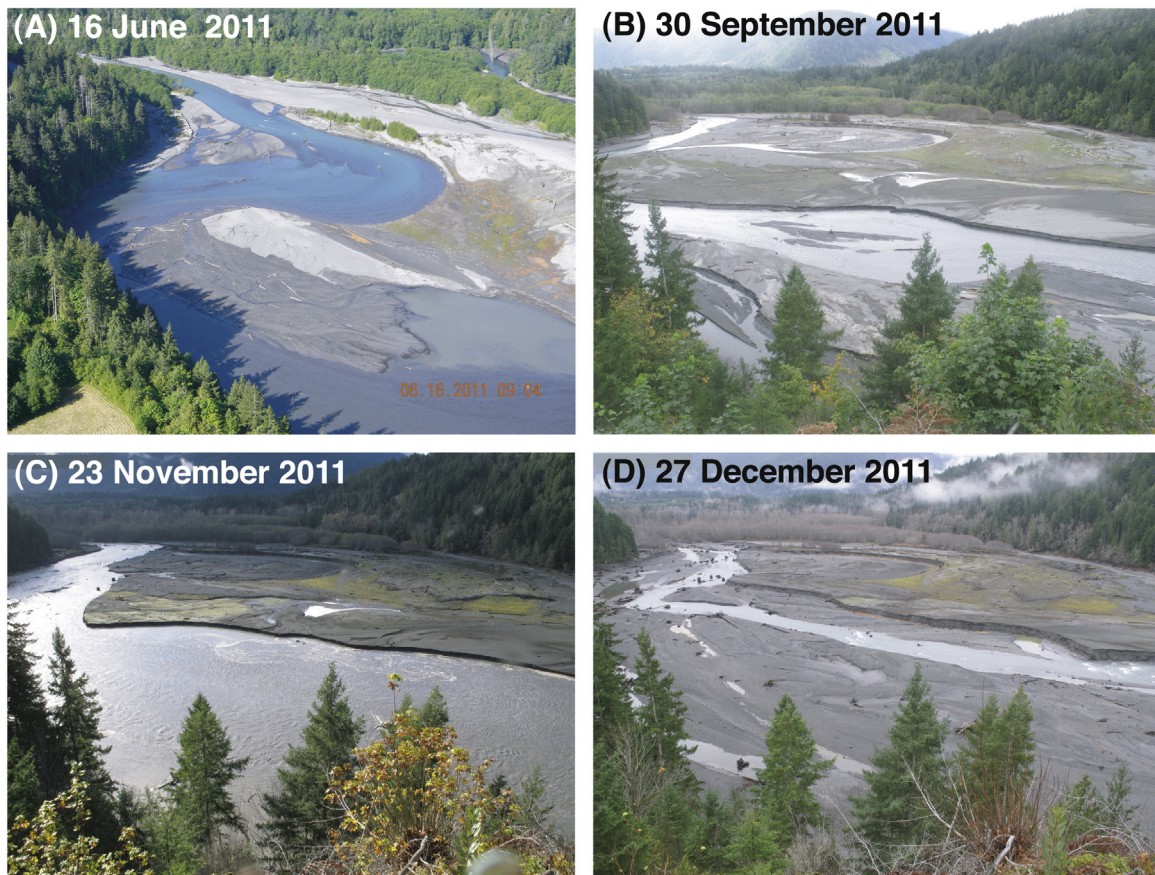


Fig. 8. Repeat web-camera photographs of the Lake Aldwell delta highlighting geomorphic changes that occurred during the summer and fall of 2011. Note the exposure of large tree stumps near the river channel in (D).

was mechanically removed, but some tree roots and buried wood were left in place. Finally, a naturally formed log jam in the path of the pilot channel was relocated across the previously dominant right channel. Lake Mills was drawn down 5 m in late October 2010 to initiate erosion

Table 4

Summary of reservoir sediment erosion during first and second years of dam removal—uncertainty is rounded to one significant figure when the leading digit is greater than two, and the second digit is greater than five, and is otherwise two significant figures, following uncertainty principles discussed in Taylor (1997).

	Lake Aldwell	Lake Mills	Totals
<i>September 2011 to October 2012 (year 1)</i>			
Total sediment erosion volume (10^6 m^3)	0.93 ± 0.05	0.17 ± 0.08	1.10 ± 0.10
Fine sediment erosion volume (10^6 m^3)	0.74 ± 0.05	0.17 ± 0.08	0.91 ± 0.10
Coarse sediment erosion volume (10^6 m^3)	0.19 ± 0.01	0.00 ± 0.00	0.19 ± 0.01
Total sediment erosion mass (10^6 t)	1.16 ± 0.23	0.19 ± 0.11	1.35 ± 0.25
Fine sediment erosion mass (10^6 t)	0.84 ± 0.21	0.19 ± 0.11	1.03 ± 0.23
Coarse sediment erosion mass (10^6 t)	0.32 ± 0.08	0.00 ± 0.00	0.32 ± 0.08
<i>October 2012 to September 2013 (year 2)</i>			
Total sediment erosion volume (10^6 m^3)	0.19 ± 0.05	5.78 ± 0.08	5.97 ± 0.09
Fine sediment erosion volume (10^6 m^3)	0.16 ± 0.05	1.67 ± 0.03	1.83 ± 0.06
Coarse sediment erosion volume (10^6 m^3)	0.03 ± 0.01	4.11 ± 0.07	4.14 ± 0.07
Total sediment erosion mass (10^6 t)	0.23 ± 0.07	8.9 ± 1.8	9.1 ± 1.8
Fine sediment erosion mass (10^6 t)	0.18 ± 0.07	1.9 ± 0.5	2.1 ± 0.5
Coarse sediment erosion mass (10^6 t)	0.05 ± 0.02	7.0 ± 1.7	7.1 ± 1.7
<i>September 2011 to September 2013 (years 1 and 2)</i>			
Total sediment erosion volume (10^6 m^3)	1.12 ± 0.07	5.95 ± 0.12	7.07 ± 0.14
Fine sediment erosion volume (10^6 m^3)	0.90 ± 0.07	1.84 ± 0.09	2.74 ± 0.11
Coarse sediment erosion volume (10^6 m^3)	0.22 ± 0.02	4.11 ± 0.07	4.33 ± 0.08
Total sediment erosion mass (10^6 t)	1.39 ± 0.24	9.1 ± 1.8	10.5 ± 1.8
Fine sediment erosion mass (10^6 t)	1.02 ± 0.22	2.1 ± 0.5	3.1 ± 0.5
Coarse sediment erosion mass (10^6 t)	0.37 ± 0.08	7.0 ± 1.7	7.4 ± 1.7

along the excavated pilot channel (Randle and Bountry, 2012) (Fig. 9B). A subsequent flood peak of $620 \text{ m}^3/\text{s}$ during December 2010 further deepened and widened the narrow pilot channel. The log jam that blocked most of the right channel was partially washed out during the December 2010 flood. However, by that time the pilot channel became the deepest channel on the delta and captured most of the stream flow. By August 2011, the channel had eroded a valley centerline path all the way downstream to the receded reservoir and more than doubled the initial pilot channel width (Fig. 10A).

4.2.2. Delta front progradation

With each drawdown increment, eroded sediment formed a new delta. Deposition on the advancing delta forced the river to migrate laterally and erode exposed sediment terraces near the delta front. By 29 October 2012, Lake Mills had been drawn down 34.7 m and the delta prograded 2160 m to Glines Canyon Dam (Fig. 10C) at an average rate of 216 m per drawdown increment. Reservoir drawdown increments in Lake Mills were large enough that the eroding coarse sediment redeposited as a new delta across the entire width of the receded reservoir. An exception was fall 2012 when the flow was less than half of the average annual flow and the delta front only extended about 100 m downstream and laterally. The most rapid delta growth occurred during peak flows in November 2011 and January 2012 and during a period of high sediment supply from valleywide lateral erosion during the period February through July 2012 (Fig. 10B), when reservoir capacity had dropped to a third or less of the 2010 capacity. Delta progradation resulted in coarse sediment deposition (2 to 10 m thick) on top of the fine prodelta and bottomset deposits (Fig. 11).

