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Large-scale dam removal on the Elwha River, Washington, USA: Source-to-sink sediment budget and synthesis

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ABSTRACT

Understanding landscape responses to sediment supply changes constitutes a fundamental part of many problems in geomorphology, but opportunities to study such processes at field scales are rare. The phased removal of two large dams on the Elwha River, Washington, exposed 21 ± 3 million m^3, or ~30 million tonnes (t), of sediment that had been deposited in the two former reservoirs, allowing a comprehensive investigation of watershed and coastal responses to a substantial increase in sediment supply. Here we provide a source-to-sink sediment budget of this sediment release during the first two years of the project (September 2011–September 2013) and synthesize the geomorphic changes that occurred to downstream fluvial and coastal landforms. Owing to the phased removal of each dam, the release of sediment to the river was a function of the amount of dam structure removed, the progradation of reservoir delta sediments, exposure of more cohesive lakebed sediment, and the hydrologic conditions of the river. The greatest downstream geomorphic effects were observed after water bodies of both reservoirs were fully drained and fine (silt and clay) and coarse (sand and gravel) sediments were spilling past the former dam sites. After both dams were spilling fine and coarse sediments, river suspended-sediment concentrations were commonly several thousand mg/L with ~50% sand during moderate and high river flow. At the same time, a sand and gravel sediment wave dispersed down the river channel, filling channel pools and floodplain channels, aggrading much of the river channel by ~1 m, reducing river channel sediment grain sizes by ~16-fold, and depositing ~2.2 million m^3 of sand and gravel on the seafloor offshore of the river mouth. The total sediment budget during the first two years revealed that the vast majority (~90%) of the sediment released from the former reservoirs to the river passed through the fluvial system and was discharged to the coastal waters, where slightly less than half of the sediment was deposited in the river-mouth delta. Although most of the measured fluvial and coastal deposition was sand-sized and coarser (>0.063 mm), significant mud deposition was observed in and around the mainstem river channel and on the seafloor. Woody debris, ranging from millimeter-size particles to old-growth trees and stumps, was also introduced to fluvial and coastal landforms during the dam removals. At the end of our two-year study, Elwha Dam was completely removed, Glines Canyon Dam had been 75% removed (full removal was completed 2014), and ~65% of the combined reservoir sediment masses—including ~8 Mt of fine-grained and ~12 Mt of coarse-grained sediment—remained within the former reservoirs. Reservoir sediment will continue to be released to the Elwha River following our two-year study owing to a ~16 m base level drop during the final removal of Glines Canyon Dam and to erosion from floods with larger magnitudes than occurred during our study. Comparisons with a geomorphic synthesis of small dam removals suggest that the rate of sediment erosion as a percent of storage was greater in the Elwha River during the first two years of the project than in the other systems. Comparisons with other Pacific Northwest dam removals suggest that these steep, high-energy rivers have enough stream power to export volumes of sediment deposited over several decades in only months to a few years. These results should assist with predicting and characterizing landscape responses to future dam removals and other perturbations to fluvial and coastal sediment budgets.

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1. Introduction

Landscape response to changing sediment flux constitutes one of the oldest and most fundamental problems in geomorphologic research (e.g., Gilbert, 1917; Eschner et al., 1983; Madej and Ozaki, 1996; Lisle et al., 1997; Hoffman and Gabet, 2007; Covault et al., 2013). However, it is not often possible to investigate the effects of rapid, major sediment-supply changes comprehensively over field scales, because of the unanticipated nature of most such events (Sutherland et al., 2002; Gran and Montgomery, 2005; Casalbore et al., 2011; Pierson and Major, 2014) and because of the logistical challenges of quantifying source-to-sink sediment budgets. Intentional dam removals provide perhaps the best opportunities to quantify major sediment movements from watershed source regions, through fluvial systems, and into the coastal zone.

Dam removal has become a viable means to decommission unnecessary or unsafe structures and improve aquatic ecosystems (Graf, 1999; Babbitt, 2002; Heinz Center, 2002; Poff and Hart, 2002; Stanley and Doyle, 2003; Doyle et al., 2008; Service, 2011; De Graff and Evans, 2013; Pess et al., 2014). One common challenge of removing dams, and large dams in particular, is how to manage large volumes of sediment deposited within, and occasionally filling, the reservoirs (Shuman, 1995; Pizzuto, 2002; Hepler, 2013; Wildman, 2013). Reservoir sedimentation occurs from upstream watershed sediment supplies that settle in the relatively quiescent waters behind dams, building deltaic landforms and lakebed deposits in the reservoirs (Morris and Fan, 1997). By the time dam decommissioning is considered, decades, if not over a century, of watershed sediment may have been deposited within the reservoir (Minear and Kondolf, 2009; Sawaske and Freyberg, 2012; Merritts et al., 2013). Because these decadal to centennial time scales of sediment supply are substantially larger than the day-to-annual time scales of dam-removal projects, dam removal may greatly increase sediment supplies to downstream waters and landscapes, resulting in higher water turbidity, increased channel and floodplain sedimentation, greater sediment export from the watershed, and increased nutrient fluxes to downstream waters, all of which have potential effects on downstream hydrology and ecosystems (Stanley and Doyle, 2002; Ahearn and Dahlgren, 2005; Doyle et al., 2005; Riggsbee et al., 2007; Major et al., 2012; Merritts et al., 2013; Wilcox et al., 2014).

Thus, it is imperative to better understand the patterns, rates, and processes of sediment redistribution during and following dam removal and, in doing so, to better understand source-to-sink landscape response to major sediment flux over a range of temporal and spatial scales. Building this understanding through field-based observations, especially in river systems formerly regulated by large dams (taller than 10 m) that hold large quantities of sediment (>10 times the mean annual sediment load), would address the general lack of information about these kinds of systems and the potential for future removals of large dams (Poff and Hart, 2002; Sawaske and Freyberg, 2012; De Graff and Evans, 2013).

The removal of two large, hydroelectric dams on the Elwha River, Washington (Fig. 1), represents a unique opportunity to expand the understanding of the geomorphic and ecological effects of phased, concurrent dam removals (Duda et al., 2008, 2011). Because this project is the largest to date—whether measured by dam height or sediment volume stored in the reservoirs—it serves as an important endmember for the growing body of dam removal research. For example, the formerly 64-m-tall Glines Canyon Dam on the Elwha River (Table 1) was higher than any other previously removed dam. Furthermore, the two dams on the Elwha River stored ~21,000,000 m^3 of sediment prior to removal (Table 1), which is more than an order of magnitude greater than the volume of sediment exposed during the removal of Condit Dam, Washington (1,800,000 m^3 of sediment; Wilcox et al., 2014), and substantially greater than at Milltown Dam, Montana (5,500,000 m^3 of sediment, 40% of which was excavated; Evans and Wilcox, 2013), or Barlin Dam (failure), Taiwan (10,500,000 m^3 of sediment; Tullos and Wang, 2014).

The goals of this paper are to (i) synthesize the new geomorphic research from the Elwha River during dam removal and (ii) develop source-to-sink sediment budgets for the river and its coast during the first two years of dam removal. Our synthesis is drawn largely from four companion papers that provide more detailed information on methods and results about sediment redistribution within the two reservoirs (Randle et al., 2015-in this issue), river suspended and bedload sediment fluxes (Magirl et al., 2015-in this volume), geomorphic change in the river (East et al., 2015-in this issue), and geomorphic change along the coast of the Elwha River delta (Gelfenbaum et al., 2015-in this issue). Combined these studies provide detailed information from which the sediment mass balance was developed and compared to predictions made prior to the Elwha River dam removals (e.g., Randle et al., 1996; Konrad, 2009) and to the results of other dam removals (e.g., Major et al., 2012; Sawaske and Freyberg, 2012; Wilcox et al., 2014) to expand the understanding of the fluvial and coastal geomorphic responses to large sediment-supply perturbations.

2. Background

2.1. Geomorphic effects of dams and dam removal

The geomorphic effects of dams on river systems are well described (Williams and Wolman, 1984; Kondolf, 1997; Graf, 1999, 2006; Yang et al., 2006; Schmidt and Wilcock, 2008; Walter and Merritts, 2008). Many of these physical effects are driven by the deposition of sediment in reservoirs and the hydrologic modifications that occur downstream from dams (Brune, 1953; Ibàñez et al., 1996; Vörösmarty et al., 2003; Magilligan and Nislow, 2005). Although these effects vary widely among river systems, the general pattern that arises is reduced sediment flux downstream of the dam, which may cause channel incision, bed armoring, modified rates of lateral channel movement, and lower rates of sediment deposition in the downstream channel and on the floodplain (Williams and Wolman, 1984; Petts and Gurnell, 2005; Graf, 2006; Draut et al., 2011; Dai and Liu, 2013). The effects of dams on coastal sediment budgets, where sediment supplies are necessary for wetlands and littoral cells, can also be pronounced (Ly, 1980; Willis and Griggs, 2003; Syvitski et al., 2005; Warrick et al., 2009; Yang et al., 2011).

The removal of dams can reintroduce two sources of sediment to the river and its downstream landforms and habitats: sediment that had previously settled within the reservoir and is made available through erosion and sediment that is supplied from geomorphic processes in the watershed upstream of the reservoir. Combined, these new sources of sediment may result in downstream effects including increased rates of suspended and bedload sediment transport, deposition within the channel and its margins, and modification of the streambed grain size (Doyle et al., 2003; Cheng and Granata, 2007; Riggsbee et al., 2007; Major et al., 2012; Draut and Ritchie, 2013; Evans and Wilcox, 2013; Wilcox et al., 2014). The net effects of these renewed sediment supplies can vary greatly as a function of the amount and type of sediment released, the style and rate of dam removal, and the physical setting of the former reservoir(s) and downstream landscape (Doyle et al., 2003; Sawaske and Freyberg, 2012).

For example, both Marmot and Condit dams released >10% of their stored sediment during the first 24 h after the hydraulic opening of these dam structures; and both systems eroded the majority (>50%) of their total reservoir sediment within several months (Major et al., 2012; Wilcox et al., 2014). Following two years of erosion after the removal of Marmot Dam and the observation that the remaining sediment was isolated high above armored or bedrock banks, Major et al. (2012) concluded that it is 'unlikely that substantial additional sediment from the reservoir site will enter the system unless very large flows occur' (p. 2). In contrast, Merritts et al. (2013) reported that removal of smaller

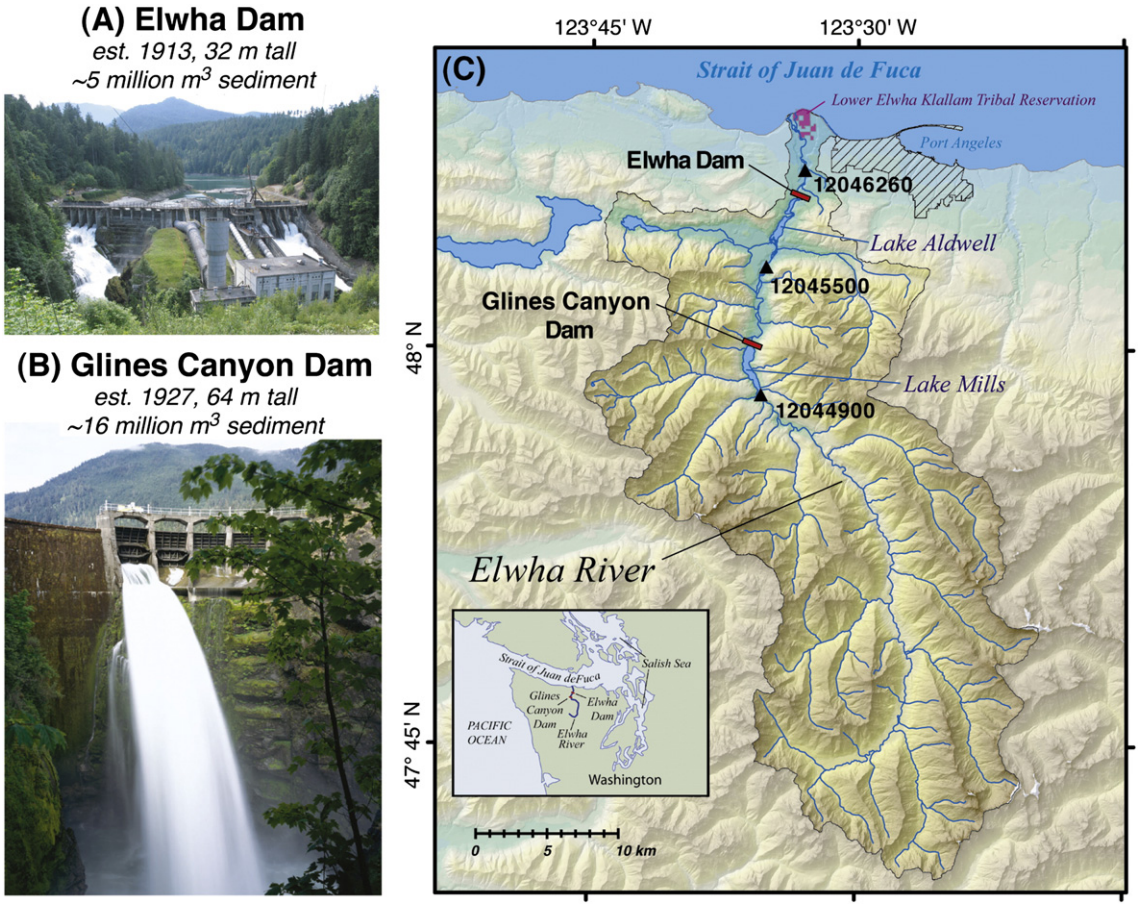

Fig. 1. (A–B) Photographs of the two former dams on the Elwha River, Washington, prior to decommissioning. (C) Map of the Elwha River watershed, showing the watershed, the locations of the dams, USGS river-gaging stations (numbered triangles), the Salish Sea regional setting (inset), and other boundaries. Photos provided by Erdman Video Systems in collaboration with the National Park Service and Scott Church.

milldams in the mid-Atlantic region of the USA resulted in at least several decades of increased sediment production owing to stream bank erosion of the former slackwater sediments (cf. Walter and Merritts, 2008). Other dam removals, such as the 2.2-m-high St. John Dam removed in 2003 from the Sandusky River, Ohio, resulted in export of only ~1% of sediment stored in the reservoir owing to low bed gradients in the river system (Cheng and Granata, 2007).

Thus, there have been large differences in the geomorphic responses of river systems to dam removal. It has been hypothesized that these differing responses are related to reservoir sediment and watershed hydrologic conditions (e.g., Doyle et al., 2002, 2003; Pizzuto, 2002), and a recent inventory by Sawaske and Freyberg (2012) suggests that reservoir sediment variables such as sediment cohesion, deposit geometry, channel geometry, and removal strategy significantly influence the

Table 1
Characteristics of the former dams and reservoirs on the Elwha River, Washington; sediment information after Randle et al. (2015-in this issue).

