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# Channel evolution on the dammed Elwha River, Washington, USA

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ABSTRACT

Like many rivers in the western U.S., the Elwha River, Washington, has changed substantially over the past century in response to natural and human forcing. The lower river is affected by two upstream dams that are slated for removal as part of a major river restoration effort. In preparation for studying the effects of dam removal, we present a comprehensive field and aerial photographic analysis of dam influence on an anabranching, gravel-bed river.

Over the past century with the dams in place, loss of the upstream sediment supply has caused spatial variations in the sedimentary and geomorphic character of the lower Elwha River channel. Bed sediment is armored and better sorted than on the naturally evolving bed upstream of the dams. On time scales of flood seasons, the channel immediately below the lower dam is fairly stable, but progresses toward greater mobility downstream such that the lowermost portion of the river responded to a recent 40-year flood with bank erosion and bed-elevation changes on a scale approaching that of the natural channel above the dams. In general, channel mobility in the lowest 4 km of the Elwha River has not decreased substantially with time. Enough fine sediment remains in the floodplain that – given sufficient flood forcing – the channel position, sinuosity, and braiding index change substantially. The processes by which this river accesses new fine sediment below the dams (rapid migration into noncohesive banks and avulsion of new channels) allow it to compensate for loss of upstream sediment supply more readily than would a dammed river with cohesive banks or a more limited supply of alluvium. The planned dam removal will provide a valuable opportunity to evaluate channel response to the future restoration of natural upstream sediment supply.

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## 1. Introduction

The evolution of river channels in response to natural and human forcing gives rise to one of the most substantial ways in which human settlement habits interact with geologic processes. Dams typically block the upstream sediment supply, and river regulation fundamentally alters fluvial hydrology. Sedimentary and geomorphic properties of river channels downstream of dams therefore change substantially, in ways and by degrees that are still being realized (e.g., Williams and Wolman, 1984; Collier et al., 1996; Grant et al., 2003; Topping et al., 2003; Vörösmarty et al., 2003; Walling and Fang, 2003; Renwick et al., 2005; Yang et al., 2007; Walter and Merritts, 2008; Kummu et al., 2010). Here, we investigate the influence of dams on an anabranching gravel-bed river, a class of river system less well understood than meandering or braided channels. We analyze rates and patterns of channel change over seasonal to decadal scales on the Elwha River, Washington (Fig. 1), to test two hypotheses: (1) that at the present time, after a century with dams in place, the loss of upstream sediment supply will be evident in spatial variation of (a) bed-sediment grain size and (b) channel response to floods, with coarser, less mobile sediment below than above the dams; and (2) for a given reach below the dams, loss of upstream sediment supply will have caused channel mobility to decrease through time. Using field surveys and historical aerial photographs to address these problems, we thereby compile the first such comprehensive record of spatial and temporal influence of dams on a river of this geomorphic class.

Because the two large dams on the Elwha River are slated for removal as part of a major river restoration effort, this study also provides a record of channel behavior with which changes after dam removal will be compared. In the continental U.S., more than 75,000 river-regulation structures have been built to provide water storage, flood control, and hydropower (Graf, 1999). The cost of maintaining aging dams, and the growing understanding of their widespread ecologic consequences (Bain et al., 1988; Dynesius and Nilsson, 1994; Ligon et al., 1995; Lessard and Hayes, 2003; Nilsson et al., 2005; Syvitski et al., 2005; Thoms et al., 2005), in some places have prompted dam removal and riparian restoration (Grant, 2001; Graf, 2003, 2005). Elwha and Glines Canyon dams, 12 km apart on the Elwha River, were completed in 1913 and 1927 and stand 32 and 64 m high, respectively. Removal of both dams will allow unimpeded flow along approximately 70 km of the mainstem river in a nearly undeveloped watershed, most of which is within Olympic National