New delta topset slopes that formed after each reservoir drawdown were only 5 to 10% (0.0005) of the upstream channel slope during the first 9 months of dam removal from fall 2011 through spring 2012.

Table 5
Lake Mills sediment volume calculations.

Zone	Sediment volume (% of total)	Sediment volume (10^6 m^3)	Average sediment thickness (m)	Surface area (% of total)
Delta in Rica Canyon	7%	1.1	14	4%
Delta	49%	7.8	19	21%
Pro-delta	24%	3.8	9.5	21%
Reservoir bottom	16%	2.6	5.5	25%
Hillslope	Not measured			26%
Cat Creek	4%	0.59	11	3%
Boulder Creek	1%	0.18	8.4	1%
Totals	100%	16		100%

After spring 2012, when less than 20% of the 2010 reservoir storage capacity remained, the topset slope steepened to about one-third of the upstream channel slope until the delta reached the dam in fall 2012. The prograding delta foreset maintained a slope of approximately 0.3 (Fig. 12B, C), reflecting a composition of primarily sand and gravel.

4.2.3. Channel degradation, knickpoint migration, and aggradation

Channel degradation over the first two years of dam removal was greatest (20 m) at the pre-removal delta front (station 2715 m, which is the distance upstream from Glines Canyon Dam) (Figs. 13A, 14). The degradation was half that amount (10 m) in the former prodelta (station 1960 m) and < 10 m farther downstream within the prograded delta sediments. The degradation of 15 m at station 3635 m was less than at station 2715 m because the delta thickness decreased in the upstream direction. As a result of the slower rate of degradation at the upper end of the delta, the average channel slope steepened from 0.006 to 0.009 during the first year of dam removal (Table 6).

During the second year, an additional 10 m of degradation occurred along the middle and upstream portions of the delta even though dam removal activities were on hold. The channel slope flattened from an average of 0.009 back to 0.006 during this time (see Fig. 12). In November and December 2012, channel degradation was most active in the upper half of the reservoir, while lateral erosion and reworking of the prograded delta sediment dominated in the lower reservoir, resulting in aggradation rather than degradation (see Fig. 11). In late December 2012, the degradation began in the lower portion of the reservoir as the sediment supplied from erosion of the upper reservoir was exhausted. From January through September 2013, the degradation continued throughout the whole reservoir. The degradation in the lower part of the reservoir occurred through prograded delta sediment and reached the surfaces of the lakebed and prodelta sediment about 1 km upstream of the dam. As a result, 2 to 4 m of the prograded coarse delta sediment still remained below the channel in the downstream 1 km of the reservoir at the end of this analysis period. In the middle portion of the reservoir, the channel

degraded up to 10 m through the prograded delta sediment and into the prodelta sediment. Farther upstream, the delta degraded up to an additional 8 m.

By September 2013, the profile was flattest in the downstream-most 1.5 km and steepest where it encountered the predam surface about 2.5 km upstream of the Glines Canyon Dam (see Fig. 12). After channel degradation reached the predam valley floor, incision slowed because of armoring and increased resistance from in-place tree stumps with intact root systems, and from more compact soils. Tree stumps from the predam valley-bottom surface began to emerge in the upper half of the reservoir by April 2013. By August 2013, tree stumps were visible on portions of the valley bottom for about two-thirds of the reservoir length.

Degradation, or channel incision, begins when the reservoir water surface elevation is lowered below the elevation of the delta pivot point (slope break between the topset and foreset slopes). However, the amount of degradation at the pivot point is less than the amount of reservoir drawdown (Fig. 13C) because a river channel slope forms downstream toward the dam or new delta front where the lowered reservoir water surface is encountered. The amount of incision (I_L) at any reservoir cross section can be estimated from the longitudinal river channel slope (S) over the distance (L) between the dam and reservoir cross section and the amount of reservoir drawdown (D) relative to the initial sediment elevation at the cross section:

$$\frac{I_L}{D} = 1 - \frac{(SL)}{D} \quad (4)$$

In cases where the prograding delta has not yet reached the dam, the distance (L) can be redefined as the distance between the new delta front and the reservoir cross section.

We found that the average channel erosion slope can be estimated from the upstream delta slope or computed using a sediment transport equation developed for the average bed-material sediment size along the delta (e.g., sand and gravel mixture for the Elwha River). The relative delta incision at three representative cross sections after two years of dam removal is presented in Table 7. The relative incision was about 50% when the average erosion slope was between 0.0056 and 0.0070. However, the relative incision at the gage in Rica Canyon (station 3635 m) was less (37%) because the average channel slope was steeper (0.0074) (because of coarser sediment along the upstream portion of the delta) and over a longer distance.

4.2.4. Channel widening

At the start of dam removal in September 2011, the delta channel degraded and widened (30 to 70 m) but was still relatively narrow, presumably because of resistance or cohesion provided by buried wood and tree roots within the top layer of the previously forested delta.

Table 6
Lake Mills drawdown results from June 2011 to September 2013.

Drawdown increment (m) and portion of total (%)	Peak flows (m^3/s)	Mean flow (m^3/s)	Average channel slope	Total sediment erosion (years 1 and 2)	Reservoir capacity (relative to 2010)	Phased drawdown dates	Hold period after drawdown completion
0 Pilot channel drawdown: 4.3	631	55	0.55%	3%	79%	October 18 to 29, 2010	8 weeks with refilling completed December 24, 2010
1 5.1 (10%)	112	43	0.0056	1%	78%	July 6 to 26, 2011	10 weeks
2 4.1 (18%)	292	40	0.0062	6%	62%	October 4 to 27, 2011	10 weeks
3 3.7 (25%)	103	51	0.0064	2%	50%	January 7 to 20, 2012	3 1/2 weeks
4 5.2 (35%)	72	41	0.0078	3%	35%	February 10 to March 3, 2012	2 weeks
5 4.3 (44%)	59	37	0.0085	7%	22%	March 19 to April 1, 2012	2 weeks
6 0.7 (45%)	137	67	0.0081	15%	15%	April 13 to 18, 2012	10 1/2 weeks
7 5.6 (56%)	156	68	0.0080	7%	7%	July 1 to 16, 2012	2 weeks
8 2.4 (61%)	75	24	0.0080	3%	<5%	July 28 to August 3, 2012	2 weeks
9 4.6 (70%)	44	11	0.0085	1%	<5%	September 15 to 23, 2012	2 weeks
10 2.9 (75%)	215	46	0.0091 to 0.0064	53%	0%	October 5 to 27, 2012	1 year

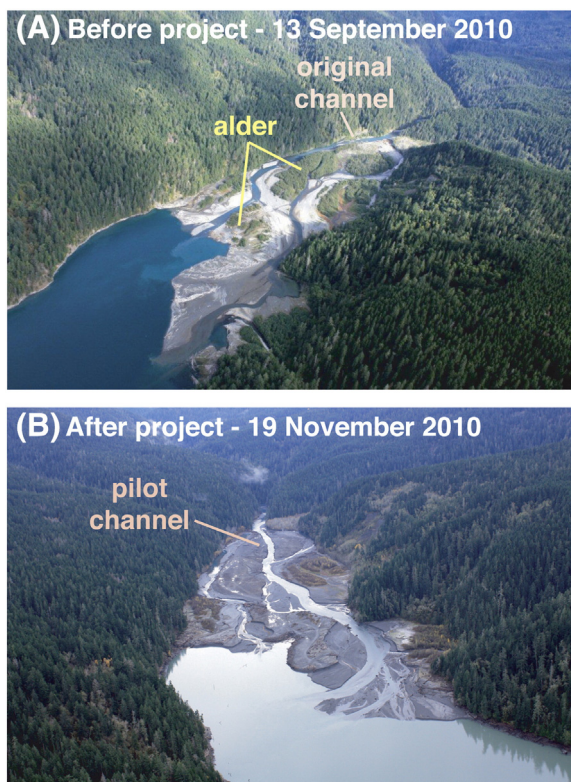


Fig. 9. Oblique aerial photographs of the Lake Mills delta before and after clearing of the alder forest and excavation of a pilot channel during September 2010.