	Elwha Dam	Glines Canyon Dam
Reservoir name	Lake Aldwell	Lake Mills
Year of completion	1913[a]	1927
Location on river (Rkm)	7.9 Rkm	21.6 Rkm
Dam type	Concrete gravity	Concrete arch
Total height (m)	32 m	64 m
Height of hydraulic control of reservoir water surface above original channel bed, flood gates open (m)	24 m	52 m
Power generation	12 MW, four units, 30 m head	16 MW, one unit, 59 m head
Reservoir water storage at construction (million m^3)	10 million m^3	50 million m^3
Sediment stored at removal (million m^3)	4.9 ± 1.4 million m^3	16.1 ± 2.4 million m^3
Sediment grain-size distribution at removal (by volume)[b]	53% fine 47% coarse	44% fine 56% coarse
Sediment stored at removal (million t)	6.8 ± 2.3 million t	23 ± 6 million t
Sediment grain-size distribution at removal (by mass)[b]	43% fine 57% coarse	35% fine 65% coarse

[a] The original Elwha Dam was built during 1911–1912, but failed catastrophically on 31 October 1912. The second dam took just over one year to build.
[b] *Fine* and *coarse* sediments are distinguished at the sand–silt grain-size diameter threshold of 0.063 mm according to the Wentworth scale.

rate of sediment erosion and export. We will reexamine these findings and hypotheses below following a presentation of the Elwha River data.

2.2. Elwha River study site

The Elwha River drains northward from the steep landscape of the Olympic Mountains and discharges into the Strait of Juan de Fuca about 10 km west of Port Angeles, Washington, USA (Fig. 1). The majority of this 833-km^2 watershed lies within Olympic National Park, which is a UNESCO World Heritage Site and a UN International Biosphere Reserve with minimal development (Duda et al., 2011). Detailed descriptions of the history and hydrology of the river and coastal settings can be found in Tabor (1987), McNulty (1996), Brandon et al. (1998), Montgomery and Brandon (2002), Mosher and Hewitt (2004), Polenz et al. (2004), Draut et al. (2008, 2011), Duda et al. (2008, 2011), Warrick et al. (2009, 2011), and Magirl et al. (2011, 2015-in this volume), and a few relevant highlights of these findings are summarized below.

The Olympic Mountains developed from Eocene to Miocene marine metasedimentary, sedimentary, and volcanic rocks that are part of the broader accretionary wedge along the Cascadia subduction zone (Tabor, 1987; Brandon et al., 1998). Vertical uplift of the Olympic Mountains continues at rates of ~0.3–0.6 mm/y, owing to the active tectonics of this region (Brandon et al., 1998; Montgomery and Brandon, 2002). The study area has also been shaped by Quaternary glacial processes, which include continental ice sheets that carved the Strait of Juan de Fuca and alpine glaciers that shaped the watershed hinterlands (Easterbrook, 1986; Porter and Swanson, 1998; Mosher and Hewitt, 2004; Polenz et al., 2004).

The hydrology of the Elwha River is dominated by winter precipitation, which comes as both rain and snow (Duda et al., 2011). This causes two kinds of high flow events during the hydrologic year: winter storm runoff events and the spring snowmelt freshet. Peak flows commonly occur during late fall or early winter rainfall, and the 2-, 10-, and 100-year annual recurrence interval floods are calculated to be 400, 752, and 1240 m^3/s, respectively (USGS Station 12045500; Elwha River at McDonald Bridge, Fig. 1C; Duda et al., 2011). The drier summer season (July–September) is represented by lower flows, and the median summer discharge is typically 20–40 m^3/s (Duda et al., 2011).

The combination of active tectonics and high precipitation—up to 5 m/y of mean annual precipitation in the watershed headlands (Duda et al., 2011)—result in relatively high rates of denudation and sediment supply compared to similarly sized watersheds throughout the world (Montgomery and Brandon, 2002). Curran et al. (2009) used sediment measurements and load-estimation techniques to estimate that the average total annual sediment load above the former Lake Mills ranged from 217,000 to 510,000 t/y (USGS station 12044900; Fig. 1C). This flux of sediment is equivalent to a sediment yield of 410–960 t/km^2/y from the 531 km^2 of upper watershed draining to this station. This result can be compared with the 16 million m^3, or ~23 million t, of sedimentation within Lake Mills over its 84-year measurement interval, which suggests that an average of 270,000 t/y of sediment was deposited in the reservoir (cf. Table 1). Assuming that the measured trap efficiency of Lake Mills (80%; Magirl et al., 2015-in this volume) is applicable to the lifetime of this reservoir, reservoir sedimentation suggests that the upper watershed sediment load is 340,000 ± 80,000 t/y (Magirl et al., 2015-in this volume), consistent with the Curran et al. (2009) results. The sediment supplied and available to the river is derived from a broad distribution of grain sizes (clay to boulder) owing to the parent material and the glacial history of the watershed (Childers et al., 2000; Czuba et al., 2011; Randle et al., 2015-in this issue).

2.2.1. Geomorphic effects of the Elwha River dams

Two large, privately owned dams were built on the Elwha River during the early twentieth century for hydropower (Table 1). These dams substantially reduced sediment flux to the lower watershed and completely blocked upstream fish migration. Elwha Dam was completed in 1913 and was located at river kilometer 7.9 (Rkm; river stationing convention in kilometers upstream from the river mouth at the Strait of Juan de Fuca), whereas Glines Canyon Dam was completed in 1927 and was located at Rkm 21.6. Since 1975, both reservoirs were kept full and freely allowed to spill water that exceeded hydroelectric usage needs, an operation status described as largely *run-of-the-river* (USBR, 1996; Johnson, 2013).

At the time of dam removal in 2011, ~21 million m^3 of sediment was stored in the two reservoirs, more than half of which was sand-sized and coarser (>0.063 mm; Table 1). Fluvial and coastal landforms downstream from the dams exhibited geomorphic fingerprints of these dam-influenced sediment reductions (Pohl, 2004; Warrick et al., 2009; Draut et al., 2011). For example, Draut et al. (2011) reported that the fluvial bed sediment upstream of the dams within Olympic National Park was poorly sorted with extensive patches of sand, whereas in the first few kilometers downstream from the dams the bed sediment was coarser, less mobile, and better sorted. Mean grain size of the active river channel bed increased from 39 mm upstream of the dams to 120 mm in a reach centered 1.5 km downstream from the dams (Draut et al., 2011), reflecting substantial bed coarsening in response to sediment retention in the reservoirs. Similarly, Warrick et al. (2009) used topographic mapping, aerial photographs, and grain size measurements to show that the Elwha River delta shoreline had been erosional during the latter twentieth and early twenty-first centuries, and that erosion rates had increased significantly with time to average rates of 3.8 m/y during 2004–2007. This beach erosion resulted in a broad, flat, armored, low-tide terrace of cobble clasts too large to be transported by the coastal waves and currents (Warrick et al., 2009).

2.2.2. Elwha River dam removal schedule

The full removal of the Elwha and Glines Canyon dams occurred to restore the Elwha River ecosystem and native anadromous fisheries in a manner that was deemed safe, environmentally sound, and cost effective (Randle et al., 2015-in this issue). Removal of both dams was conducted by incremental, or phased, dismantling of the dam structures and draining of the reservoirs (Figs. 2 and 3). Dam removal was halted during planned *fish windows* to protect downstream anadromous fish at various life stages, planned *holding periods* to adaptively manage sediment redistribution and releases, and unplanned project delays (Randle et al., 2015-in this issue). Both sites also had early pre-removal drawdown increments to initiate erosion processes prior to the commencement of dam removal activities (Randle et al., 2015-in this issue).

Elwha Dam was removed by a sequential series of excavations and channel switching through two alignments, the spillway and the original canyon, owing to the geometry and amount of rock fill upstream of this structure (Fig. 2A–C). The fill material near the dam included rocks, wood *mattresses*, hydraulically placed sediment, and gunnite placed to help rebuild the concrete dam after the original structure failed in 1912. During removal, switching between the two channels was orchestrated by use of temporary earthen cofferdams, and the final channel change back into the original canyon was conducted on 16 March 2012, six months after removal began (Fig. 2D). Once the river was diverted into the natural canyon alignment for the last time, the dam and spillway sites were graded and revegetated (Fig. 2D, E). Excavation of the dam fill material from the river channel continued in late March and April 2012, and these activities resulted in a lowering of the river channel elevation and full progradation of the reservoir's delta (Fig. 4) to the dam site in late April 2012.

During the removal of Glines Canyon Dam, water was passed through the dam's gated spillways while a hydraulic hammer—mounted on an excavator that was floating on a barge—was used to chip away at the dam's concrete structure (Fig. 3A). As the dam was lowered below the spillways, water passed directly over the remaining crest of the dam, which was still being removed by hydraulic hammer (Fig. 3B). The lowering of Lake Mills water levels resulted in delta progradation toward Glines Canyon Dam (Fig. 4A). Beginning in July

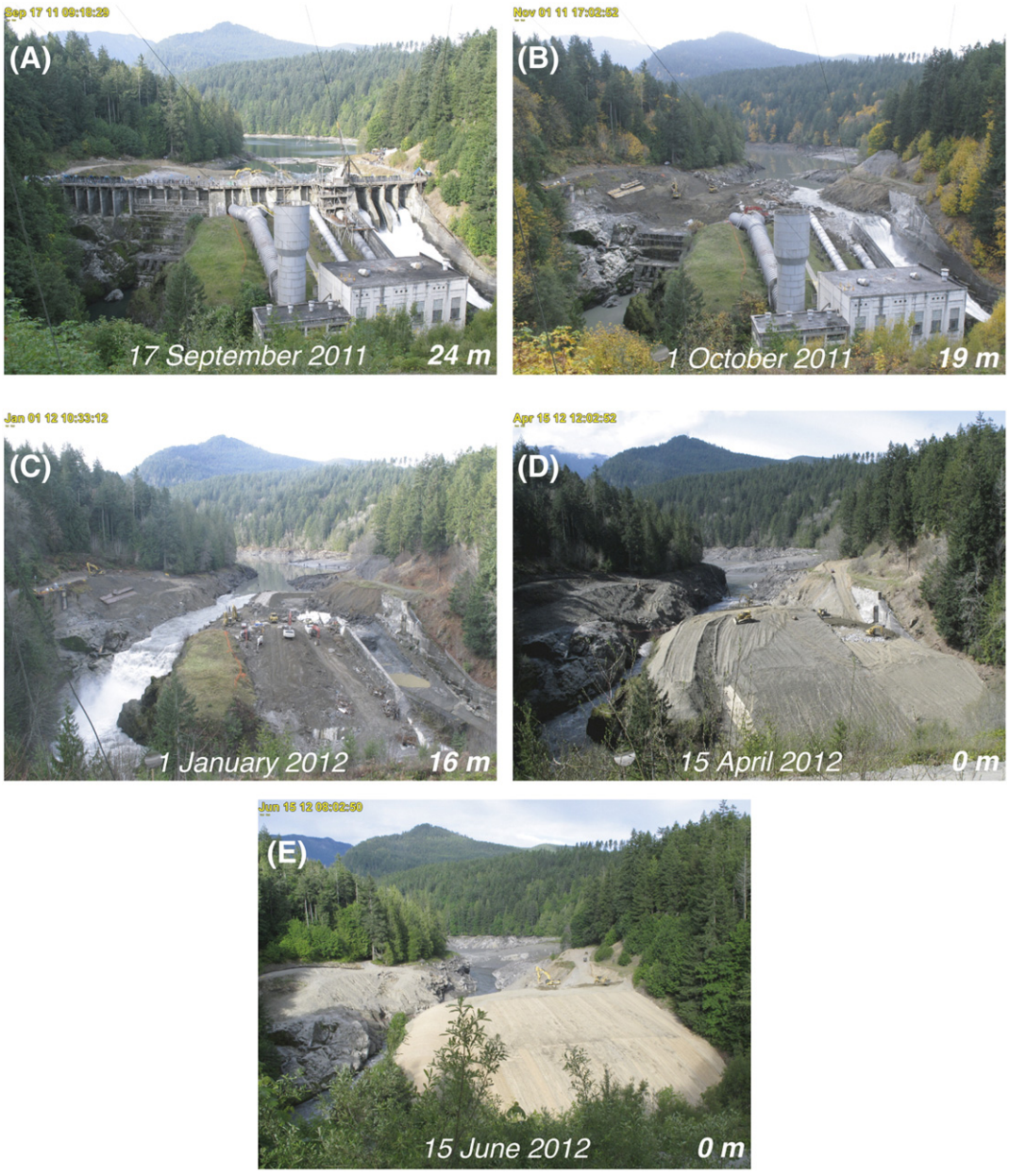

Fig. 2. Decommissioning of Elwha Dam as shown by photos from National Park Service time-lapse cameras. Dates and remaining heights of the water surface above the original channel bed are shown in each photo. (A) The initiation of dam removal in mid-September 2011. Removal of the dam involved successive excavation of the spillway (B; right side of photo) and the dam structure (C; left side of photo) and multiple managed shifts using earthen cofferdams to alter the river course through these waterways. (D) The Elwha River in the spring of 2012 following the final managed river shift into the excavated canyon. (E) Final graded hillside of the Elwha Dam site following dam removal. Photos provided by Erdman Video Systems in collaboration with the National Park Service.

2012, explosives were used to remove 4- to 14-m vertical increments of the dam in alternating notches. Once coarse reservoir sediment began to spill past Glines Canyon Dam in late October 2012, dam removal was halted and did not resume again until October 2013. At the end of the two-year interval of time reported upon here, Glines Canyon Dam was 16 m high over the original channel bed elevation (Fig. 3D). The final dam removal activities were planned for—and occurred—in 2014.

3. Methods

The methods used to collect and analyze the data presented here will be described briefly, and readers will be directed to a number of source documents—most of which are the companion papers—for the details of data collection. The methods described include topographic surveys to characterize changes in the reservoir, downstream river and coastal areas, sediment mass flux measurements, and development of the sediment mass balance for the first two years of dam removal.