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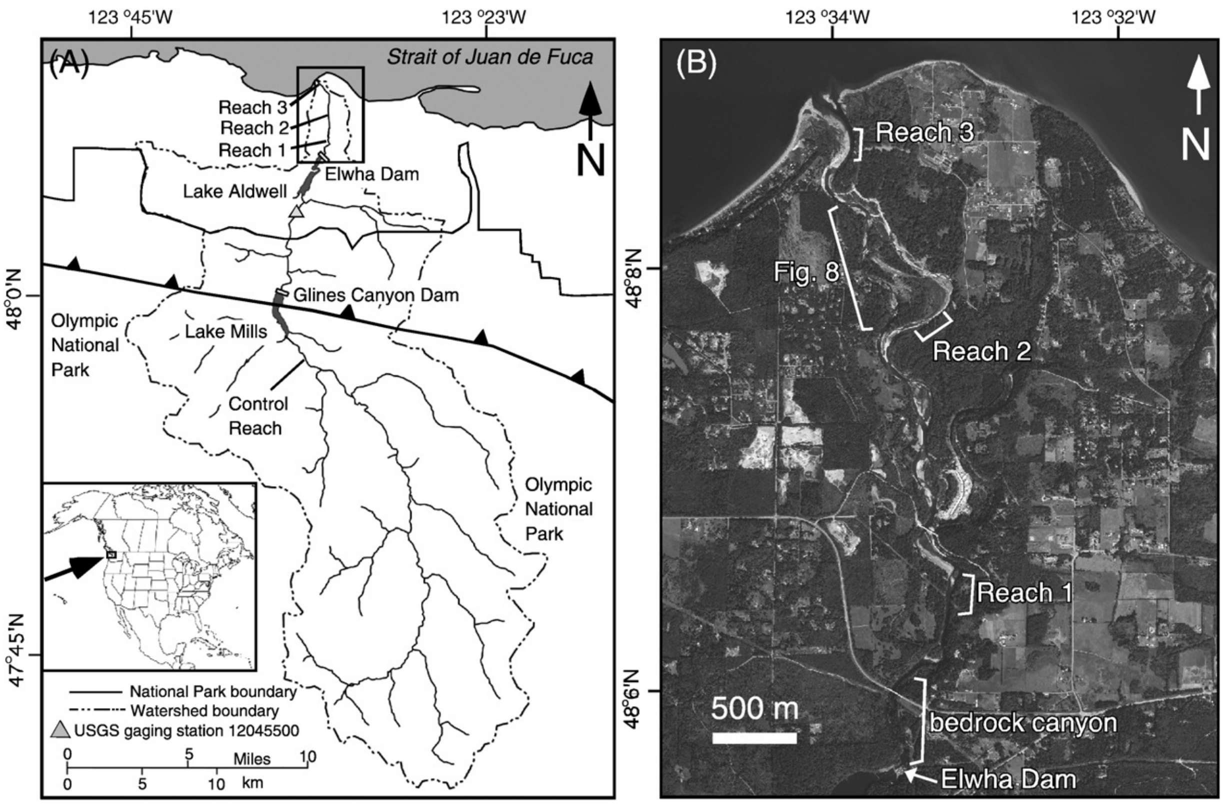


**Fig. 1.** The Elwha River watershed, northwest Washington. (A) Index map showing the locations of Elwha and Glines Canyon dams and reservoirs (Lakes Aldwell and Mills) and the control reach surveyed in this study. Reaches 1, 2, and 3 are within the box that indicates the area shown in (B). The approximate trend of a terrane-bounding thrust fault is shown; the Olympic Subduction Complex occurs south of the fault, and the Coast Range terrane to the north. (B) Aerial photograph of the lower Elwha River, taken in 2009.

Park; a major goal of dam removal is to restore access to spawning habitat of anadromous fish species whose populations have declined precipitously (Nehlsen, 1997; Beechie et al., 2001; Grossman, 2002; Pess et al., 2008; Kocovsky et al., 2009). After dam removal, sediment in the two reservoirs (Lakes Aldwell and Mills) will be transported by natural flows downstream into the lower river and toward the ocean (Randle et al., 1996).