The channel widened by two to three times in some locations during winter storms during late November 2011 and early January 2012. From January to July 2012, the river in the upstream half of Lake Mills became highly braided, changing course daily while reworking noncohesive coarse delta sediment at flows ranging from 30 to 160 m³/s. Aggradation, rather than degradation, occurred during this period, which likely further encouraged lateral erosion. By May 2012 during spring snowmelt, lateral erosion almost completely spanned the valley, reaching widths of up to 340 m (see Fig. 10B). Nearly the entire surface of the pre-project delta had been occupied by the river at least once during the first year of dam removal (Fig. 15).

The channel width throughout the reservoir was highly variable spatially and temporally during the second year, averaging 132 m with a standard deviation of 102 m. The river channel was narrower (averaging 100 m) where it came in contact with more cohesive sediment in the upper and middle portions and wider (average width of 230 m) where it contacted more coarse and noncohesive sediment in the lower portion of the reservoir. Channel widening was most active from late September 2012 through early February 2013 in the newly exposed downstream portion of the reservoir at flows between 20 and 215 m³/s (about half the two-year flood). The channel became highly braided and widened up to tenfold until it reached the full valley width, similar to the response in the delta area the previous year. By September 2013, the channel in the downstream portion of the reservoir narrowed as it degraded into cohesive lakebed sediment during the one-year hold period, reducing the average channel width by a factor of two to three (see Fig. 10D).

4.2.5. Sediment export past Glines Canyon Dam

During the first two years of dam removal, 37% of the sediment volume from Lake Mills was eroded and transported past the dam site in response to incremental reservoir drawdown and subsequent channel degradation and widening (see Table 4). Of the total sediment

eroded and released from Lake Mills during the first two years of dam removal (5.95 ± 0.12 million m³), only 3% of the erosion occurred during the first year because the remaining reservoir trapped the prograding delta sediments (Fig. 16). The majority of sediments released were coarse (sand and gravel).

5. Discussion

During the first two years of dam removal on the Elwha River, unprecedented large-scale reservoir sediment erosion occurred. Our data provide valuable insight on how a river evolves when nearly a century of a mixed grain size sediment deposit is exposed in two concurrent, phased dam removals in the same watershed. While published channel evolution models (Morris and Fan, 1998; Doyle et al., 2002; Pizzuto, 2002; Cannatelli and Curran, 2012) and empirical relationships (Sawaske and Freyberg, 2012) have already identified key physical processes and variables important in a dam removal, they were based on experience from small, mostly instantaneous dam removals that respond over short time frames. Previous studies highlight the need for incorporation of more quantitative data and large-scale dam removal cases to extend our understanding and help improve predictive capabilities and sediment management decisions for future dam removal cases. Here we compare and highlight differences in the evolution of the two Elwha River reservoirs with existing channel evolution models, empirical relationships, pre-removal predictions for the Elwha River Restoration Project, and selected case studies. We draw upon this comparison to provide insights on reservoir evolution pathways and sediment management opportunities for future large-scale cases of either dam removal or reservoir drawdown.

5.1. Comparison to channel evolution models and case studies

A few generalized conceptual models exist that use geomorphic analogies to describe reservoir sediment erosion and channel evolution in response to dam removal (e.g., Doyle et al., 2002; Pizzuto, 2002; Cannatelli and Curran, 2012). Starting at dam removal, the following channel evolution steps are categorized: (i) reservoir drawdown and base-level lowering, (ii) degradation and knickpoint migration, (iii) continued degradation and widening, (iv) aggradation and widening, and (v) quasi-equilibrium once vegetation and floodplain development occur (Doyle et al., 2002; Pizzuto, 2002). Cannatelli and Curran (2012) expanded upon this model to note the linkages between hydrologic cycles and degradation and widening and aggradation and narrowing. Ferrer-Boix et al. (2014) used laboratory experiments and a numerical model to describe the effects from three dam removal increments on the erosion of a reservoir nearly full of poorly sorted sediment. They observed an additional channel evolution step of degradation and narrowing, followed by degradation and widening.

5.2. Unique factors of Elwha River reservoirs not documented in existing channel evolution models

Channel evolution in Lake Aldwell and Lake Mills generally followed documented channel evolution steps in the first two years. However, channel evolution within these reservoirs was complicated by three factors not documented in the channel evolution models referenced above, or in recently published case studies (Randle and Greimann, 2004; Wildman and MacBroom, 2005; Walter and Tullos, 2010; Major et al., 2012; Bountry et al., 2013; Evans and Wilcox, 2013; Tullos and Wang, 2014; Wilcox et al., 2014). First, each Elwha River reservoir began with a pool that was 70 to 80% of the original reservoir length at the time of dam construction. Combined with a phased dam removal, this provided an opportunity to redistribute eroded reservoir sediment through a process of iterative delta progradation not possible in dam removals where sediment has already reached the dam at the start of the project or where dams are suddenly breached. This also allowed

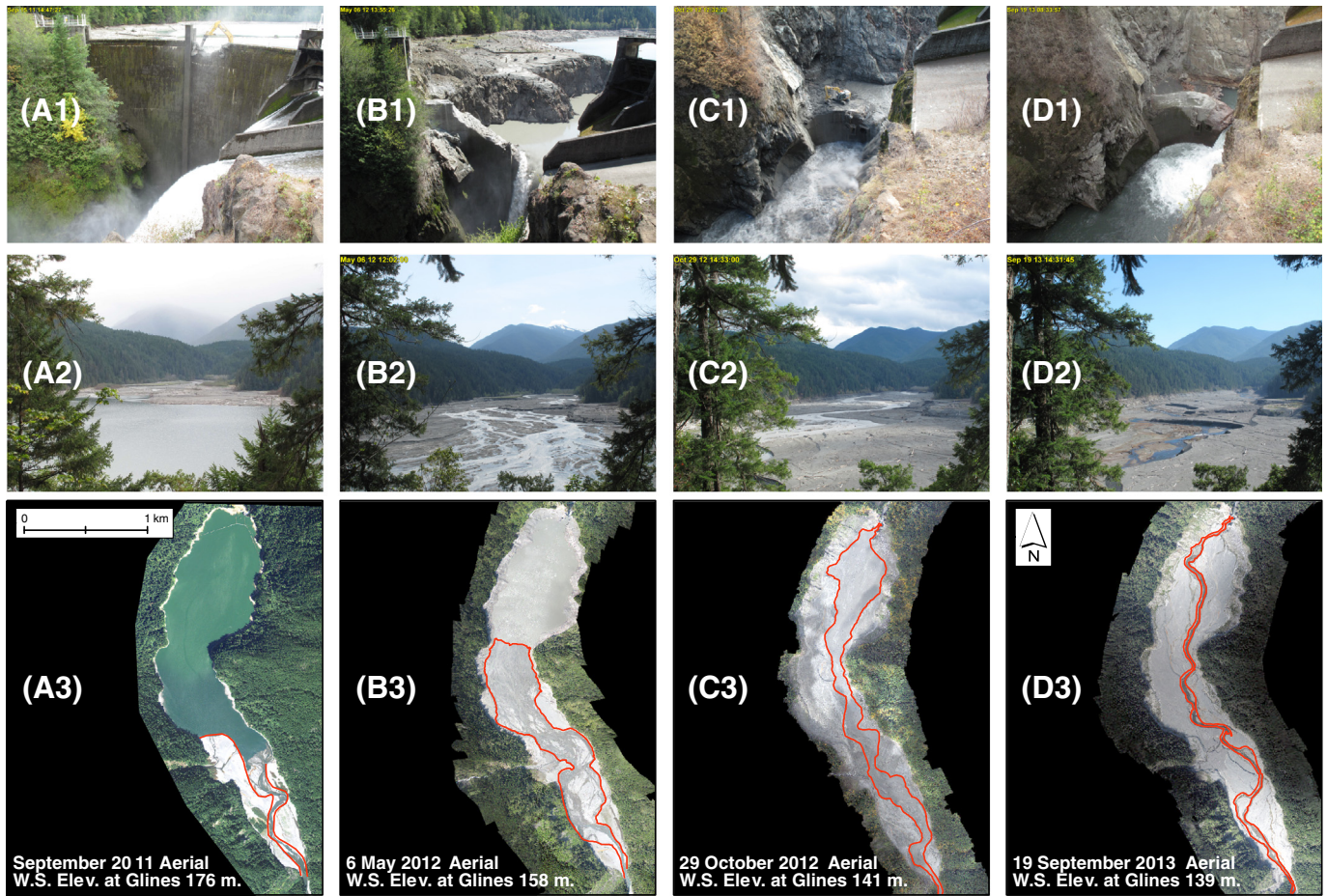


Fig. 10. Repeat photographs looking upstream at Glines Canyon Dam (top row: A1, B1, C1, D1), looking upstream at Lake Mills delta (middle row: A2, B2, C2, D2), and repeat aerial photographs of Lake Mills (bottom row: A3, B3, C3, D3) highlighting geomorphic changes that occurred during two years of dam removal. The red lines indicate the left and right banks of active channel erosion at each time step. Note the downstream advancement of the delta over time and evolution of the channel planform from narrow and sinuous (A) to wide and braided (B), to narrower and incised (C), and to even more narrow and incised (D). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sediment deposition to be largely contained within the reservoirs during initial dam removal until the delta reached the dam.