3.1. Surveys and sampling

The primary data used to identify and track changes to the Elwha River and its landforms were topographic and bathymetric surveys. Observations of the reservoirs utilized numerous data sources and field techniques including historical maps, real-time kinematic (RTK) global positioning system (GPS) surveys using a rover and base station, combined RTK-GPS and single-beam fathometers from watercraft for the subaqueous portion of the reservoirs, aerial lidar surveys, time-lapse cameras, digital elevation models (DEMs) generated from aerial photographs, surveyed ground control points, Structure-from-Motion (SfM) photogrammetry, and dam crest elevations at each dam site that were

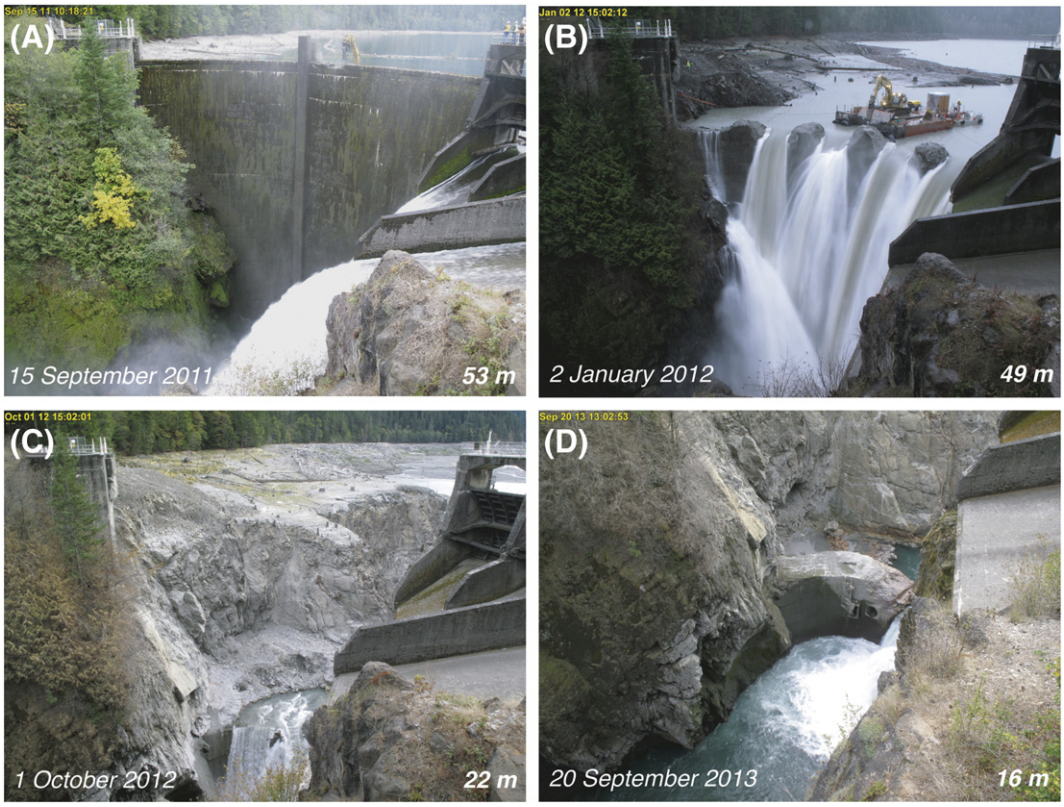

Fig. 3. Decommissioning of Glines Canyon Dam as shown by photos from National Park Service time-lapse cameras. Dates and heights of the water surface above the original channel bed are shown in each photo. (A) The initiation of dam removal in mid-September 2011. An excavator floating on a barge and equipped with a hydraulic hammer can be seen near the center of the dam. (B) After 3.5 months the upper portion of the dam had been removed, and river discharge no longer could be passed through the spillways in the foreground. (C) After 1 year the reservoir sediment delta had prograded to within 100 m of the dam. (D) Although the reservoir delta prograded to the dam during high flows of October 2012 and sediment could spill directly into the channel below, the river had low turbidity during the summer low flow season of 2013. Photos provided by Erdman Video Systems in collaboration with the National Park Service.

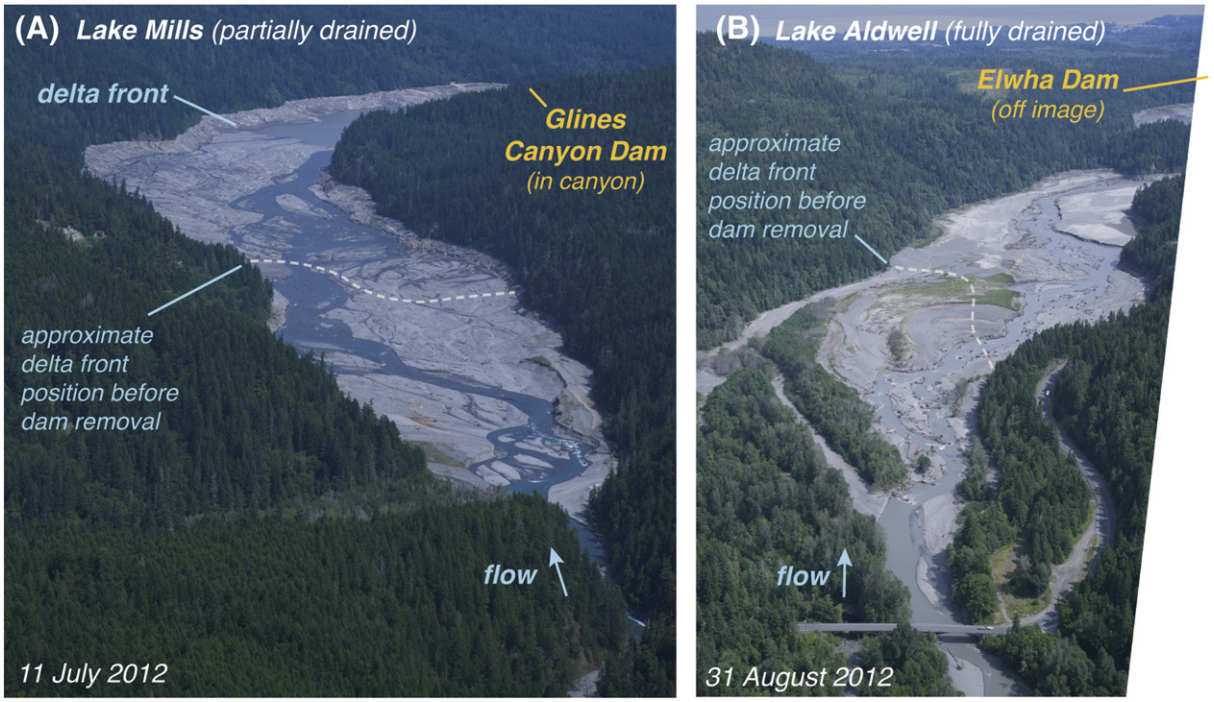

Fig. 4. Oblique aerial photos of deltas in the two Elwha River reservoirs during dam removal. Pre-removal delta front positions approximated from Czuba et al. (2011). (A) Lake Mills behind Glines Canyon Dam showing the delta prograding toward the dam during the summer of 2012. (B) Lake Aldwell behind Elwha Dam showing the exposed delta sediments and large woody debris immediately downstream of the Olympic Highway (Route 101) bridge. Photos provided by Neal and Linda Chism of LightHawk.

Table 2
Summary of the sediment dry bulk densities measured in the Elwha River system.

Location, sediment type[a]	Bulk density, mean ± S.D. (kg/m^3)	Bulk density, range (kg/m^3)	Number of samples	Reference
Lake Mills, coarse sediment[b]	1630 ± 220[b]	1030–2010[b]	79[b]	Wing (2014)
Lake Mills, coarse sediment	1760 ± 120	1670–1940	4	Childers et al. (2000)
Lake Mills, coarse sediment	1420	1420	1	Mussman et al. (2008)
Lake Mills, fine sediment[b]	1140 ± 60[b]	880–1260[b]	75[b]	Wing (2014)
Lake Mills, fine sediment	1090	1090	1	Mussman et al. (2008)
Lake Aldwell, coarse sediment	1730 ± 220[b]	830–2050[b]	31[b]	Wing (2014)
Lake Aldwell, coarse sediment	1290 ± 160	1180–1410	2	USBR (1996)
Lake Aldwell, mixed sediment	1270 ± 240	720–1600	11	USBR (1996)
Lake Aldwell, fine sediment	1120 ± 170[b]	260–1530[b]	104[b]	Wing (2014)
Lake Aldwell, fine sediment	1080	1080	1	USBR (1996)
Elwha River, channel margin deposits	1192 ± 157	900–1400	13	East et al. (2015)
Elwha River delta, intertidal sands	1335 ± 6	1330–1340	3	Ian Miller (pers. comm.)
Elwha River delta, intertidal muddy sands	900 ± 140	750–1030	3	Ian Miller (pers. comm.)
Elwha River delta, intertidal organic debris	230	230	1	Ian Miller (pers. comm.)

[a] Wing (2014) used a 2-mm diameter to separate coarse and fine sediments, the remaining measurements used 0.063 mm.
[b] Wing's results.

measured by the project contractor (Randle et al., 2015-in this issue). Combined, these techniques provided topographic information at daily to weekly time scales, and these data were integrated with pre-removal sediment cores and grain-size samples (cf. Gilbert and Link, 1995) in a geographical information system (GIS) to track the fine-grained and coarse-grained sediment budgets (separated at the 0.063-mm sediment diameter) within each reservoir (Randle et al., 2015-in this issue).

The monitoring of the Elwha River fluvial landforms and bed sediment also utilized a number of sources of data, including continuous water-surface stage sensors from which discharge-corrected water stages were computed to track relative changes in bed elevations; high-resolution topographic surveys at 21 river cross sections in four river reaches using rod-and-total-station and terrestrial lidar scans; sediment deposition surveys of eight of the extant 40 floodplain channels connected to the mainstem river; thalweg profiles surveyed within the floodplain channels; longitudinal profiles of mainstem channel bed and water elevations using a boat equipped with GPS and an acoustic Doppler profiler (ADCP) or single-beam depth sounder; sediment grain size analyses from physical pebble counts, bulk sampling, and photographic techniques; aerial orthoimagery; and DEMs generated from SfM techniques and aerial lidar surveys (East et al., 2015-in this issue).

Coastal landforms and processes were monitored with RTK-GPS surveys using multiple rovers and base stations; integrated RTK-GPS and single-beam fathometers from watercraft for the submarine portion of the study area; Swath-sonar bathymetry and acoustic backscatter of the seafloor collected from the R/V Snavely; physical samples of the subaerial, intertidal, and submarine sediment for grain size analyses; photographic samples of beach shoreface sediment grain size; benthic tripod-mounted underwater camera systems and ADCPs to monitor coastal currents and wave properties; and a Delft3D numerical model to characterize and scale processes relevant to sediment dispersal in the coastal waters (Gelfenbaum et al., 2015-in this issue).

The sediment fluxes in the river were primarily monitored at a station downstream from both dams (USGS gaging station 12046260; Fig. 1C; Magirl et al., 2015-in this volume). Monitoring at this station included physical samples of suspended sediment using standard USGS flow-integrated techniques, continuous monitoring of river stage, continuous monitoring of water turbidity using two different optical sensors, continuous monitoring of river velocities and acoustic backscatter properties with an acoustic Doppler profiler (ADP), daily pumped physical samples of river water for suspended-sediment concentration analyses, and continuous surrogate monitoring of bedload with geophones attached to steel plates spanning the channel (Magirl et al., 2015-in this volume; Hilldale et al., 2014). Additional streamflow gaging occurred at the USGS stations McDonald Bridge (USGS 12045500; Fig. 1C) to measure discharge and upstream of Lake Mills (USGS 12044900; Fig. 1C) to characterize upper watershed sediment conditions. This upstream site was especially difficult to maintain owing to over 10 m of stream channel incision during the study related to erosion from the dam removal (Magirl et al., 2015-in this volume). Source data from these observations are provided by Curran et al. (2014) and through the USGS National Water Information System (NWIS).

Table 3
Sediment dry bulk densities utilized for the Elwha River sediment mass balance.

Location	Bulk density (kg/m^3)	Reference
Reservoirs, coarse sediment	1700[a]	Randle et al. (2015-in this issue)
Reservoirs, fine sediment	1100[a]	Randle et al. (2015-in this issue)
Fluvial, all sediment	1450[b]	East et al. (2015-in this issue)
Coastal, coarse sediment	1500[c]	Gelfenbaum et al. (2015)
Coastal, fine sediment	480[c]	Gelfenbaum et al. (2015)

[a] Bulk densities of the reservoir sediment during the drawdown (i.e., non-submerged) conditions.
[b] This is the mean of the range of fluvial deposit bulk densities reported to be 1200–1700 kg/m^3 by East et al. (2015-in this issue). The range was incorporated into uncertainty calculations.
[c] The coastal sediment masses were estimated with Eq. 3.2.7 of van Rijn (2005) to estimate bulk density from field-sampled sediment grain sizes.

3.2. Sediment mass balance

All sources of sediment storage, erosion, deposition, and flux were integrated into a source-to-sink sediment budget (cf. Swanson et al., 1982; Reid and Dunne, 1996; Walling and Collins, 2008; Hinderer, 2012). The development of watershed-scale sediment mass balances can pose important challenges because (i) most geomorphic measurements are obtained in units of depth or volume and must be converted to masses with dry bulk densities of sediment and (ii) uncertainty in volume and mass measurements must be properly handled to support conclusive results (Kondolf and Matthews, 1991; Grams and Schmidt, 2005; van Rijn, 2005). Regarding the first challenge, sediment bulk densities (which are measurements of mass per unit volume) are known to vary throughout a watershed owing to differences in sediment grain size and compaction; and it is commonly difficult to obtain enough measurements to adequately capture this variability (e.g., Verstraeten and Poesen, 2001). Owing to the difficulty of this problem, recent dam-removal studies have used single values of dry bulk density across the entire study area (e.g., 1700 kg/m^3 in the Marmot Dam–Sandy River system, Major et al., 2012; 1500 kg/m^3 in the Condit Dam–White Salmon River system, Wilcox et al., 2014), which—for all intents and purposes—reduces the sediment mass balance to a volume balance. Here we examine the available bulk density measurements for the

Elwha River system and describe how these were used to develop geographically and grain-size-varying dry bulk density assumptions.

The majority of bulk density measurements collected in the Elwha River watershed have been within the sediments of the two reservoirs (Table 2; USBR, 1996; Childers et al., 2000; Mussman et al., 2008; Wing, 2014). The bulk density of these samples varied widely from 260 to 2050 kg/m^3, and there was a strong grain size dependence in these results, consistent with other reservoirs (Table 2; Morris and Fan, 1997). Bulk density samples were also collected in the sediment deposits lining the river channel margins in March 2013, and these samples ranged from 900 to 1400 kg/m^3 and averaged ~1200 kg/m^3 (Table 2; Draut and Ritchie, 2013). Coastal bulk density samples were collected only in the intertidal zone of the new sediment deposits immediately east of the river mouth (I. Miller, Washington Sea Grant, unpublished data), providing estimates of ~1340 kg/m^3 in the sandy regions, ~900 kg/m^3 in the muddy sand regions, and 230 kg/m^3 in the organic debris that littered small sections of the beach shoreface (Table 2).

These combined measurements revealed that Elwha River sediment dry bulk densities exhibited spatial and grain size variations, and these variations were included in the sediment mass balance by using the values presented in Table 3. In the reservoirs, where we tracked sediment erosion using coarse (sand-sized and coarser) and fine (silt and clay) fractions separately, the dry bulk densities of each fraction were assumed to be 1700 and 1100 kg/m^3, respectively. The bulk densities of river channel deposits were sampled only within channel-margin deposits as of March 2013 (no samples were obtained on central gravel bars, which were much coarser than the channel margins, but unstable and largely submerged at that time), so a broad range of 1200–1700 kg/m^3 with a mean of 1450 kg/m^3 was used to incorporate the range of grain sizes present in the river deposits and the sampling biases (East et al., 2015-in this issue). Lastly, the beach samples, while not fully representative of submarine sediment deposits, gave evidence that the grain-size-dependent marine sediment bulk density relationships, such as van Rijn (2005), were applicable to the study area. Use of the van Rijn (2005) relationships resulted in coarse and fine sediment bulk densities of 1500 and 480 kg/m^3, respectively (Table 3), and mean coastal deposit bulk densities that ranged between 1360 and 1470 kg/m^3 for the sand and gravel-dominated deposits depending on survey date (Gelfenbaum et al., 2015-in this issue).