Having studied channel behavior downstream of the Elwha dam sites will present an unprecedented opportunity to understand fluvial adjustment not only to a century-long loss of sediment supply but also, in the future, to its restoration. Although scientists have had valuable opportunities to study fluvial response to removal of dams less than 15 m high (Bushaw-Newton et al., 2002; Pizzuto, 2002; Wildman and MacBroom, 2005; Major et al., 2008; Schenk and Hupp, 2009), much remains to be learned about channel response to dams and their removal, indicating the need for landscape-scale case studies before, during, and after dam removal (Grant, 2001; Doyle et al., 2002; Pizzuto, 2002; Graf, 2003).

### 1.1. Geology and hydrology of the Elwha watershed

The 833-km$^2$ Elwha watershed drains steep, mountainous terrain of the Olympic Peninsula (Fig. 1A), which comprises parts of two geologic terranes within the forearc high of the Cascadia subduction zone (e.g., DeMets and Dixon, 1999). Mountains in the Elwha headwaters comprise metasedimentary rocks of the Olympic Subduction Complex, an uplifted part of the accretionary wedge that is structurally overlain by the ophiolitic Coast Range terrane (Tabor and Cady, 1978; Brandon et al., 1998; Gerstel and Lingley, 2003; Polenz et al., 2004; Stewart and Brandon, 2004). Steep slopes in the upper Elwha basin, maintained by rapid uplift (Brandon et al., 1998; Batt et al., 2001), produce landslides that generate substantial quantities of sediment (Acker et al., 2008).

Pleistocene continental ice sheet extent culminated ca. 14 ka in southward advance of ice to 11 km inland of the present coastline in the Elwha region (McNulty, 1996; Porter and Swanson, 1998; Mosher and Hewitt, 2004; Polenz et al., 2004), and alpine glaciation occurred contemporaneously in the upper Elwha watershed. Sedimentary deposits related to ice damming remain in the lower Elwha basin; these range from poorly sorted glacial outwash alluvium to glaciolacustrine silt and clay (Tabor, 1975, 1987; McNulty, 1996; Polenz et al., 2004). Proglacial deposits are exposed in bluffs along the lower Elwha River and are the most substantial modern source of sediment downstream of Elwha Dam.

The river flows through a bedrock canyon in some reaches, and forms an alluvial floodplain in others. The area likely to be most affected by renewed sediment supply after dam removal (aside from the reservoir deltas) is the 7.8-km-long reach known as the lower river, which is downstream of both dams and will receive sediment from both reservoirs (Fig. 1B). Within the upper 1.3 km of this reach, the river is confined to a narrow bedrock gorge, whereas the lowermost 6.5 km are best described as having an anabranching channel form; although in some alluvial reaches the Elwha River has a single wandering gravel-bed channel (order B2 of Nanson and Croke, 1992), elsewhere it has multiple channels separated by bars and vegetated islands excised from the floodplain (cf. Smith and Smith, 1980; Harwood and Brown, 1993; Knighton and Nanson, 1993). The islands can be large relative to the channel width and are commonly stable on decadal time scales. Individual channels meander or may exhibit smaller-scale braiding but eventually rejoin. The Elwha floodplain is heavily vegetated with hardwood and conifer trees.

Because their reservoirs are small, Elwha and Glines Canyon dams have little effect on the magnitude and duration of high flows and are not used for flood control (Fig. 2). Dam-released flows are near "run of the river" except that, owing to hydropower production, they have fluctuated more rapidly and had lower daily minimum flows than is