Second, the thick reservoir deposits and burial and compaction of fine lakebed sediments by prograding coarse delta sediments resulted in high terrace banks that continued to exceed critical bank height stability conditions well after the river reached predam surfaces. The deposition of several meters of coarse delta sediment on top of fine lakebed sediment, especially in Lake Mills, undoubtedly caused some compaction and increased the cohesive properties of the underlying layer of fine lakebed sediment. As the layered terrace banks eroded, the upper layer of coarse sediment would collapse and temporarily bury and buttress the underlying bank of fine sediment.

Finally, the phased and concurrent removal of the Elwha Dam and Glines Canyon Dam resulted in multiple base-level lowering increments with several superimposed channel evolution cycles occurring at different locations and times within the reservoirs. We address the specific effects of phased and concurrent drawdown in driving reservoir response within the documented evolution steps described in the literature.

5.3. Degradation and knickpoint migration

As described in conceptual channel evolution models, the degradation occurred immediately upstream of the base-level lowering at all observed stream flows of the Elwha River and tributaries entering the reservoirs. The degradation within the first 0.5 km upstream of a given drawdown location was not limited by grain size. For example,

the short Boulder Creek delta (tributary to Lake Mills)—containing larger grain sizes than the Lake Mills delta—degraded and kept pace with reservoir drawdown even with less stream flow than the Elwha River. The channel immediately upstream of the base-level change had a steep slope resembling a short cascade, which was also reported for Anaconda Dam (Wildman and MacBroom, 2005), Marmot Dam (Major et al., 2012), and Savage Rapids Dam (Bountry et al., 2013). During the removal of Condit Dam, knickpoints rapidly migrated upstream owing to the composition of finer grain reservoir sediments (60% sand, 35% silt and clay, 5% gravel) and the very rapid drawdown of the reservoir (Wilcox et al., 2014). During the removal of Marmot Dam, the knickpoint initially migrated rapidly upstream at a rate of meters per minute for the first several minutes (150 m in 50 min), but then slowed substantially (Major et al., 2012).

As the Lake Mills delta eroded and prograded downstream toward the dam, the length of the sediment erosion channel increased over time. As the channel lengthened, the upstream migration of the knickpoints tended to stall during low flows where knickpoints encountered cobbles and boulders. Higher flows, near the mean-annual flood, were required for continued upstream advancement of the knickpoint into the upper reservoir, which agrees with the findings of Pizzuto (2002) and with the results from Anaconda Dam (Wildman and MacBroom, 2005) and Marmot Dam (Major et al., 2012).

Once the river reached the predam surface, the degradation slowed. Because Lake Mills had a one-year hold period with a portion of the dam still remaining, the channel did not reach the predam surface in the

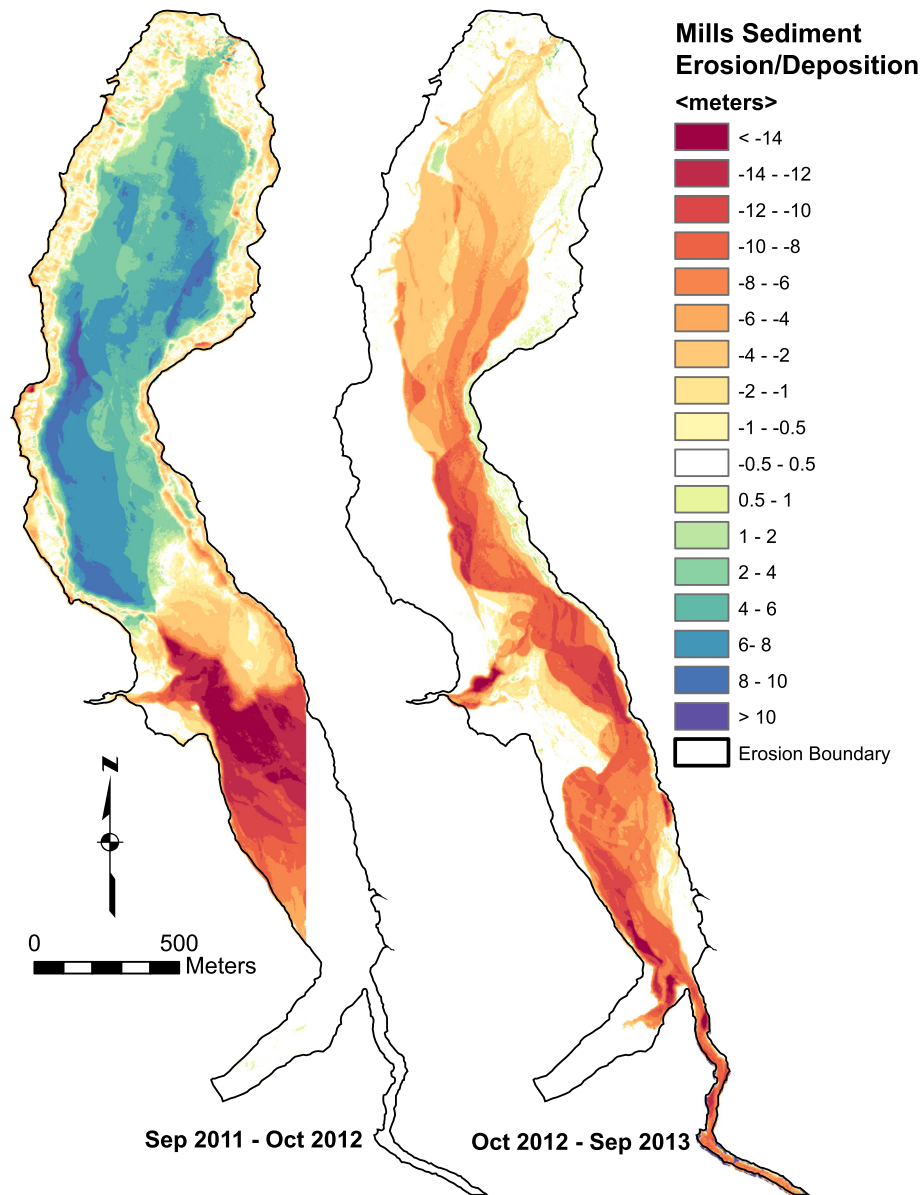


Fig. 11. Sediment erosion and deposition patterns in Lake Mills at the end of year 1 and year 2 as measured using bathymetry, LiDAR, and structure-from-motion (SfM)-based photogrammetry data.

downstream half of the reservoir, although it did in the upstream half where incision slowed dramatically. As multiple knickpoints migrated upstream for the entire length of the reservoir, the longitudinal slope of the erosion channel in the downstream reservoir (where the channel was perched on redeposited sediment) became flatter (0.005) than the predam channel slope (0.007).

5.4. Degradation and narrowing

When multiple channels existed at the beginning of a reservoir drawdown increment, the channel with the most flow tended to degrade first and capture the flow from the other channels. This was the plan for the pilot channel excavated at Lake Mills. Stream capture was also reported at the Anaconda Dam (Wildman and MacBroom, 2005) and Marmot Dam (Major et al., 2012). As the dominant channel continued to degrade in Lake Aldwell and Lake Mills, the width of incision became narrower than the combined width of the multiple channels. Degradation and narrowing were also observed in Lake Aldwell and

Lake Mills when the river channel initially incised through the upper layer of coarse sediments into the underlying layer of fine cohesive sediments.