Regarding the second challenge of sediment mass balances—quantifying uncertainty—all sediment mass-balance numbers that we present included assessments of uncertainty. Many of these uncertainty values are at the 2-σ level, although as noted below, the uncertainty for some parameters some could only be calculated as ranges of minima and maxima.

We also estimated sediment mass balance of the fine and coarse sediment fractions (separated at 0.063 mm) and for the first and second years of dam removal owing to the inclusion of these thresholds in most sampling programs. Grain size information was derived from sampling and analyses of the sediment throughout the system, much of which is presented in the complementary papers.

4. Results

Observations are organized by three primary time intervals, or stages, of the dam removals that define the fundamental hydrologic and geomorphic changes that occurred (Fig. 5). These intervals are: stage 1—reservoirs still containing some slack water, initial sediment releases related to dam removal; stage 2—full removal of Elwha Dam and Lake Aldwell reservoir water, increased sediment supply to the river; and stage 3—removal of Lake Mills reservoir water, progradation and release of Lake Mills coarse-grained sediment downstream of Glines Canyon Dam, exceptional sediment supply to the river.

4.1. Stage 1 — initial decommissioning (Sept. 2011 —Mar. 2012)

River suspended-sediment concentrations increased during physical drawdown of the reservoir water and higher flows related to winter precipitation (Fig. 5A, B, D; Warrick et al., 2012; Magirl et al., 2015-in this volume). Although these flows were some of the highest during the two-year record reported here, the total flux of sediment out of the two reservoirs and past the USGS gage in stage 1 was low compared to the latter stages of dam removal (Fig. 5C, E). For example, during the six months from 15 September 2011 to 14 March 14 2012, ~200,000 t of suspended sediment was discharged past the most downstream USGS gage, ~27% of which was sand (Fig. 5E). If added to an estimated 35,000 t of bedload discharge for the same interval of time (Magirl et al., 2015-in this volume), roughly 235,000 t of sediment discharge occurred, a value that is less than the ~340,000 t mean annual sediment discharge of the watershed.

The geomorphic effects of these renewed sediment supplies during stage 1 were minor. For example, Draut and Ritchie (2013) reported relatively thin (<20 cm) deposits of mud and sand along the banks of the Elwha River downstream of both dams (i.e., the 'lower reach' of the river) during the spring of 2012 (Fig. 6B). During this time, relative river water stages did not increase (Fig. 5G), indicating that the thin channel margin deposits exhibited no hydraulic control on the river flow (East et al., 2015-in this issue). The primary coastal effect observed during stage 1 was the several-kilometer-scale turbid buoyant plume that commonly extended from the river mouth into the Strait of Juan de Fuca (Fig. 7B; Gelfenbaum et al., 2015-in this issue).

4.2. Stage 2 — Elwha Dam removed (Mar.–Oct. 2012)

Downstream sediment flux increased markedly after the Elwha River was placed into its natural canyon alignment past the former Elwha Dam site on 16 March 2012 and Lake Aldwell, having been drained of water, no longer functioned as a sediment trap. These physical conditions, coupled with spring high flows, resulted in suspended-sediment concentrations in the downstream river that regularly exceeded 1000 mg/L and suspended-sand fractions that approached 50% during most of the spring of 2012 (Fig. 5D). The river discharged ~410,000 t of suspended sediment and ~70,000 t of bedload during the 22 days between 13 April and 5 May, and roughly half of this suspended-sediment discharge was sand (Fig. 5D, E). These measurements of total sediment flux in the river (~480,000 t) were roughly equivalent to the total volume of sediment exported from the reservoirs during the same 22 days; Lake Aldwell sediment storage decreased by ~430,000 m^3 and Lake Mills sediment storage decreased by ~50,000 m^3 (Fig. 5C). The smaller amount of export from Lake Mills was not from lower erosion rates of this reservoir's delta, but rather from continued deposition of eroded sediment within the remaining boundaries of the reservoir. That is, the Lake Mills delta continued to incise and prograde during the spring and summer of 2012 (Figs. 3 and 4A; Randle et al., 2015-in this issue). In summer when discharge waned, suspended-sediment concentrations and sand fractions decreased, such that from mid-August to mid-September of 2012, suspended-sediment concentrations were only 50–100 mg/L with <5% sand (Fig. 5D).

Approximately 930,000 t of suspended-sediment was discharged past the downstream-most USGS station during the first year of dam removal, over two-thirds of which occurred during stage 2 (Table 4; Fig. 5E). An additional 170,000 t of bedload discharge from former Lake Aldwell was estimated for this time interval, which combined to 1.1 million t of total sediment discharge, or about 3 times the mean annual supply from the upper watershed (Table 4; Magirl et al., 2015-in this volume). During the first year of dam removal ~1.1 million t of sediment was exported from Lake Aldwell and ~230,000 t was exported from Lake Mills (Table 4; Fig. 5C).

Geomorphic effects during stage 2 were more pronounced than those of stage 1 in the river and in the coastal regions. Although relative

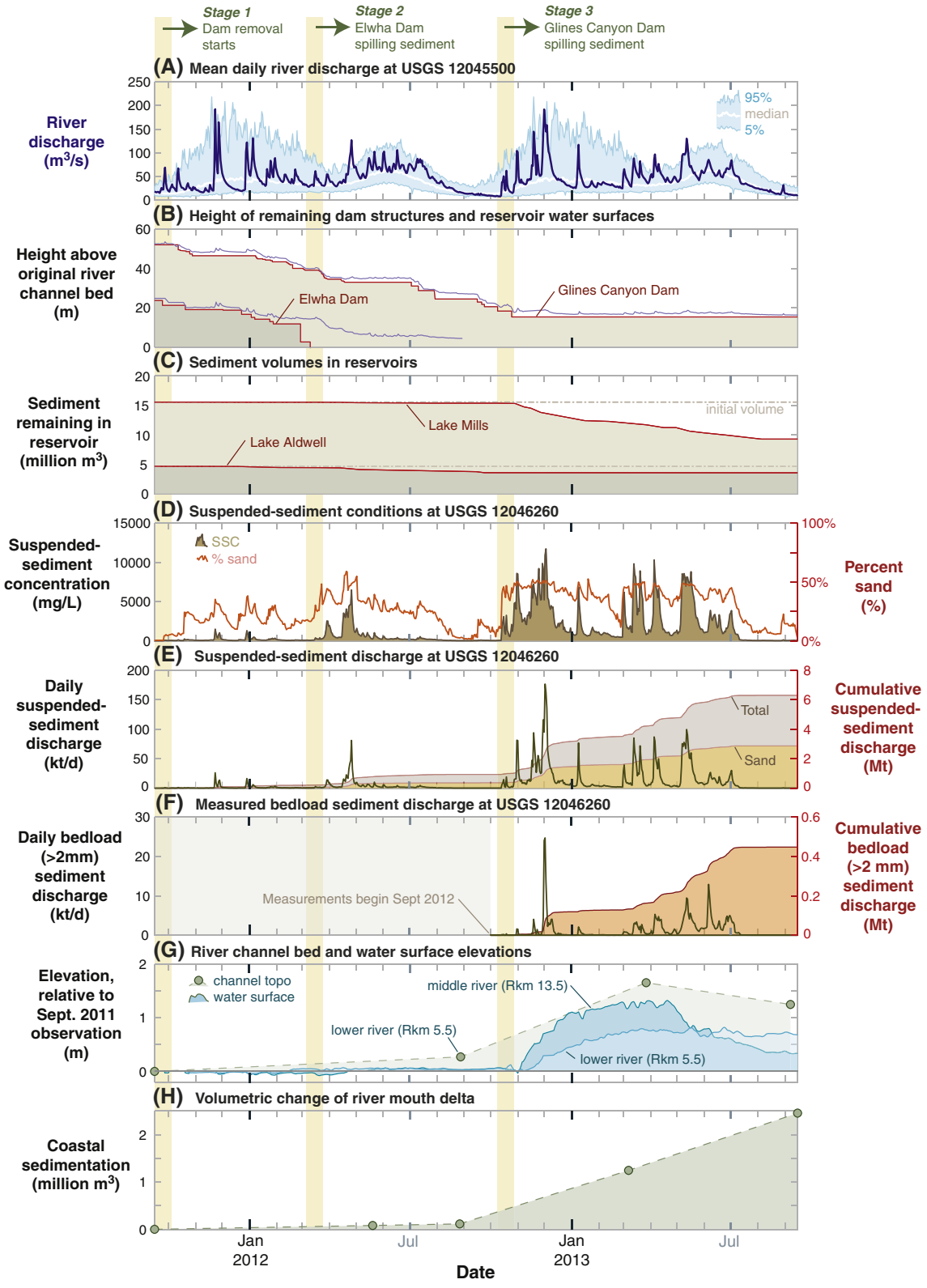

Fig. 5. Time series of reservoir, river, and coastal measurements showing the geomorphic effects of dam removal on the Elwha River. Three primary intervals of time, or *stages*, that are highlighted in the text are shown with vertical bars. (A) Elwha River discharge during the study (dark line) over the 99 years of daily records. The 5% and 95% percentiles of discharge on each day of the year are by the extents of the light shading. (B–C) Reservoir heights and sediment volumes (after Randle et al., 2015-in this issue). (D–F) River sediment discharge measurements (after Magirl et al., 2015-in this volume). (G) River vertical geomorphic change from water level and channel cross-section topographic measurements (after East et al. (2015-in this issue)). (H) Coastal volumetric change of the river mouth delta (after Gelfenbaum et al., 2015-in this issue).

river water surface levels continued to show no changes during stage 2, topographic surveys through the mainstem channel downstream of Elwha Dam revealed centimeters to tens of centimeters of deposition in the thalweg, and more where pools filled (Fig. 5G; East et al., 2015-in this issue). These results showed that river sedimentation was generally limited to pools between riffles and slow velocity areas along

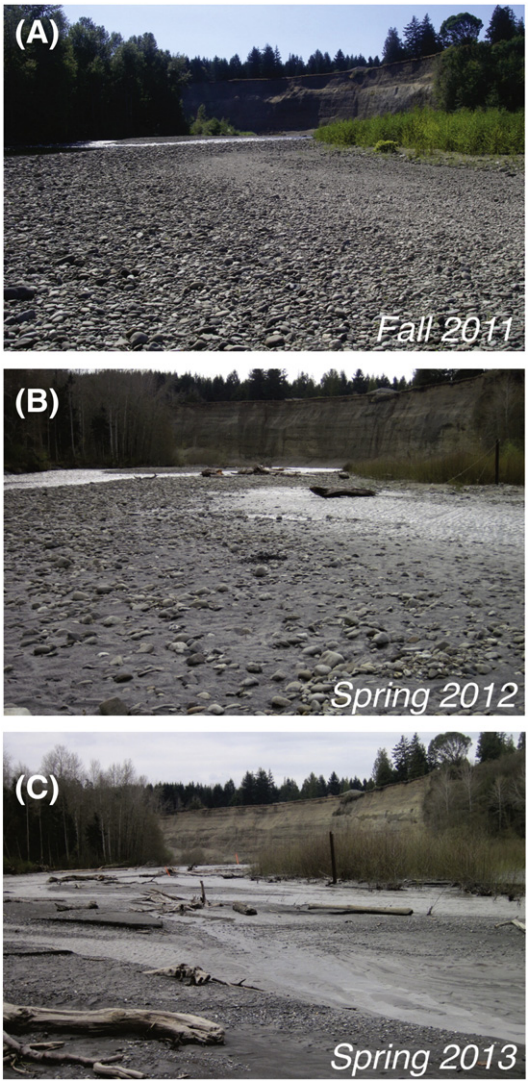

Fig. 6. Geomorphic change on the downstream-most point bar of the Elwha River during dam removal. Approximately 2 m of deposition occurred, which included an increase in woody debris, during the two years between photos (A) and (C). All photos taken looking upstream at Rkm 0.6 along the *Reach 3* topographic profile transects of Draut et al. (2011) and East et al. (2015-in this issue). Photos provided by Amy Draut/East of USGS.

channel margins (East et al., 2015-in this issue) but had not yet occurred on the riffle crests that exert hydraulic control on water-stage elevations. In total ~80,000 t of sediment, or roughly 7% of the measured river sediment flux, was deposited during the first year of dam removal in the mainstem and floodplain channels of the Elwha River's lower reach (i.e., the reach between Elwha Dam and the coast), most of which occurred during stage 2 (Table 4). The 2012 coastal surveys revealed that ~240,000 t of sediment was deposited immediately offshore of the river mouth, which was roughly 22% of the total measured sediment flux in the river (Fig. 5H; Table 4; Gelfenbaum et al., 2015-in this issue).

4.3. Stage 3 — Lake Mills delta fully prograded (Oct. 2012–Sept. 2013)

The rates of sediment flux and geomorphic change increased substantially following the complete draining of water from Lake Mills and full progradation to Glines Canyon Dam of the reservoir delta in October 2012 (Fig. 5). Although total annual river discharge was slightly above average in 2012–2013, peak river discharge did not exceed the 2-year recurrence interval during this year (Fig. 5A; Magirl et al., 2015-in this volume). Regardless, over a third of the Lake Mills sediment volume, or roughly 6 million m^3 of sediment (~8.9 million t), was exported out of the reservoir during this second year of dam removal (Fig. 5C). This massive export of sediment increased river suspended-sediment fluxes and resulted in vertical changes exceeding 1 m in the river and estuary and exceeding 7 m at the river mouth (Fig. 5; Gelfenbaum et al., 2015-in this issue). For example, the average daily suspended-sediment concentration exceeded 1000 mg/L for 214 days during the second year and exceeded 5000 mg/L for a cumulative 56 days (or roughly 59% and 15% of the year, respectively; Fig. 5D). During the highest flows, such as those that had an instantaneous peak of 214 m^3/s on 1 December 2012 (only 54% of the two-year flood-peak value for the Elwha River), river suspended-sediment discharge exceeded 150,000 t in a single day (Fig. 5E); and when combined with estimates of total bedload, this daily flux exceeded 230,000 t (Magirl et al., 2015-in this volume).

This high rate of export from the former Lake Mills altered the river channel geomorphology as a dispersive sediment wave proceeded downstream from this site (East et al., 2015-in this issue). Aggradation —as shown by relative water surface levels in the river—was first observed in the middle reach of the river (i.e., between both dams) beginning on 31 October 2012 and weeks to a month later in the river's lower reach (Fig. 5G; East et al., 2015-in this issue). Aggradation resulted in wholesale aggradation not only in pools but across the channel thalweg and on riffle crests that provided hydraulic control to water-surface elevations; bars formed and enlarged in many areas of the mainstem channel (Figs. 6C and 8). Similarly, an average of 0.50 ± 0.38 m of aggradation was measured in the surveyed floodplain channels (Fig. 9; East et al., 2015-in this issue). The new sediment deposited in the fluvial landforms was finer-grained than the cobble-dominated channel bed that existed before dam removal, and the bulk grain-size distributions fined by ~4 ϕ, a 16-fold decrease (East et al., 2015-in this issue). Channel braiding index, which is a ratio of total channel length to the mainstem channel length (Friend and Sinha, 1993), also increased by nearly 50%, as the fluvial system transitioned toward more aggradational-style avulsion processes (East et al., 2015-in this issue).