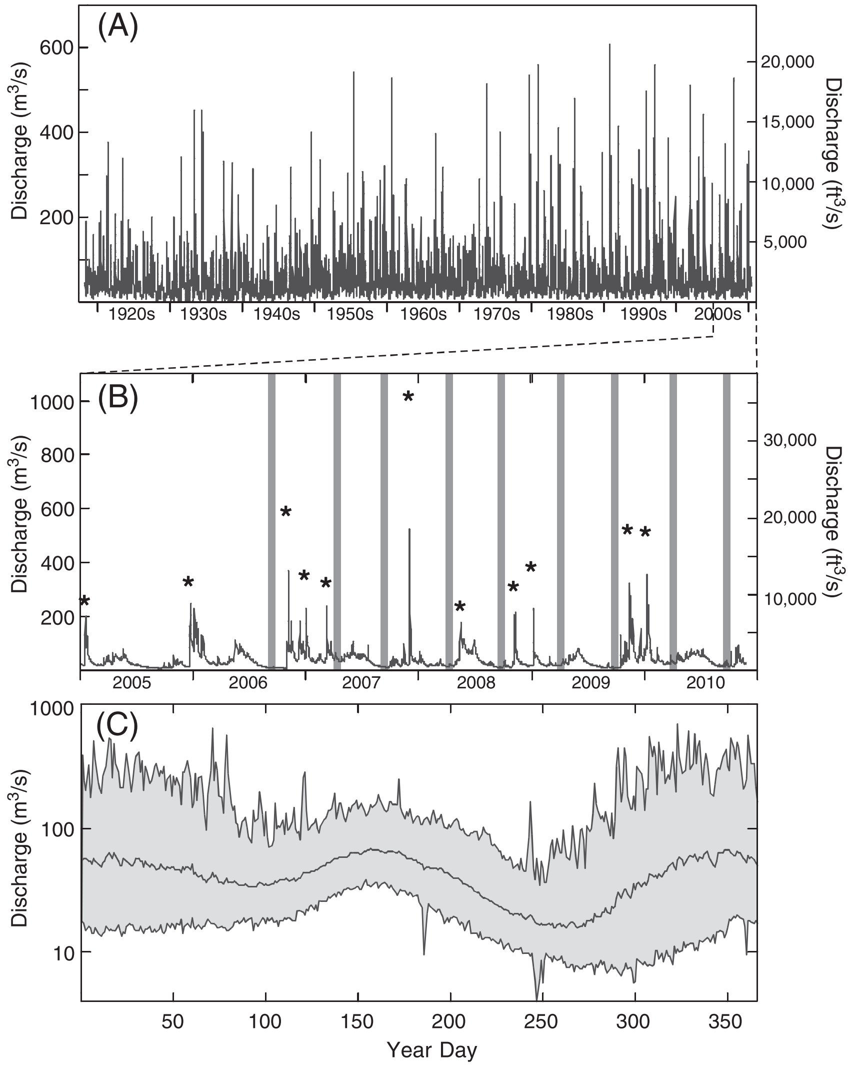


**Fig. 2.** Hydrographs of the Elwha River, showing discharge measured at USGS gaging station 12045500 (location on Fig. 1). (A) Daily average discharge from 1918 to 2010, when discharge has been measured continuously at this gage. (B) Daily average discharge (black line) for 2005 through 2010, showing flows during and shortly before this field study. Asterisks indicate instantaneous peak discharge of the largest floods in those years. The flood peak of 1016 $m^3/s$ on 3 December 2007 was the second-highest flow recorded on the Elwha River. Vertical gray bars indicate times when channel topography and grain size were surveyed in the field. (C) Seasonal trends in Elwha River flows. Gray envelope shows the historical range of daily average discharge, by year day (envelope boundaries are maximum and 5th percentile flows; minimum flows are strongly affected by dam operations and are not shown). Black line through the gray envelope shows mean discharge.

natural (Johnson, 1994; Pohl, 1999). Annual peak discharges are between October and March in response to fall and winter rain storms, with three fourths of the peaks occurring in November, December, and January (Fig. 2). Secondary peaks with longer duration occur in late spring in response to snowmelt; June has the highest mean monthly discharge (62.9 $m^3/s$; Fig. 2C). The upstream sediment supply to the lower Elwha River has been virtually eliminated by the dams except for suspended-sediment passage during large floods. Fluvial sediment delivery to the coastal ocean is estimated to be around 2% of the pre-dam load (EIS, 1996).