5.5. Degradation and widening

Channel degradation and widening were prevalent at Lake Aldwell and Lake Mills as predicted by Doyle et al. (2002). As predicted by Cannatelli and Curran (2012), channel widening was more rapid when streamflows were greater than the mean annual flow. However, the extent of channel widening was significantly affected by whether the river was eroding into coarse (noncohesive) sediment or the fine-sediment layers in the reservoirs.

Channel evolution models and the case study at the Anaconda Dam (Wildman and MacBroom, 2005) suggest that the channel will degrade down to the armored predam channel bottom and then widen. For the removal of the Marmot Dam, channel widening of the reservoir sediments began after knickpoint passage and slowing of channel incision

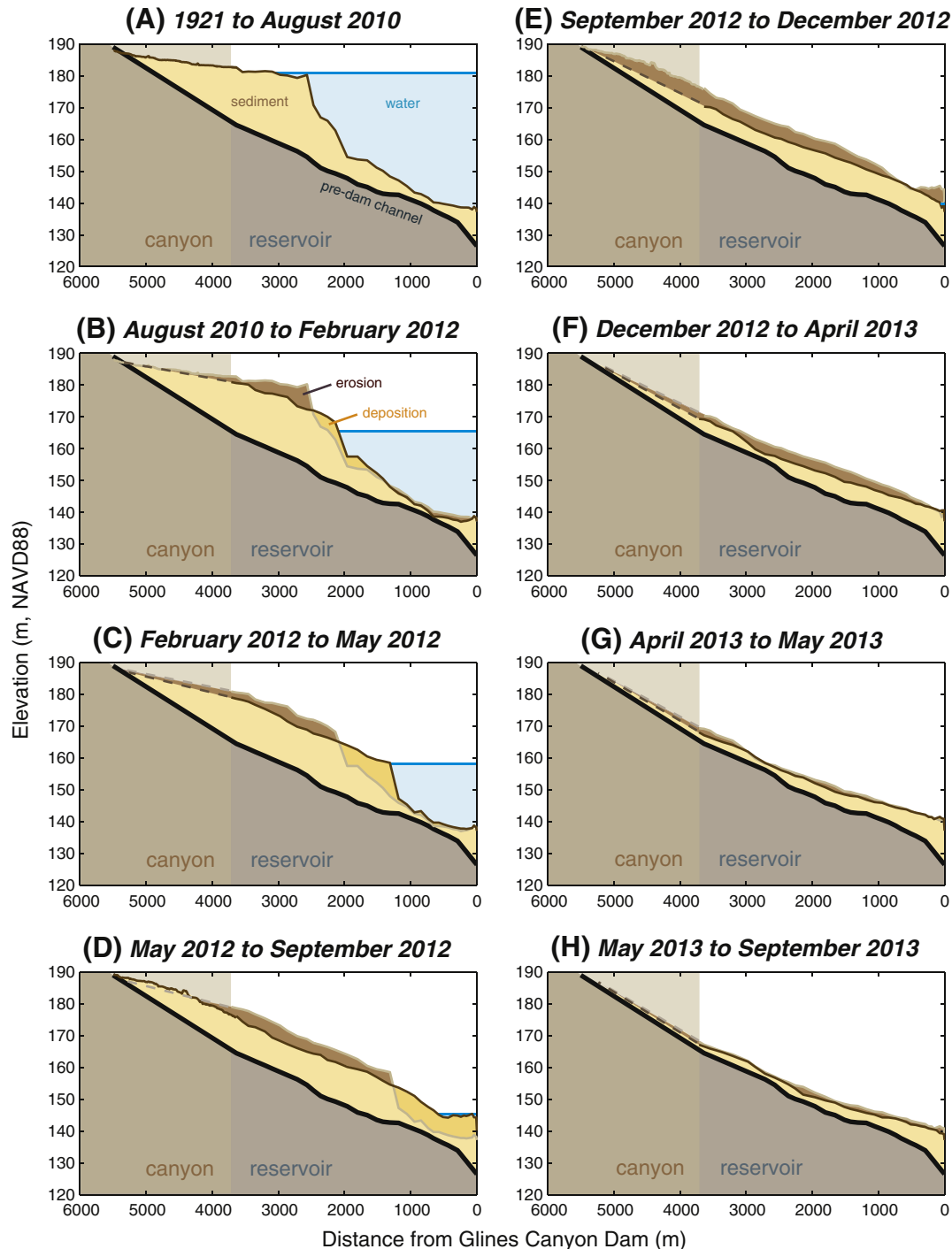


Fig. 12. Longitudinal profiles of the Elwha River thalweg through Lake Mills and the lower Rica Canyon. Each subplot shows the longitudinal reservoir profile for the initial and ending of the time interval noted. Regions of erosion and deposition are highlighted with colored shading. Longitudinal profiles of Rica Canyon were either approximated assuming uniform slopes between survey data and the initial extent of sedimentation (dashed lines, B–H) or obtained from local minimum in the 2010 and 2012 aerial LiDAR surveys (solid lines, A–B, D–E). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Major et al., 2012). Channel widening at Lake Mills and Aldwell did accelerate after degradation had significantly slowed or stopped, either after the channel had adjusted to the new base level corresponding to the reservoir drawdown or after reaching the coarse sediment of the predam river surface.

The braided erosion channels in the coarse sediment layers of Lake Aldwell and Lake Mills were much wider than channels eroding through the underlying fine-sediment layer. One departure from the conceptual models was that the critical height of the channel banks was exceeded

in both reservoirs. The mass wasting described by Doyle et al. (2002) occurred in both reservoirs, in fine sediment layers and in coarse sediment layers with fine sediment and woody material. Channel widening occurred with increases in streamflow and because of channel braiding in coarse sediments and migration of meander bends in fine sediment.

Channel widening also occurred as eroding delta sediments deposited across the entire width of the receding reservoir. This occurred every time the reservoir drawdown increment exceeded 2 m and the streamflow was near or above the mean annual flow. The erosion width from this

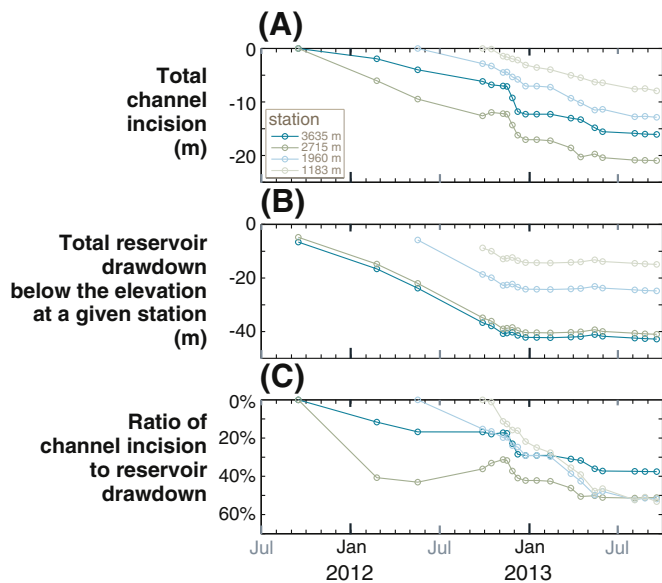


Fig. 13. Time series plots of total channel incision (m) (A), total Lake Mills reservoir drawdown (m) below the sediment elevation at a given station (B), and the ratio of channel incision to reservoir drawdown (C) at locations on the pre-project delta (stations 3635 and 2715 m), prodelta (station 1960 m), and lakebed (station 1183 m).

process generally equaled the local reservoir width at the delta front and gradually decreased in the upstream direction for a distance approximately equal to the local reservoir width.

The predam surface of both Elwha reservoirs had abundant stumps from primary forests that were logged as part of dam-building, before the reservoirs were filled. Log jams and these large stumps acted in concert with compacted soil and fluvial lag deposits of the predam surface to limit lateral erosion and slow incision. The effect of the exposed wood is not documented in the conceptual models. For the Elwha reservoirs, log jams could limit or slow lateral erosion but be undermined by degradation. Large tree stumps were less likely to be undermined but could be outflanked. Log jams that formed on large stumps seemed most resistant to degradation and to outflanking.