Although sediment supply from Lake Mills continued through much of this second year (stage 3), the middle reach mainstem channel partially incised through the recently deposited sediment during the spring and summer of 2013 (Fig. 5G). Widespread incision was not observed in the river's lower reach, however (Fig. 5G). Incision within the fluvial deposits of the middle reach was coincident with a slight coarsening of the channel sediments, whereas the deposits in the lower reach—where incision was observed only locally—continued to fine during the spring and summer of 2013 (East et al., 2015-in this issue).

At the coast, a massive expansion of the river mouth delta was observed during the second year of dam removal, such that the river-mouth wave-breaking zone moved over 200 m in the offshore direction (Fig. 7C). Detailed coastal surveys revealed that this expansion was associated with ~2.2 million m^3 (~3.3 million t) of sediment deposited during the second year of dam removal (Fig. 5H; Gelfenbaum et al., 2015-in this issue). Although most of this sediment was sand and gravel, a broad patch of mud was found to cover the seafloor 0–2 km west of the river mouth, where coastal hydrodynamics were more quiescent and less conducive to transport (Gelfenbaum et al., 2015-in this issue). A secondary region of sand deposition was observed ~1.5 km east of the river mouth in 0–5 m water depths, and this 1–2 m thick deposit resulted from eastward transport of sediment deposited initially offshore of the river mouth (Gelfenbaum et al., 2015-in this issue). In contrast to the massive expansion of the river mouth delta, erosion was still measured along 1 km of the deltaic shoreline to the east and directly downdrift of the river mouth during the second year of dam removal (stage 3). This indicates that the massive supply of sediment did not immediately reverse the sediment deficit for this littoral cell (Gelfenbaum et al., 2015-in this issue).

4.4. Sediment budget

The elements of the Elwha River sediment budget—including annual values and grain-size partitions—are presented in Table 4. Based on

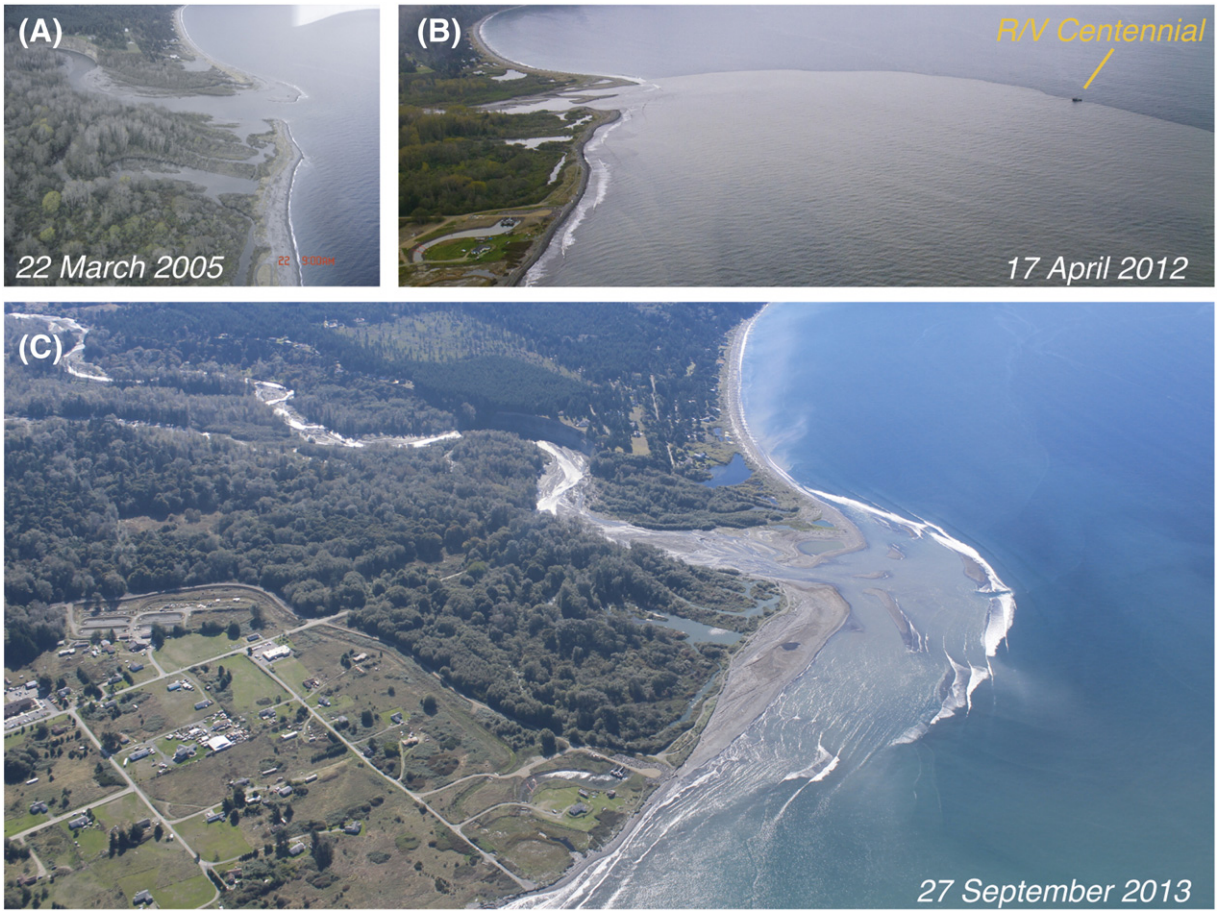

Fig. 7. Oblique aerial photos of the Elwha River mouth before and during dam removal. Photos show (A) the river mouth wetlands before dam removal, (B) the turbid buoyant coastal plume that occurred during much of the dam removal project, and (C) the expansion of the river mouth delta by ~2.4 million m^3 of sediment deposition. The R/V Centennial shown in (B) is 18 m in length. Photos provided by Ian Miller of Washington Sea Grant, Jonathan Felis of USGS, and Neal and Linda Chism of LightHawk.

detailed measurements, the first two years of dam removal produced ~10.5 million t of erosion from the two reservoirs, ~8.2 million t of flux measured in the river, and coastal deposition of ~3.5 million t (Table 4). The dominant terms, reservoir erosion and river sediment flux, remained imbalanced by ~2.3 million t. This deficit of sediment could not be fully attributed to fluvial deposition between the reservoirs and the USGS gage, which was at most 0.9 million t and was more likely ~0.7 million t (cf. Table 4). Rather, the sediment deficit was within the range of uncertainty of the dominant terms because the total uncertainty in reservoir sediment erosion was ~2 million t and the uncertainty in river sediment flux was over 4.5 million t (Table 4). It was for these reasons that the sediment budget graphics (Figs. 10–12) presented the mean values shown in Table 4 and noted the sediment imbalances that occurred at the USGS gage. However, these figures do not include the imbalance as an input or output to the graphical representation of the budget but rather split the imbalance between the dominant factors of the budget.

The total sediment budget for the first two years of dam removal revealed that the sediment released from the dams was over 100 times greater than the upstream sediment supply and that ~90% of the released sediment passed through the river system to the coast (Fig. 10). Though volumetrically minor relative to the sediment flux to the coast, fluvial channel fill was the most substantial sediment sink upstream from the river mouth. The river system captured 1.2 ± 0.4 million t of sediment over the two-year study interval, approximately three-quarters of which was deposited within the mainstem channel and the remainder in floodplain channels (Fig. 10). Deposition on the floodplain outside of floodplain channels was negligible, owing to the low flows that limited spatial redistribution of sediment. Thus, the mass of fluvial sedimentation that remained in storage along the river channel was ~15-fold greater than the sediment supplied from the upper watershed during these two years (Fig. 10). At the coast, ~3.5 million t of sediment was deposited near the river mouth, and this represented a little less than half of the total sediment discharged to the sea. The remaining sediment, which was calculated to be ~5 million t, was dispersed farther offshore of the submarine river delta into the Strait of Juan de Fuca, and presumably dispersed by currents and waves (Fig. 10; Gelfenbaum et al., 2015-in this issue).

Separating the sediment budget into two grain-size fractions revealed differences in the sources, transport, and fate of fine- and coarse-grained sediment (separated at 0.063 mm; Fig. 11). Sediment export from Lake Mills was dominated by coarse-grained sediment (77% of export), whereas export from Lake Aldwell was largely fine-grained (73% of export). As such, Lake Mills provided ~70% of the total two-year fine-grained sediment mass to the river and ~95% of the total coarse-grained sediment because the volume exported from Mills was so much greater than from Aldwell (Fig. 11). Fine-grained sediment passed through the river and coastal systems relatively efficiently because deposition within these landforms was only ~4% and ~7% of the total estimated supply, respectively. Coarse-grained sediment, in contrast, did not pass through as efficiently; and fluvial and coastal deposition was ~14% and ~44% of the total estimated supply, respectively. However, fine-grained sediment represented significant portions of some of the fluvial, estuarine, and coastal sediment deposits especially along channel banks, within floodplain channels, and on the seafloor where overlying coastal waters were relatively quiescent (Draut and Ritchie, 2013; East et al., 2015-in this issue; Gelfenbaum et al., 2015-in this issue). Lastly, it is important to note that the fine-grained sediment

Table 4
Sediment mass balance for the Elwha River during the first two years following dam removal; all values have been rounded to two significant figures.

Location (listed in upstream to downstream order)	Type[a]	Year 1 sediment mass[b] (kt)	Fine:coarse ratio[c]	Year 2 sediment mass[b] (kt)	Fine:coarse ratio[c]	Total sediment mass[b,d] (kt)	Fine:coarse ratio[c]
1. Flux from upper watershed	Flux	**38** (27–50)	50:50	**45** (33–60)	50:50	**83** (60–110)	50:50
2. Net change in Lake Mills	In	**190** (80–300)	100:0	**8900** (7100–10,700)	21:79	**9100** (7300–10,900)	23:77
3*(a)*. Middle reach sedimentation, mainstem channel	Out	**0** (–)	NA	**350** (280–410)	5:95	**350** (280–410)	5:95
3*(b)*. Middle reach sedimentation, floodplain channels	Out	**0** (–)	NA	**190** (94–310)	80:20	**190** (94–310)	16:84
4. Net change in Lake Aldwell	In	**1200** (900–1400)	72:28	**230** (160–300)	79:21	**1400** (1100–1600)	73:27
5*(a)*. Suspended-sediment discharge at diversion weir	Flux	**930** (470–1400)	61:39	**5400** (2700–8100)	53:47	**6300** (3200–9400)	54:46
5*(b)*. Bedload sediment discharge at diversion weir	Flux	**170** (20–330)	0:100	**1700** (210–3300)	0:100	**1900** (240–3700)	0:100
6*(a)*. Lower reach sedimentation, mainstem channel	Out	**50**[e,f] (–)[f]	5:95	**450**[e,f] (–)[f]	5:95	**500**[e] (410–580)	5:95
6*(b)*. Lower reach sedimentation, floodplain channels	Out	**28**[g,h] (–)[h]	12:88	**92**[g,h] (–)[h]	61:39	**120**[g] (62–200)	50:50
7. Estuary sedimentation	Out	**11** (–)[i]	90:10	**6** (–)[i]	90:10	**17** (–)[i]	90:10
8. Coastal sedimentation	Out	**240** (160–320)	3:97	**3300** (2400–4200)	6:94	**3500** (2500–4500)	6:94

[a] Type of sediment budget variables include: *In* = input (source), *Out* = output (sink), *Flux* = sediment discharge.
[b] Sediment budget numbers are reported as best value (in bold) and range of uncertainty (in parentheses).
[c] Grain sizes reported as the ratio between fine-grained and coarse-grained sediment, separated at 0.0625 mm.
[d] Total mass is equivalent to the sum of the first two years, although rounding errors occur.
[e] Mainstem channel sedimentation in the river's lower reach occurred upstream of USGS river gage 12046260 (~28% of the total sedimentation) and downstream of the gage (~72% of the total sedimentation).
[f] Total mainstem sedimentation was assumed to be 10% during year 1 and 90% during year 2; no uncertainty available for these values.
[g] Floodplain channel sedimentation in the river's lower reach occurred upstream of the USGS river gage 12046260 (~3% of the total sedimentation) and downstream of the gage (~97% of the total sedimentation).
[h] Total floodplain channel sedimentation was assumed to be 23% during year 1 and 77% during year 2; no uncertainty available for these values.
[i] Uncertainty not computed.

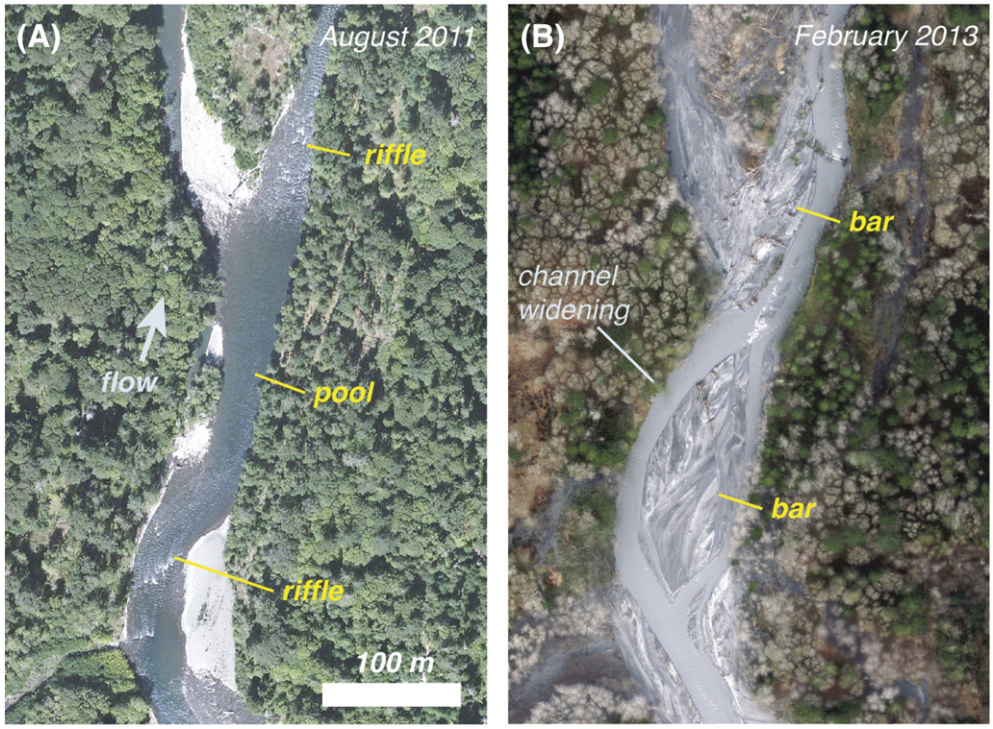

Fig. 8. Aerial orthoimages of the middle reach of the Elwha River, i.e., between the two former dams, showing sedimentation within a riffle–pool sequence following sediment release over Glines Canyon Dam resulting in the formation and growth of river bars. Photos are centered on the pool that was located at Rkm 17.9. Photos provided by Andy Ritchie of the National Park Service.

Fig. 9. An example of the sedimentation and geomorphic change that occurred within the Elwha River floodplain channels during dam removal. An average of 0.50 m (±0.38 m) of deposition occurred in the eight floodplain channels surveyed (East et al., 2015-in this issue). Photos taken looking upstream at the Boston Charley floodplain channel, which enters the Elwha River at Rkm 0.6. Photos provided by Mike McHenry, Lower Elwha Klallam Tribe.

budget obtained better closure at the mid-river USGS gage than the coarse-grained sediment budget and had an imbalance of only +8% (coarse-grained imbalance was −40%; Fig. 11).

Separating the sediment budget into two years—the first year representing stages 1 and 2 and the second year representing stage 3 as defined in Sections 4.1–4.3 above—also revealed differences in the sources, transport and fate of sediment (Fig. 12). The primary difference between the two years was the importance of the two reservoirs in the supply of sediment to the budget. During the first year, Lake Aldwell contributed ~1.2 million t of sediment to the river, which was ~85% of the total sediment supplied. During the second year, Lake Aldwell provided only 0.23 million t of sediment, which was <3% of the total sediment supplied (Fig. 12). The total sediment supply also increased ~7-fold between the first and second years; and combined with the greater abundance of coarse-grained sediment from Lake Mills, sedimentation in the fluvial and coastal landforms increased by over an order of magnitude. For example, total fluvial sedimentation increased from ~0.08 million t to ~1.1 million t from year one to year two, and coastal sedimentation increased from ~0.24 million t to ~3.3 million t (Fig. 12).

5. Discussion

The first two years of dam removal on the Elwha River resulted in a massive sediment release within a small, steep river from which a better understanding of landscape response to major sediment-supply perturbations can be built. Here we provide a synthesis of the geomorphic effects of the Elwha dam removals with a conceptual model, compare the Elwha River results with predictions for this system and with other dam removals, use this information to develop expectations for this river-restoration project, and provide lessons learned and future research directions for other dam removals.

5.1. Geomorphic conceptual model

The dominant geomorphic changes to the reservoirs, river, and coastal zone of the Elwha River system are summarized in the graphics and text of Fig. 13 and the following discussion. In 2011, prior to the start of dam removal, the reservoirs contained delta, prodelta, and lakebed sediment deposits (Fig. 13). The delta deposits extended upstream of the reservoir full-pool elevations and into the reservoirs, and they tended to be inversely graded with depth and coarser upstream and finer downstream. Prodelta and lakebed deposits were composed of fine sediment draped across the reservoir bottoms of both lakes Aldwell and Mills (Randle et al., 2015-in this issue).

Progradation of reservoir deltas during the phased dam removals resulted in the burial of the silt-and-clay prodelta and lakebed deposits that lined the deeper—and more distil—portions of the reservoir (Fig. 13; Randle et al., 2015-in this issue). One effect of burial of the lakebed deposits was the exclusion of some of the fine-grained sediment from subsequent erosion and export during the two years studied here. This effect was particularly significant in Lake Mills where the lakebed sediment was several meters thicker than in Lake Aldwell and a portion of the dam still remained intact at the end of our study interval, which protected the lowest-elevation portion of the lakebed from eroding (Fig. 13). Thus, although the original Lake Mills sediment was ~35% fine-grained by mass, the sediment export from this reservoir was only ~23% fine-grained by mass (Tables 1 and 4).

The magnitude and extent of the downstream geomorphic responses were greater in the second year of dam removal (stage 3) owing to the coarse sediment wave that dispersed downstream from Lake Mills (Fig. 13; cf. Lisle et al., 2001; East et al., 2015-in this issue). River pools exhibited some sedimentation but generally did not fill during the first year following the release of Lake Aldwell sediments past Elwha Dam (Fig. 13). In contrast, after the release of Lake Mills' coarse sediment during the second year, widespread aggradation and planform change were noted along the entire river downstream from Glines Canyon Dam. Deposition occurred even on riffle crests during stage 3, affecting hydraulic control and changing water-stage elevation measurably as the sediment wave evolved (East et al., 2015-in this issue). Deposition patterns were also expressed at the coast, where the river mouth delta expanded greatly during the second year of dam removal (Fig. 13).

In addition to the transport of sediment in the Elwha River system, an abundance of woody debris was exhumed from the reservoirs and transported downstream to the river and coast (Fig. 14). This wood was derived from a number of sources, including erosion of forested subaerial banks in the Lake Aldwell delta and exhumation of pre-dam stumps and woody debris from sediments of the former reservoirs (Fig. 14). The new supplies of wood added complexity to the river within the former reservoirs (Fig. 14A, B) and the fluvial and coastal landforms downstream of the dams (Fig. 14C, D). This included coarse

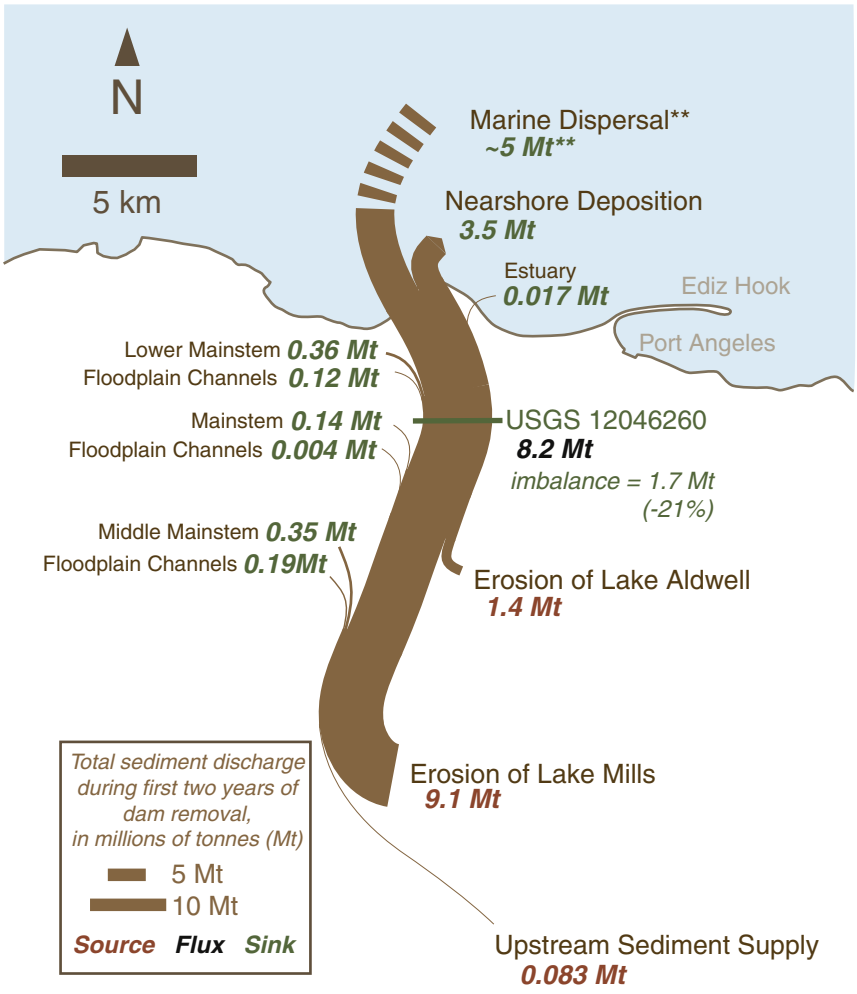

Fig. 10. Total sediment budget for the Elwha River system during the first two years of dam removal (Sept. 2011 to Sept. 2013). The reported imbalance is the difference between the river sediment discharge measurements at the USGS gage and the calculated sediment flux from the upper watershed sediment balance. The imbalance is reported in units of both mass and percent of computed flux from the upper watershed. For graphical presentation this difference was split between the erosion from the reservoirs and the flux past the gage owing to it being within measurement uncertainties. The mass of sediment dispersed far offshore of the submarine delta is shown as a dashed line and is starred (**) owing to the estimation of these values from mass balance.

organic debris—pieces of leaves, stems, and wood ranging in size from wood chips to branches—that accumulated within fluvial sediment deposits (Draut and Ritchie, 2013) and in lags, sediment deposits, and large piles on the beach (Fig. 14D). Larger woody debris formed logjams in the river mainstem and floodplain channels (e.g., Fig. 14A, C), although many of the middle and lower reach logjams were partially buried in sediment during the second year of dam removal (cf. Fig. 8). Old-growth stumps that were exhumed from the Lake Aldwell delta were the dominant driver of logjam development in this reach of the river, added ecologically significant complexity to this portion of the floodplain (Fig. 14B; cf. Coe et al., 2009; Collins et al., 2012), and—as noted in the next section—may be partially responsible for the ~80% reduction of sediment erosion from Lake Aldwell during the second year of dam removal studied here.

5.2. Comparison with predictions

Before dam removal began, there were four major efforts to predict the Elwha River's potential geomorphic response: (i) Bromley (2008) conducted scaled physical model experiments of Lake Mills to investigate the rates and styles of sediment erosion; (ii) Randle et al. (1996) provided two-dimensional mass-balance predictions of reservoir sediment erosion and one-dimensional downstream predictions of sediment flux and river aggradation; (iii) Konrad (2009) utilized 1-D numerical techniques 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; and (iv) Gelfenbaum et al. (2009) utilized two- and three-dimensional coastal hydrodynamic models to predict regions of marine sedimentation following increased sediment discharge from the Elwha River.

One of the main findings of Bromley's (2008) laboratory experiments was that the position of the river channel through the reservoir delta at the start of dam removal would alter the patterns and rates of reservoir sediment erosion. Erosion volumes were much lower when the channel started near a sidewall of the reservoir than when the channel started in a central position. With these results in mind and with the intention to make Lake Mills erosion as efficient as possible, the Lake Mills delta was cleared of vegetation and the river channel was placed in a central delta position in 2010 before dam removal began (Randle et al., 2015-in this issue). The Lake Aldwell delta, in contrast, was not altered; and the channel remained in its eastern sidewall position at the start of dam removal. Consistent with the findings of Bromley (2008), the Lake Mills delta eroded much more efficiently and completely than did the Lake Aldwell delta (Fig. 15; Randle et al., 2015-in this issue). In fact, the majority of the western Lake Aldwell delta, which represents roughly two-thirds of the delta surface area, did not erode

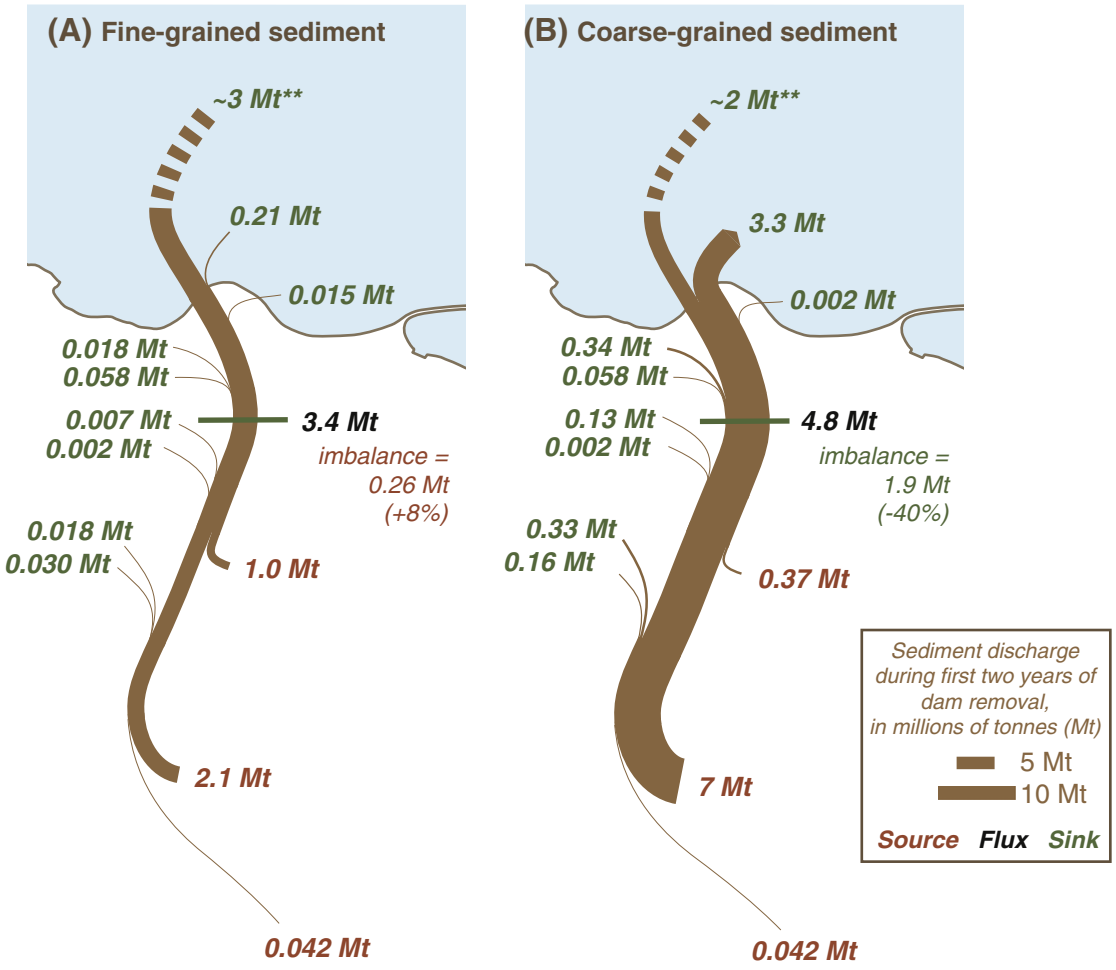

Fig. 11. The fine-grained and coarse-grained sediment budgets for the Elwha River system during the first two years of dam removal (Sept. 2011 to Sept. 2013). Sediment is partitioned by the 0.063-mm grain-size threshold. See Fig. 10 for an explanation of figure details.

during the first two years of dam removal as discussed in detail below (cf. Fig. 14A, B; Randle et al., 2015-in this issue).

Randle et al. (1996) and Konrad (2009) predicted that large quantities of sediment would erode from the reservoirs and would be transported through and deposited within the mainstem channel and floodplain, consistent with our observations. Yet, there were important differences between the models and the observations. Perhaps the most fundamental difference was that the models used total reservoir sediment volumes of ~13.5 million m^3 based on reservoir sediment volumes present in 1994, which were ~7.5 million m^3 less than actual volumes in the source areas as of the start of dam removal based on updated measurements of additional sedimentation between 1994 and 2010 (Randle et al., 1996; 2015-in this issue; Konrad, 2009; cf. Table 1). This difference makes a direct comparison of observations with model results difficult, because one should not expect simple linear transformation of the modeling results based on sedimentation volumes. Regardless, there are a few model assumptions and results that are important to compare.