Dense vegetation grew on the exposed fine sediment surfaces, primarily the lakebed mud on the valley slopes of Lake Aldwell and Lake Mills. The original delta remnant terraces in Lake Aldwell also grew dense vegetation, but vegetation has been much slower to grow on the coarse, well-drained terraces in Lake Mills. While vegetation helped to control aeolian and rill erosion, it has not stopped or slowed bank erosion.

5.6. Aggradation and widening

In conceptual models and in the case study of the Anaconda Dam (Wildman and MacBroom, 2005), aggradation is reported to help form a new floodplain with more natural channel geometry. In Lake Mills

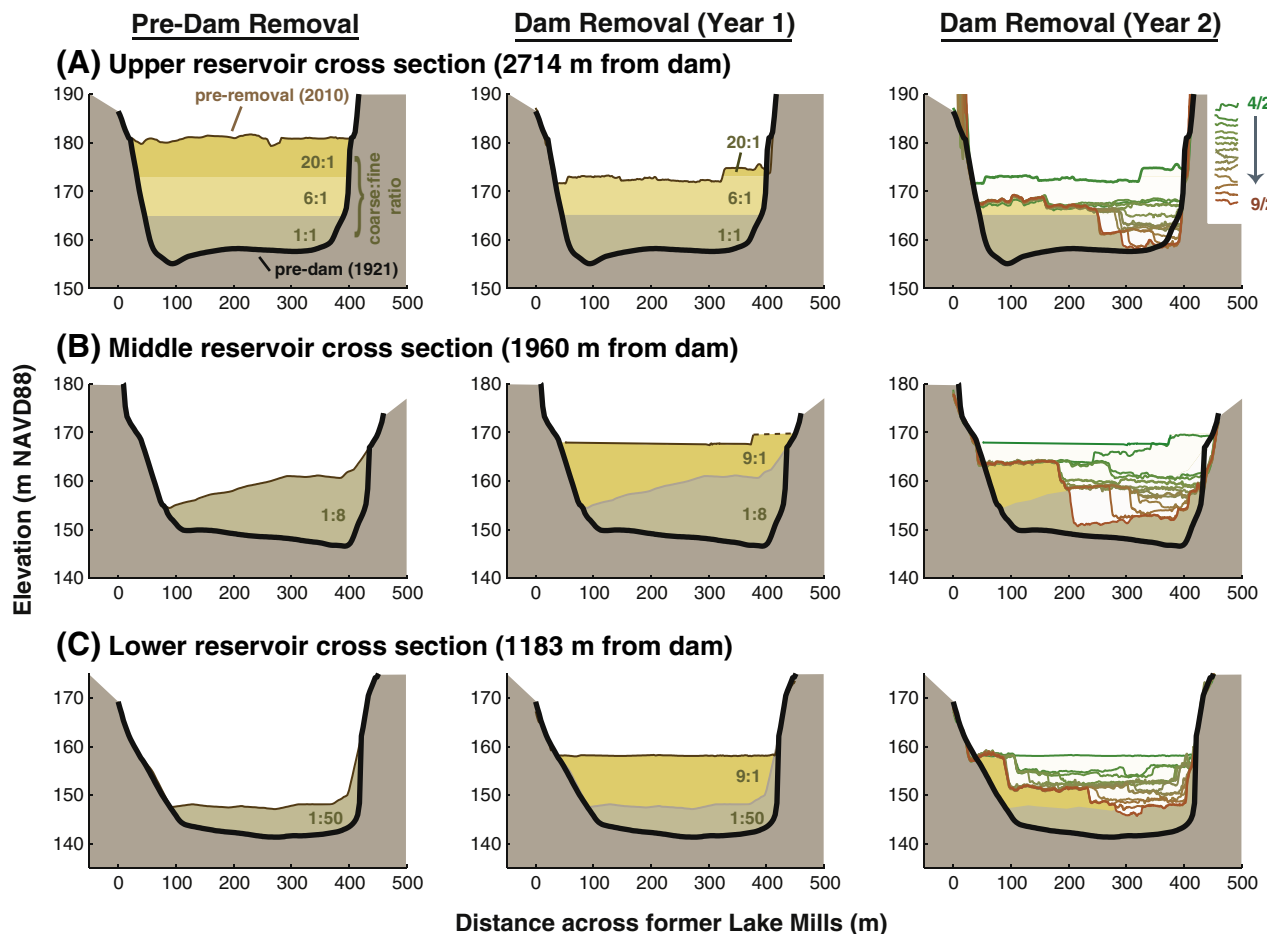


Fig. 14. Evolution of Lake Mills cross sections in the delta (A), prodelta (B), and lakebed (C), which are located 1180 m, 1960 m, and 2715 m upstream from Glines Canyon Dam, respectively. The pre-removal conditions (July 2010) are presented for each cross section along with conditions one and two years after the beginning of dam removal (October 2012 and September 2013). The proportions of coarse and fine sediment are presented for the pre-removal conditions and after one year of dam removal. The greatest proportion of coarse sediment was in the upper layer of the pre-removal delta (A) while the greatest proportion of fine sediment was in the pre-removal lakebed (C).

Table 7
Relative delta incision by September 2013 at three representative cross sections.

River station (km above Glines Canyon Dam)	Erosion slope	Reservoir drawdown at river station (m)	Incision at river station (m)	Measured incision relative to drawdown	Computed incision relative to drawdown
1183	0.00564	14.9	7.9	53%	55%
1960	0.00595	24.8	12.9	52%	53%
2715	0.00695	41.0	21.0	51%	54%
3635	0.00744	42.8	16.1	38%	37%

and Lake Aldwell, 1 to 3 m of aggradation occurred because of excess sediment supply from degrading upstream reaches, as described by Doyle et al. (2002), but additional causes not identified in the conceptual evolution models were also important: the deposition of delta sediments into the receded reservoir lengthened the river channel, reducing the slope and driving aggradation. Sediments aggraded the river channel in an upstream progression from the advancing delta to achieve a longitudinal slope capable of transporting large sediment loads. Typically the aggradation progressed upstream until the channel was confined and helped to drive lateral erosion. Channel aggradation also occurred because of the bedrock canyon constrictions at the former dam sites, which caused backwater pools upstream during floods. Large boulders left at the former site of the Elwha Dam resulted in higher riverbed elevations than the predam condition, which caused aggradation for hundreds of meters upstream.

5.7. Quasi-equilibrium

Conceptual models and case studies designate the final evolution stage following dam removal as when a new floodplain has developed as a result of aggradation and when channel degradation and widening have slowed or completed (Doyle et al., 2002; Pizzuto, 2002; Cannatelli and Curran, 2012). Most case studies document this cycle to be largely completed within a few months to a few years, once aggradation reduces the critical height of remaining sediment terraces such that they are no longer unstable and likely to continue eroding (Wildman and MacBroom, 2005; Walter and Tullos, 2010; Major et al., 2012; Bountry et al., 2013; Evans and Wilcox, 2013; Tullos and Wang, 2014; Wilcox et al., 2014). Lake Mills did not reach quasi-equilibrium simply because 25% of the Glines Canyon Dam still remained at the end of the first two years of dam removal, the predam surface had not been reached at all