Both fluvial modeling efforts predicted fine-grained sediment (silt and clay) erosion from the reservoirs, but assumed that this sediment would be transported efficiently and fully through the river to the coastal waters (Randle et al., 1996; Konrad, 2009). Although the vast majority (~96%) of fine-grained sediment was exported from the Elwha watershed (Fig. 11), there was nevertheless measurable fine-grained sedimentation within the river mainstem and floodplain channels (Table 4; Draut and Ritchie, 2013; East et al., 2015-in this issue). Although the deposition of small quantities of fine-grained sediment may not have a significant effect on river-water surface elevation, it can alter hydrologic and ecological characteristics of river channels and floodplains. Future modeling efforts should recognize that fluvial sedimentation of silt- and clay-sized sediment—even in short and steep drainages like the Elwha River—may be proportionally small but will not be hydrologically or ecologically negligible.

Another difference between the observations and fluvial models was the overprediction of coarse-sediment and fine-sediment export from the reservoirs. For example, Randle et al. (1996) predicted that ~4 million m^3 of the ~5.5 million m^3 of sediment eroded during the first three years (i.e., over 70%) would be fine-grained, whereas measurements suggested that only ~2.7 million m^3 of the ~7.1 million m^3 of sediment eroded during the first two years (i.e., ~40%) was fine-grained. This difference cannot be attributed to limitations of the models but rather can be attributed to the incomplete removal of Glines Canyon Dam during the two years studied here, which did not allow for full base-level drop and thus incision into the fine-grained sediments of the Lake Mills reservoir (cf. Figs. 2, 5, and 13; Randle et al., 2015-in this issue). Additionally, more extensive lateral erosion of the coarse delta deposits of Lake Mills occurred than was predicted (Randle et al., 2015-in this issue). This likely resulted from the clearing of delta trees, construction of a centrally located pilot channel, and dam-removal hold periods that coincided with high flows (winter storm runoff and spring snowmelt) when channel migration produced extensive lateral erosion in non-cohesive coarse sediment layers (Randle et al., 2015-in this issue).

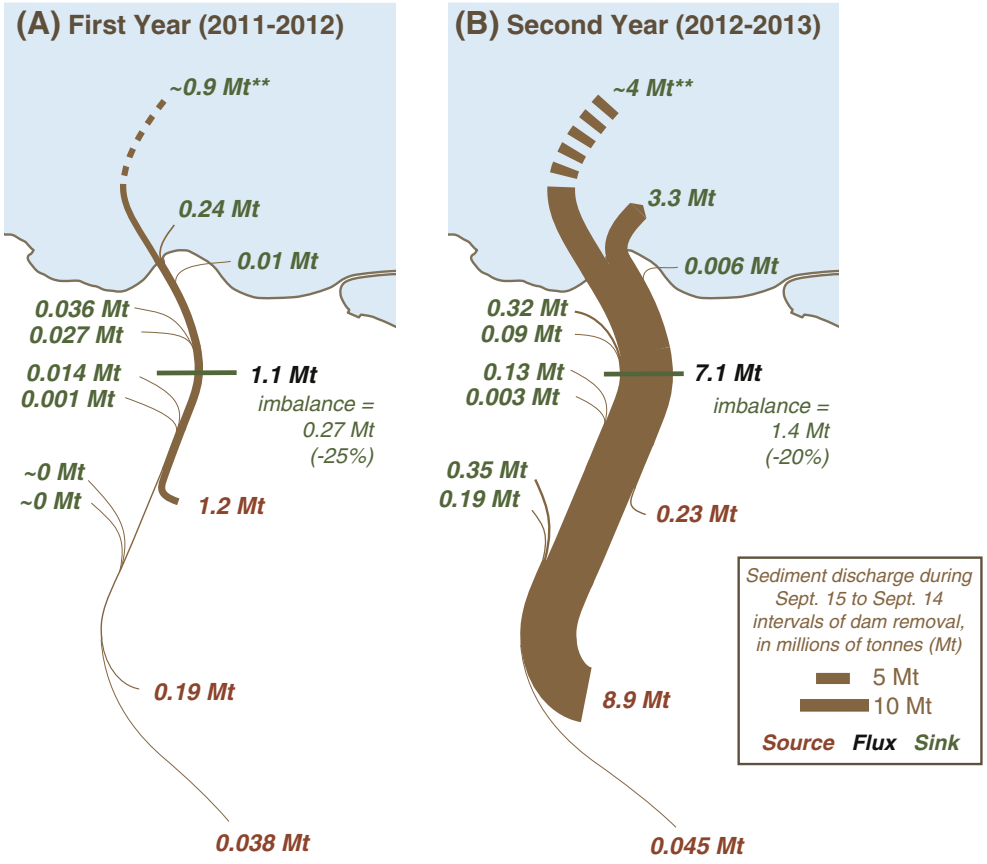

Fig. 12. The first- and second-year sediment budgets for the Elwha River system during the first two years of dam removal (Sept. 2011 to Sept. 2013). See Fig. 10 for an explanation of figure details.

Further differences between the observations and the fluvial models were found in the rate of erosion of the Lake Aldwell sediments, which slowed by ~80% during the two years studied here resulting in sediment volumes of ~4 million m^3 in the former reservoir at the end of two years (Figs. 5 and 12; Table 4). In contrast, the modeling results of Konrad (2009) revealed little slowing of Lake Aldwell erosion until sediment supplies were reduced to ~250,000 m^3. The cause of these discrepancies may lie in rates of dam removal, the initial eastern sidewall position of the channel in this reservoir, the thickness and grain sizes of the sediments in the reservoir, and the abundance of large woody debris and exposed stumps from the pre-dam land surface. Measurements revealed that the Elwha River incised through the Lake Aldwell delta to the pre-dam surface within a few months of the start of dam removal owing to the comparatively thin (<10 m) Lake Aldwell delta combined with a fairly rapid reservoir drawdown (cf. Fig. 5B). This predam surface included large old-growth stumps, cobble-sized bed material, and the cohesive bottom layers of the delta and lakebed deposits along the river banks, which—combined—slowed or limited lateral erosion (cf. Fig. 14A, B). Because of this reduction in erosion rate, two-thirds of the Lake Aldwell upper layer of coarse, non-cohesive sediment of the delta remained untouched by the river (cf. Fig. 4B; Randle et al., 2015-in this issue).

The volume of fluvial sedimentation was generally similar between the models (e.g., 0.5–1.5 m^3 over three years depending on hydrology; Randle et al., 1996) and our measurements (~0.8 million m^3 over two years). Yet both modeling efforts predicted that the greatest sedimentation during the first four years would be in the first 2–3 km downstream of Elwha Dam where the river slope is approximately half that of the reach downstream of Glines Canyon Dam (Randle et al., 1996; Konrad, 2009). In contrast, observations of fluvial sedimentation revealed more spatially uniform aggradation on the order of ~1 m thick (thicker in former pools) along the channel (East et al., 2015-in this issue). Furthermore, and in contrast with the relatively stable channel grain size predictions of Konrad (2009), East et al. (2015-in this issue) reported reductions of river channel grain sizes (e.g., Fig. 6).

The patterns of marine sedimentation predicted in Gelfenbaum et al. (2009) are generally consistent with the observations reported by Gelfenbaum et al. (2015-in this issue). Long-term two-dimensional morphodynamic modeling simulating a year of wave and tidal processes (Gelfenbaum et al., 2009) and short-term three-dimensional modeling simulating about 2 months of increased sediment supply predicted that fine-grained sedimentation would occur on the seafloor 0–2 km west of the river mouth and that coarse-grained sedimentation would occur immediately offshore and eastward of the river mouth. Coastal predictive modeling also showed the importance of the large submarine delta on the tidal currents and, ultimately, upon the sediment dispersal patterns. However, a direct comparison of the total volume deposited is not appropriate because the river sediment load in the model simulations was significantly less than the actual loads measured during the two years since dam removal began (280,000 m^3 vs. ~6 million m^3).

Combined, the predictive models for the Elwha River were found to provide reasonably accurate assessments of the general patterns of sediment erosion, transport, and deposition but were less accurate regarding short-term timing and/or magnitude of these effects. These observations are generally consistent with those for the Marmot Dam removal on the Sandy River, Oregon (Major et al., 2012). As noted above and by Major et al. (2012), there are a number of reasons for the discrepancies between predictions and observations, including differences between the project plans for decommissioning and actual implementation, differences between modeled and actual hydrology, and the limitations of existing numerical modeling techniques for assessing complex three-dimensional geomorphic processes such as knickpoint

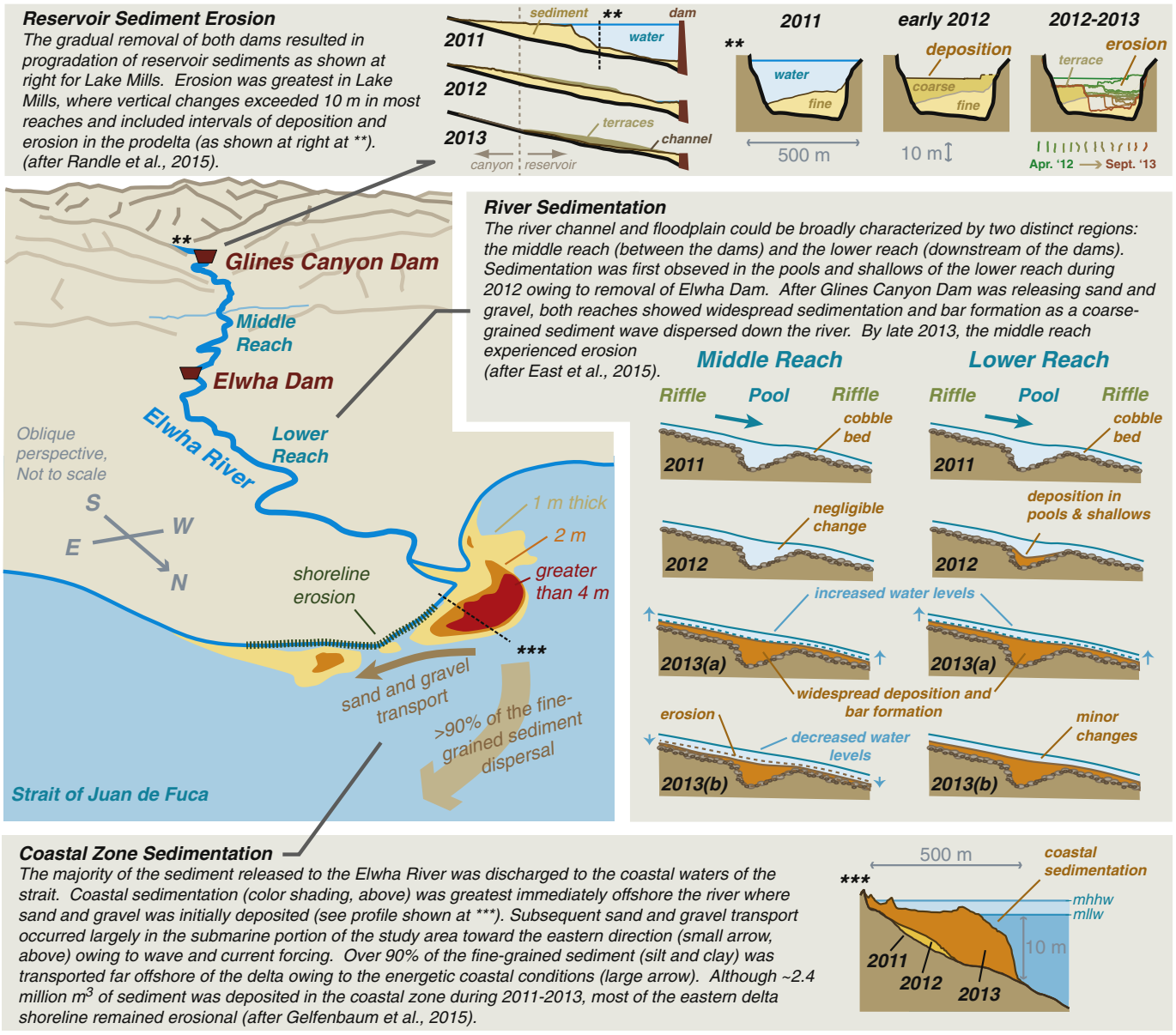

Fig. 13. Integrated conceptual model of geomorphic processes and change during dam removals on the Elwha River, Washington.

migration and lateral migration in mixed grain size sediments and the effects of wood on sediment transport and channel evolution. These discrepancies and challenges provide important opportunities for future researchers to develop better modeling parameterizations of the important geomorphic processes that occur during dam removal (cf. Pizzuto, 2002; Pearson et al., 2011; Greimann, 2013; Cui et al., 2014).

5.3. Comparison with other dam removals

It is instructive to compare the results of dam removals on the Elwha River to other large dam removal projects, as well as with the synthesis of small dam removals provided by Sawaske and Freyberg (2012). As noted in Section 1, several large dam removals (or structural failures) have occurred recently (e.g., Major et al., 2012; Tullos and Wang, 2014; Wilcox et al., 2014). An important distinction of these dam removals was the rapid removal processes for these dams (henceforth termed *instantaneous*), which contrasts with the several month to several year phased removals of the Elwha River dams (cf. Fig. 5B). Further distinctions occurred, for example, owing to the sediment grain sizes of the stored sediment—Marmot Dam removal released primarily gravel, whereas Condit Dam removal released primarily sand, silt, and clay (Major et al., 2012; Wilcox et al., 2014)—that make comparisons with the mixed-grain size release on the Elwha important.

The primary difference between the instantaneous removal of the Marmot, Condit, and Barlin dams (Major et al., 2012; Tullos and Wang, 2014; Wilcox et al., 2014) and the phased removal of the Elwha River dams was the rate of sediment export from these systems. Major et al. (2012) and Wilcox et al. (2014) provided detailed measurements showing rapid sediment export. Sediment export from Condit Dam was especially high owing to the rapid drawdown of the reservoir water levels—complete evacuation of the water occurred in 90 min—that induced mass movements of the predominantly fine-grained reservoir sediment and hyperconcentrated slurries (up to 850,000 mg/L) to the downstream river (Wilcox et al., 2014). These processes resulted in export of over a third of the 1.8 million m^3 original sediment in 6 days, and >60% of the stored sediment in 15 weeks (Wilcox et al., 2014). Although sediment export from the instantaneous removal of Marmot Dam was not as rapid as that of Condit Dam, Major et al. (2012) reported that the sediment export from the former reservoir was largely exhausted after two years.

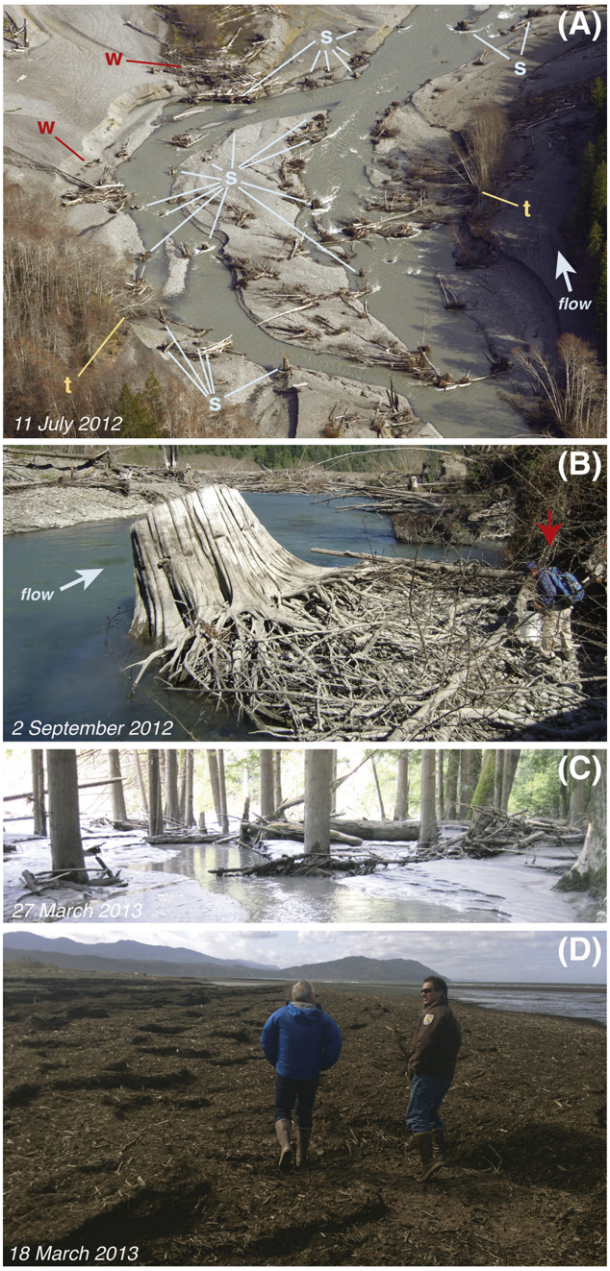

Fig. 14. Photographs of woody debris exposed and transported during dam removals on the Elwha River system. (A) Oblique aerial photo of the Lake Aldwell delta following full removal of Elwha Dam. Several sources of woody debris can be identified in the photo, including: stumps (*s*) of trees that were cut before dam construction and were buried in delta sediment; riparian trees (*t*) delivered to the river from bank erosion; and woody debris (*w*) formerly deposited on and within in the reservoir sediment. (B) A stump exhumed from the Lake Aldwell delta sediment by river erosion. A person for scale is highlighted with an arrow. (C) Sediment and woody debris deposition in an Elwha River floodplain channel at Rkm 5.4. (D) Fine woody debris on the intertidal beach of the delta ~200 m east of the river mouth during low tide. Photos provided by Neal and Linda Chism of LightHawk, Vivian Leung of University of Washington, Amy East of USGS, and Jeff Duda of USGS.

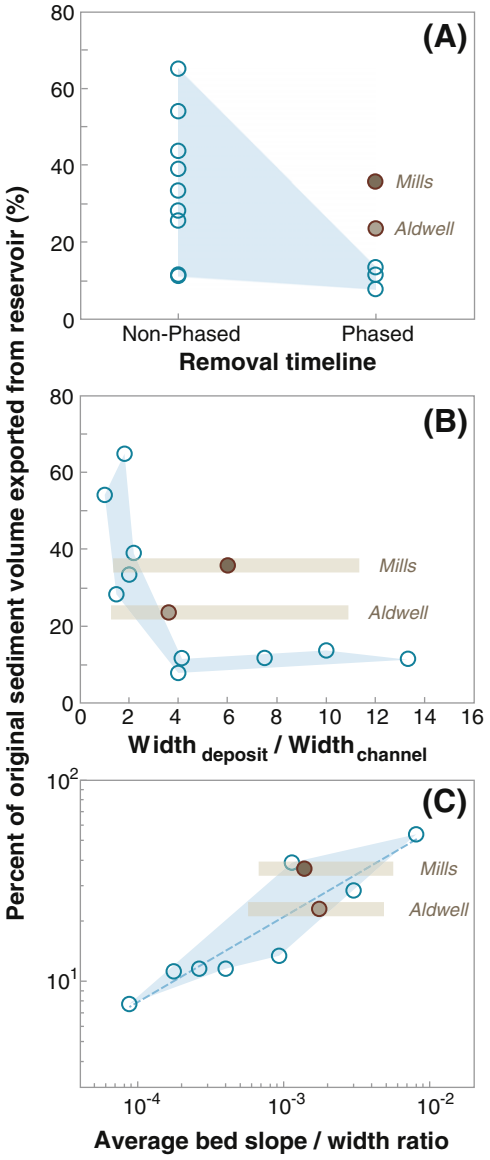

Fig. 15. Comparison of sediment export parameters from previous dam removals by Sawaske and Freyberg (2012) (blue symbols and shading) and those from dam removals on the Elwha River (brown symbols and shading) during the first two years of removal. The blue shading for the previous projects shows the range of values existing from these studies. The brown shading for Lakes Mills and Aldwell in (B) and (C) represents the range of channel widths measured during the dam removals, and the symbols are plotted for average channel width values. The dashed line in (C) is the nonlinear regression from the previous authors' work. See text for further descriptions.

In contrast to these rapid rates of sediment transport, the rates of sediment export from the two reservoirs on the Elwha River were more modest owing to (i) initial dam removal occurred while substantial reservoir capacity still remained resulting in the majority of eroded sediments depositing in the receding lakes rather than being released past the dam sites; (ii) the incomplete removal of Glines Canyon Dam after two years that resulted in only partial incision of the former Lake Mills sediment; (iii) lack of a large flood during the first two years which limited the extent of lateral erosion within the finer-grained, more cohesive deposits in the former reservoirs; (iv) the phased removal of the two Elwha River dams, which resulted in numerous small knickpoints eroding the reservoir deltas with each dam removal increment (rather than one large knickpoint) and prevented mass movements of sediment from rapid dewatering processes; and (v) the quick incision of the river through the thinner Lake Aldwell delta deposits to cohesive bottom sediment layers and the more erosion resistant pre-dam surface beneath them.

It is also valuable to compare the Elwha River results with the synthesis of dam removal results by Sawaske and Freyberg (2012), which included 12 dams smaller than 14 m high and with <800,000 m^3 stored sediment volume. Sawaske and Freyberg (2012) concluded that deposit

grain size and geometry, dam removal timelines, and stream geometry significantly influenced the rate of sediment export from dam removal sites (unfilled symbols and shaded areas, Fig. 15). The Elwha River results appear to support some of these conclusions while diverging from others. For example, the percent of sediment eroded from the Elwha River reservoirs (36% and 24%) exceeded that expected from previous projects with phased dam removals or with relatively wide sediment deposits (Fig. 15A, B). This may be associated with the slope of the Elwha River through its former reservoirs, which averaged ~0.0075 in Lake Mills and ~0.006 in Lake Aldwell; and this is shown by the better agreement of the Elwha River data with the Sawaske and Freyberg (2012) analysis when channel slope was included (Fig. 15C). However, we note that all of the watersheds summarized by Sawaske and Freyberg (2012) with highly efficient sediment export (>20%) had non-phased dam removal and narrow sediment deposits (i.e., width ratios < 2; cf. Fig. 15). Thus, the fact that the rate of sediment export from the Elwha River reservoirs was much higher than previous *phased* projects may have been more a function of the sediment deposit and river channel geometries than the project implementation.

Additionally, we found that the Elwha River channel width through the former reservoirs varied by almost a factor of 10 during the two years studied, and maximum channel widths were measured to be 340 and 220 m in Lake Mills and Aldwell, respectively. During higher flows and times of rapid sediment redistribution in the reservoirs, the Elwha River could essentially fill the entire reservoir deposit width in sections of each reservoir (e.g., Fig. 4). Thus, the average channel widths of 75 m through the Elwha River reservoirs do not represent the potential for sediment export expressed in the variables of Sawaske and Freyberg (2012; filled symbols, Fig. 15B). However, the Elwha River data may be consistent with Sawaske and Freyberg's (2012) synthesis if the highly variable nature of channel widths in these former reservoir systems is considered (shading, Fig. 15B).

5.4. Expectations for the Elwha River system

One controlling factor for the future geomorphic evolution of the Elwha River and its coast will be the volumes and characteristics of sediment remaining in and released from the former reservoirs. Overall, 10.5 ± 1.8 million t, or ~35% of the original reservoir sediment mass, was eroded and exported downstream during the first two years of dam removal (Fig. 10; Table 4). Erosion of the Lake Mills sediment was more efficient than Lake Aldwell, as ~40% of the total Lake Mills sediment mass was eroded whereas only ~20% of the Lake Aldwell sediment mass was eroded (cf. Tables 1 and 4). This suggests that ~14 million t of sediment remained in the former Lake Mills and ~5.4 million t of sediment remained in the former Lake Aldwell after two years. Of the ~20 million t of total sediment that remained, ~8 million t was fine-grained, of which ~6 million t (or 75%) was in the former Lake Mills reservoir, much of which was still buried by coarse-grained sediment (cf. Fig. 13; Randle et al., 2015-in this issue).

As the river responds to the completion of Glines Canyon Dam removal (summer 2014 and beyond), the river will continue to incise into and laterally erode the remaining Lake Mills sediments, releasing new supplies of fine- and coarse-grained sediment and woody debris. The incision of these sediments will release volumes of fine-grained sediment that will likely surpass those released during the first two years of dam removal. The continued lateral erosion and export of coarse sediment deposits remaining in Lake Mills could introduce new supplies of bed sediment that will renew dispersive sediment waves in the Elwha River. Erosion of Lake Aldwell sediment is also expected to continue; but based on the 80% reduction in erosion during year 2, this may require larger floods to laterally erode into the cohesive sediment banks and through the old-growth stumps of the original valley floor.

Ultimately, it is expected that some of the sediment in the former reservoirs will not be eroded and will remain as fluvial terraces. For example, Konrad (2009) predicted that 1–3 million m^3 of Lake Mills sediment and ~100,000 m^3 of Lake Aldwell sediment would remain in the former reservoirs after seven years. In contrast, Randle et al. (1996) predicted that 6.0–7.2 million m^3 of Lake Mills sediment and 0.9–1.9 million m^3 of Lake Aldwell sediment (i.e., 7.2–8.8 million m^3 or 53–65% of the original modeled sediment volume) would remain in the two reservoirs and '… remain stable over the long term' (p. 129). Although these predictions differ markedly in magnitude, it is likely that some portion of the original sediment will remain in the former reservoirs, especially as vegetation is established (Chenoweth et al., 2011).

One variable that will help determine the rates of sediment export and the locations of sedimentation will be the future hydrology of the Elwha River. Sediment fluxes during the first two years of dam removal were strongly related to streamflow (Fig. 5; Magirl et al., 2015-in this volume), even though streamflow did not exceed the two-year recurrence interval discharge rates. When streamflow in the future is relatively high, not only may sediment export from the former reservoirs be high, but fluvial sedimentation may extend into the widespread areas of the river's floodplain, where negligible deposition had occurred during the two years studied here (East et al., 2015-in this issue).

Although pronounced changes have occurred along the Elwha River delta coast (Figs. 7 and 13; Gelfenbaum et al., 2015-in this issue), the massive injection of sediment had surprisingly little effect on the rates of shoreline erosion in much of the downdrift littoral cell. The resupply of sediment to the littoral cell will be related to the rate of transfer of sediment from the subtidal deposits to the intertidal beach shoreface, a process that is most likely dictated by waves (cf. Hoefel and Elgar, 2003) but difficult to predict or quantify. There was evidence that sediment was being deposited in (or was being transported up to) intertidal water depths by the end of study summarized here (cf. Fig. 13; Gelfenbaum et al., 2015in this issue), which is where the majority of erosion and littoral sediment transport has occurred during the past several decades (cf. Warrick et al., 2009; Miller et al., 2011). With continued shoreward sediment movement, the beaches of the Elwha River delta may reverse their erosional trends. Measuring or predicting those potential changes is a recommended direction for future work.

5.5. Lessons learned and future directions

There are a number of lessons learned from the geomorphic studies of the Elwha River dam removals that will be applicable to future dam removals and sediment releases and that relate to the more general problem of studying landscape-scale, source-to-sink evolution of a sediment pulse. First, if sediment mass balances are desired or required, spatial and grain-size variations in sediment bulk densities must be considered. Sampling from the Elwha River system revealed that bulk densities varied significantly throughout the study area (Table 2). In lieu of using assumptions of constant bulk density for reservoir, fluvial, and/or marine sediments, we suggest that bulk densities should be measured where possible and spatial and grain-size variations in bulk density used from the measurements and/or relationships found in work such as Morris and Fan (1997) and van Rijn (2005).

Additionally, although the Elwha River sampling program had numerous physical, optical, and acoustic sensors to calculate suspended and bedload fluxes in the river, we found that the coarse-grained sediment budget retained a discrepancy of ~40% (Fig. 11). These discrepancies likely resulted from the sand fraction of sediment transported preferentially near the bed, such that suspended-sediment and bedload physical samplers undersampled it (Magirl et al., 2015-n this volume). There are no simple solutions to these measurement problems, and future studies will likely have similar difficulties monitoring the sand fractions of sediment-laden rivers (Gray and Gartner, 2009; Topping et al., 2011). In light of this, the combination of sediment flux measurements, morphometric change measurements of reservoir sediments and

downstream fluvial and coastal landforms, and bulk density information throughout these systems may be the most efficient way to complete a sediment budget and characterize temporal patterns of sediment transport.

Lastly, the synthesis of our Elwha River results with the previous dam removal summary of Sawaske and Freyberg (2012) (Fig. 15) and other large dam removals suggests that there is a need for new quantitative summaries of the geomorphic effects of dam removal to include more of the recent large dam removals and a focus on downstream effects of the removals. We hypothesize that variables such as sediment grain size, volume and deposit geometry, dam removal strategy and timing, stream gradient, floodplain width and morphology, and hydrology will dictate geomorphic response(s) to dam removal sediment releases (cf. Pizzuto, 2002; Doyle et al., 2003; Sawaske and Freyberg, 2012). There is also a great need for additional experimental research (e.g., Childers et al., 2000; Bromley, 2008) to assist with characterizing the erosion and transport rates and processes that occur during dam removal-related sediment releases—including knickpoint or headcut evolution, reservoir bank failure, erosion resistance from reservoir sediment compaction and/or cohesion, effects and patterns of woody debris, and transport of poorly sorted distributions of sediment—so that predictive capabilities continue to improve.

6. Conclusions

The removal of two large dams on the Elwha River, Washington provided a unique opportunity to track sediment movement and geomorphic evolution of a river and coastal system during a massive perturbation in the sediment supply. Our source-to-sink sediment budget indicated that ~90% of the ~10.5 Mt of sediment released to the river passed through to the coastal waters of the Strait of Juan de Fuca during the first two years of this project, causing the sand and gravel river mouth delta to expand by ~3.5 million t. Sedimentation in the river responded to rates of supply, and the release of coarse-grained sediment from the upper reservoir during the second year of study induced a dispersive sediment wave downstream causing ~1 m of aggradation and fundamental changes to the river planform morphology. Future evolution of the river and coast will be determined by the final dam removal activities at Glines Canyon Dam, which had ~16 m of vertical structure remaining after two years that helped retain some of the ~14 Mt of sediment still in the reservoir, ~40% of which was fine-grained. Thus, the story of reservoir erosion and downstream river and coastal response will continue as the Elwha River evolves and establishes a new landscape in response to the completion of dam removal and future floods.

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