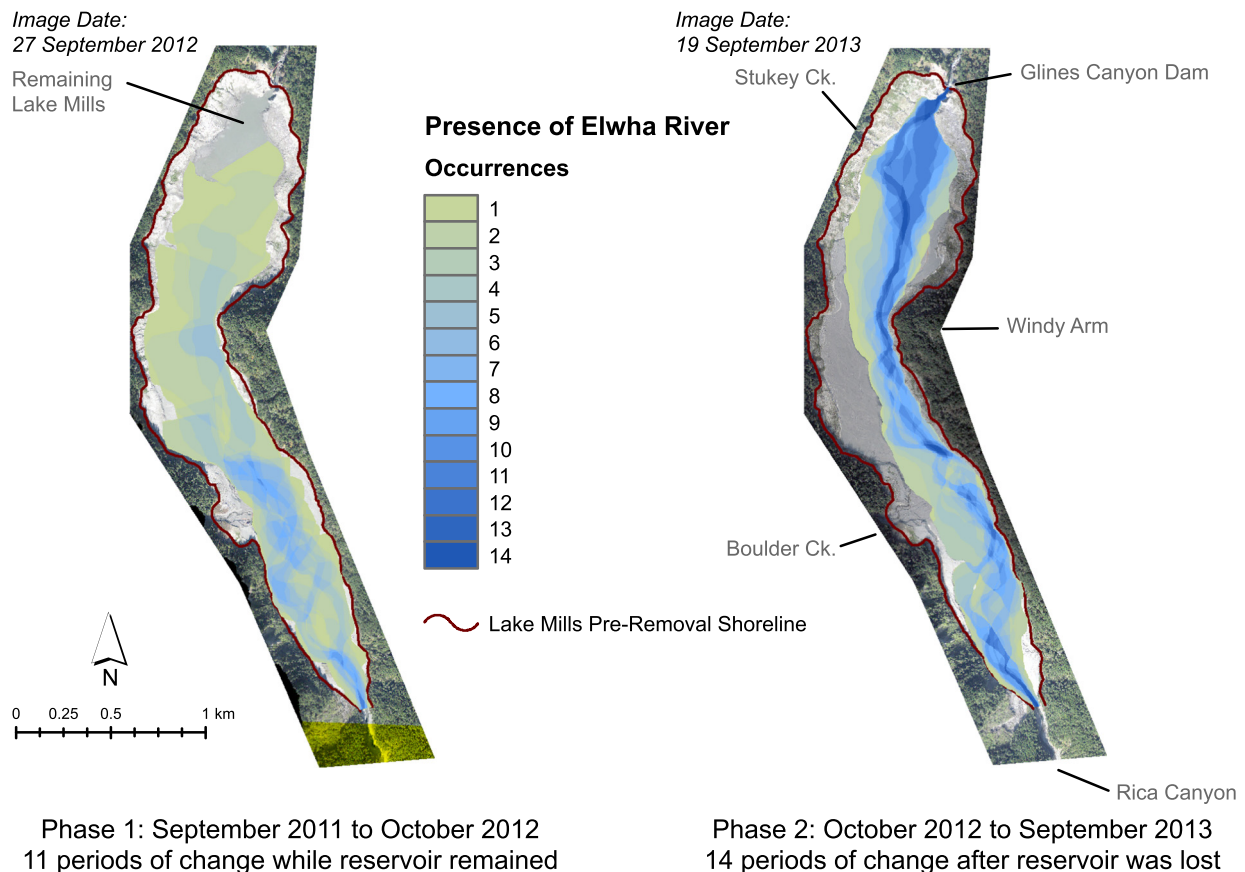


Fig. 15. Occurrences of Elwha River channel occupation across Lake Mills while a reservoir still remained and the delta was prograding downstream (phase 1) and after the reservoir was lost (phase 2). Each occurrence of channel occupation typically represents a one-month period corresponding to the intervals of structure-from-motion (SfM)-based photogrammetry. Higher numbers of occurrences represent locations more frequently occupied by the river channel during dam removal. During phase 1 the river occupied multiple locations across the valley as delta sediment was eroded and redistributed downstream toward the dam. During phase 2 the river occupied a narrower portion of the valley as the river incised into the newly deposited sediment features and began interacting within more cohesive sediment layers and the resistant predam surface.

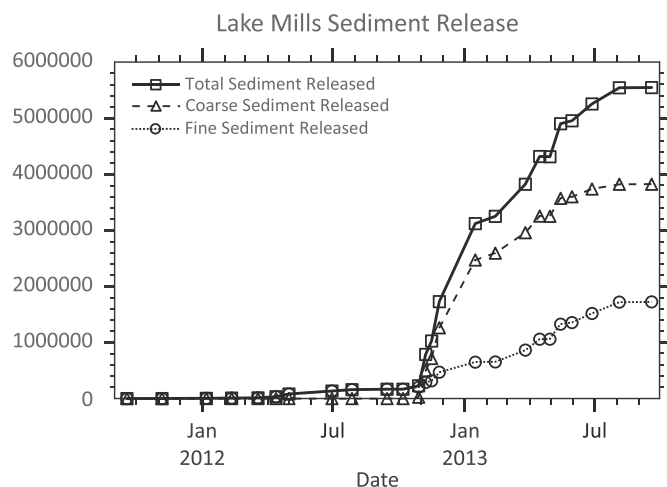


Fig. 16. Cumulative sediment volume eroded from Lake Mills by time interval for the first two years of dam removal. Data through 29 October 2012 are from field measurements. Data after 29 October 2012 are from surface differences between SfM-derived photogrammetry flights. Rica Canyon sediment volumes are not included in this figure.

locations, and significant incision and lateral widening continued to occur during the one-year hold period. Lake Aldwell was completed earlier and began to exhibit some signs of quasi-equilibrium, such as a significant reduction in lateral erosion and incision in the year following dam removal completion. However, only a few months after the completion of the Elwha Dam removal, the Lake Mills reservoir sediment release arrived at Lake Aldwell, initiating aggradation and widening unique to a project with multiple concurrent dam removals. For this reason and because of the lack of a flood (≥ 2 -year flood peak) that could again increase erosion rates, quasi-equilibrium was not reached by the end of the analysis period on Lake Aldwell.

Conceptual models also note that quasi-equilibrium includes vegetation establishment on remaining reservoir sediment to help stabilize the banks and slow rates of erosion. The terrace banks of both former Elwha River reservoirs were typically too high for new or old vegetation roots to stabilize the banks. This is different than the channel evolution model described by Cannatelli and Curran (2012).

5.8. Empirical relationships

Sawaske and Freyberg (2012) provided several empirical relationships regarding the amount of reservoir sediment eroded as a result of dam removal. They evaluated studies of 12 dam removals, all smaller than 14 m high and with $< 800,000 \text{ m}^3$ of reservoir sediment volume. Their analyses indicated that the most influential factors in determining the rate and percentage of reservoir sediment erosion volume include the median grain size, level of cohesion, spatial variability of the deposit, slope-to-width ratio, and length of time to remove the dam and drain the reservoir. These factors were also found to be important in the Elwha reservoirs.

Sawaske and Freyberg (2012) showed that in 'nonstaged' removal, reservoir sediments which comprised primarily of sand had the highest portion of erosion ($\sim 65\%$), sediments which comprised primarily of gravel had the next highest portion ($\sim 35\%$ to $\sim 55\%$), while sediment which comprised primarily of silt and clay had the lowest portion of erosion ($< 15\%$). The results presented for the three cases of 'staged' or phased dam removal are similar, except that only about 12% of the sediment eroded from the wide reservoir behind Stronach Dam on the Pine River (Michigan, USA), which was primarily composed of gravel. The portions of sediment erosion from Lake Aldwell (23%) and Lake Mills (37%) also follow the grain size pattern because the sediments predominantly eroded in the first two years were layered silt and sand from Lake Aldwell and sand and gravel from Lake Mills.

Sawaske and Freyberg (2012) suggested that the proportion of reservoir sediment erosion during staged dam removal is relatively lower than the nonstaged removal because of lower channel heights and the increased time that reservoir sediments are exposed to consolidation and revegetation. However, this suggestion does not apply to the Elwha River dam removals because the reservoir sediment deposits are much thicker than the critical bank height and too thick for vegetation to appreciably reduce the erosion rates.

Rapid removal of Condit Dam triggering mass failures of the thickly accumulated reservoir sediment, where more than 60% of the sediment eroded within 15 weeks after breaching the dam (Wilcox et al., 2014). However, the phased removal of the Elwha River dams allowed more time for the lateral erosion to occur and is believed to have increased the proportion of reservoir sediment erosion over what would have happened under a more rapid dam removal. Compilation and analysis of data from additional dam removals, as well as completing analyses of the full Lake Mills dam removal, is needed to more definitively determine how the pace of dam removal and reservoir drawdown affect the proportion of reservoir sediment erosion.

Sawaske and Freyberg (2012) found that $< 15\%$ of the reservoir sediment eroded when the reservoir sediment width was more than 2.5 times the river channel width. However, the portions of sediment erosion from Lake Aldwell and Lake Mills exceeded 15% even though the ratio of the reservoir-sediment width to the river-channel width exceeded 4. The higher percentage of erosion from Lake Aldwell and Lake Mills is believed to be a consequence of the phased dam removal. Data presented by Sawaske and Freyberg (2012) also showed that the reservoir sediment erosion rate is about the same as the watershed sediment yield. This probably means that the reservoir sediment volumes in their data sets were roughly equal to the mean annual load of the river. However, the two Elwha River reservoirs had trapped (and later eroded) decades of sediment load and, thus, do not fit the relationship.

The ratio of the channel slope to relative width does seem to explain much of the variance in the percentage of sediment erosion for the cases presented by Sawaske and Freyberg (2012). The sediment erosion from the two Elwha River dam removals also seems to fit this relationship (Warrick et al., 2015), but the percentage of reservoir sediment erosion is expected to increase over time, especially for Lake Mills.

The data presented by Sawaske and Freyberg (2012) showed declining reservoir sediment erosion rates over time and the data from the two Elwha River reservoirs agree with this trend. Sawaske and Freyberg (2012) evaluated the data using the dimensionless sediment erosion efficiency, which is defined as the ratio of the reservoir sediment volume eroded to the total volume of streamflow during a specific time interval. Because of the phased dam removal on Elwha, we computed sediment erosion efficiency on a temporal scale for each increment of drawdown. The highest erosion efficiency ratios occurred during hold periods coinciding with moderate to high winter or spring snowmelt flows.

5.9. Comparison to predictions

Patterns of delta erosion in Lake Mills were quite similar to the laboratory results described by Bromley (2007). The scaled laboratory model of Lake Mills represented 1994 delta conditions but did not include the fine lakebed sediments. Experiments were conducted to evaluate the sediment erosion volume in response to the magnitude of base-level lowering and the starting position of the incising channel. In both cases, general patterns of incremental dam removal, degradation and knickpoint migration, delta deposition in the receded reservoir, and channel braiding and widening occurred. Bromley (2007) found that when the channel incised along the middle of the delta, rather than along the margins of the delta, the sediment erosion volumes were much larger because meander bends were able to more fully develop and the channel had a greater overall freedom to adjust laterally over

the entire delta surface. This matched the extensive lateral erosion that occurred across the entire delta surface in Lake Mills.

Randle et al. (1996) developed a numerical mass balance model to simulate the sediment erosion, redistribution, and release from Lake Mills and Lake Aldwell. This mass balance model used empirical rules to simulate the lateral erosion processes. Konrad (2009) utilized a one-dimensional numerical model to assess ecological variables such as the frequency of high sediment concentrations and the riverbed areas experiencing sedimentation that would be detrimental to spawning salmonids. Konrad (2009) predicted most but not all of the sediment would be eroded from the two reservoirs (97% from Lake Aldwell and 70 to 90% from Lake Mills). In contrast, Randle et al. (1996) predicted that reservoir sediment erosion would be 40 to 60% from Lake Aldwell and 30 to 40% from Lake Mills. These predictions are much closer to the measured erosion after two years of dam removal (23% erosion from Lake Aldwell and 37% from Lake Mills). More erosion is expected in the future; but the erosion rates are slowing down at both reservoirs, and a significant portion of the original sediment is expected to remain in the former reservoirs.

Randle et al. (1996) underpredicted the amount of coarse sediment erosion from Lake Mills (10 to 25% predicted versus 46% measured) and overpredicted the amount of fine sediment erosion from both reservoirs (50 to 60% predicted versus 26 to 34% measured). The coarse and noncohesive sediments of the reservoir delta offered little resistance to lateral erosion, while the fine sediment of the prodelta and lakebed proved to be much more resistant even though laboratory tests indicated that the fine sediments were nonplastic.

Randle et al. (1996) assumed that knickpoints would migrate to the upstream end of each reservoir before the next drawdown increment, based upon observations during the 1994 Lake Mills drawdown experiment (Childers et al., 2000). However, the knickpoints tended to stall more than 0.5 km from the reservoir when stream flows were less than the mean annual discharge.

5.10. Management implications

Reservoir sediment management during dam removal can be of critical importance when there may be impacts to downstream water users, infrastructure, or the aquatic environment. The amount and configuration of the sediments left in the reservoir may be of importance for future land use or habitat. Lessons learned from monitoring reservoir evolution during the Elwha Dam removals can be applied to future reservoir sediment management strategies to increase or reduce the magnitude and timing of erosion and downstream release and can be used to identify where uncertainty still exists that may require flexibility in project plans.

Initiating channel incision of the delta along a center alignment (possibly by excavating a pilot channel) can help with lateral erosion of the delta. An initial channel alignment near the predam alignment will help the incision to recover the natural channel. A pilot channel was excavated along the Lake Mills delta. More than 80% of the delta was eroded and redistributed downstream, and the degraded river channel is near the predam channel alignment. In contrast, no pilot channel was excavated on the Lake Aldwell delta. Only about one-half of this delta was eroded, and the new Elwha River channel alignment does not match the predam channel alignment through the former delta. Physical modeling of Lake Mills by Bromley (2007) demonstrated that erosion initiated along the center of the delta was much more effective at eroding the delta than erosion initiated along the reservoir margin.

The phased removal of the Elwha River dams was effective at controlling the rate of reservoir sediment erosion and downstream release. This may be especially important when the amount of reservoir sediment is many times more than the river's mean-annual sediment load. Reservoir hold periods were effective at inducing lateral erosion during periods of moderate to high flow and leaving the remaining sediment in

a series of terraces of varying heights. The optimum reservoir draw-down increment may vary as the reservoir is drained and the length of the erosion channel increases. The hydrologic cycles (low flow or high flow) should be considered when scheduling the dam removal increments.

Flexibility in the schedule for the removal of the Glines Canyon Dam proved essential for limiting the amount of sediment released downstream from Lake Mills during the second year of the project. Wildman and MacBroom (2005) also recommended flexibility for the dam removal sequence and schedule and a broad scope in the permit application.

6. Conclusions

The removal of the Elwha and Glines Canyon Dams on the Elwha River, Washington, provided a unique opportunity to investigate reservoir sediment erosion and channel evolution in response to tens of meters of base-level lowering from phased dam removal. A phased dam removal with river erosion of reservoir sediment effectively controlled the rate and extent of reservoir sediment erosion and downstream release. The seven to ten reservoir drawdown increments of the phased dam removal (3 to 5 m) were enough to initiate channel degradation and delta progradation across the width of the receding reservoir and to redistribute decades worth of accumulated delta sediment throughout the reservoir while the lake still remained.

Even though flows never exceeded the 2-year flood peak, about one-third of the total impounded sediment volume was released during the first two years, representing nearly four decades of sediment supply from the upstream watershed. Despite relatively low clay content, the cohesive properties of fine sediment deposits limited lateral erosion in the wide reservoirs by a factor of one-third to one-half relative to the coarse, noncohesive sediment.

The results from the Elwha River Dam removals are consistent with conceptual models and other studies which find that reservoir sediment erosion and channel evolution are influenced by the hydraulic height of the dam, rate and style of dam removal, sediment management strategies, deposit thickness, impounded sediment volume relative to the mean annual load, deposit and reservoir geometry, grain size and degree of cohesion, and hydrology. Findings from the Elwha River Dam removals suggest that existing channel evolution models could be extended to include the starting position of the delta channel—cases where there is still a reservoir pool between the delta and the dam (common to large reservoirs)—and the superimposed channel evolution cycles occurring from a phased dam removal.

Acknowledgments

The authors would like to thank and acknowledge the following individuals (in alphabetical order) for their field monitoring, analysis, modeling, and help in preparing and reviewing this manuscript: Barnard Construction (monitoring data at dam site); Brian Cluer, NOAA Fisheries (monitoring, time-lapse camera installation); Jeff Duda, U.S. Geological Survey (peer review); Anna Geffre and Heidi Hugunin, NPS, Olympic National Park (monitoring); Sean Kimbrel, Bureau of Reclamation (monitoring, processing of data); Vivian Leung, University of Washington (monitoring, input on large wood); Chris Magirl, U.S. Geological Survey (monitoring, peer review); and Jon Warrick, U.S. Geological Survey (manuscript figure generation). In addition, two anonymous reviewers, Dr. Tom Lisle, and Prof. Richard Marston (Editor, *Geomorphology*) provided insightful comments to greatly improve the value of the paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.geomorph.2014.12.045>.

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