### 1.2. Previous work

The hypotheses outlined above follow from previous studies of factors that control channel form and sediment content. Field studies demonstrate incision, narrowing, and bed armoring downstream of large dams (e.g., Leopold et al., 1964; Livesey, 1965; Galay, 1983; Simon et al., 2002; Grant et al., 2003; Rinaldi, 2003; Grams et al., 2007; Schmidt and Wilcock, 2008; Gaeuman et al., 2009). Bed armoring (winnowing) occurs as river flows evacuate fine sediment below dams, eroding sand from the main channel bed, in eddies, and along the channel margin (Laursen et al., 1976; Dietrich et al., 1989; Kearsley et al., 1994; Wright et al., 2005; Hazel et al., 2006). Armoring depends upon post-dam flows having the capacity to transport more fine sediment than is available; however, fine sediment may accumulate downstream of a dam if regulated flows sufficiently reduce fluvial carrying capacity relative to sediment availability (Grams and Schmidt, 2005). Dam-induced changes in flow and sediment supply also can alter the sinuosity and degree of braiding in the downstream channel (Marston et al., 2005). Other studies have documented channel response to changing sediment supply unrelated to dams: Smith and Smith (1984) and Kondolf et al. (2002) showed that channel braiding and width/depth ratio increased in response to new bedload influx, whereas decreased sediment supply prompted degradation and narrowing. The relationship between sediment supply and channel form was explored in experiments by Bryant et al. (1995) and Ashworth et al. (2004), in theoretical formulation by, e.g., Parker (1976) and Heller and Paola (1996), and was reviewed by Ferguson (1993), among others.

Although multithread channels such as that of the lower Elwha River occur globally in a wide variety of environments (Nanson and Knighton, 1996; Tooth and McCarthy, 2004; Judd et al., 2007) and are common in the Pacific Northwest, this channel form is less well understood than meandering or braided rivers (Church, 1983; Huang and Nanson, 2007; North et al., 2007). This is largely because studies of channel avulsion are hindered by the rarity of major avulsion events in rivers and thus by the difficulty of simulating them in statistically meaningful patterns (Heller and Paola, 1996). Nevertheless, an anabranching planform is likely a more common state for unaltered streams than has been recognized previously (Walter and Merritts, 2008). This river morphology provides important biological functions because of the interconnected nature of the main channel, backwaters, side channels, and floodplain and serves as habitat for many plant and animal species (Church, 2002; Beechie et al., 2006). Examples of anabranching rivers include many in the Pacific Northwest with wandering gravel beds similar to the Elwha and others that drain mountainous terrain in western Canada (Smith and Smith, 1980, 1984; Gottesfeld and Johnson-Gottesfeld, 1990), although those represent larger watersheds with channels wider and more sinuous than those of the Elwha River.

Several previous field studies quantified the evolution of anabranching rivers on annual to decadal time scales. On the Olympic Peninsula, O'Connor et al. (2003) measured rates of channel change and floodplain turnover on the undammed Queets and Quinault Rivers. Burge (2006) studied bifurcation processes in the gravel–cobble Renous River, New Brunswick, Canada, quantifying node formation and channel switching. Avulsions in such systems can reoccupy abandoned channels of lower elevation than the floodplain, either during high flow (Nanson and Knighton, 1996; Jain and Sinha, 2004) or in response to local obstructions such as log jams (Gottesfeld and Johnson-Gottesfeld, 1990). Channel evolution in anabranching rivers, therefore, occurs by avulsion forming new bifurcations and also by lateral meander migration within individual anabranches. As with other channel types, the greatest geomorphic change on anabranching rivers typically is triggered by floods (e.g., Jain and Sinha, 2004). In humid settings, vegetation is an important stabilizing influence on anabranching channel geometry (e.g., Knighton and Nanson, 1993; Nanson and Knighton, 1996; Burge, 2006; Rodrigues et al., 2006; Joeckel and Henebry, 2008).

Because dam removal on the Elwha River has been anticipated for nearly 20 years, a substantial body of work documents river-corridor conditions there for post-removal comparison. Previous studies have assessed floodplain vegetation, anadromous fish and nutrient cycling, large woody debris, and sediment supply to the nearshore marine environment, among other topics (Duda et al., 2008; McHenry and Pess, 2008; Morley et al., 2008; Shaffer et al., 2008). Cochrane et al. (2008) and Warrick et al. (2008, 2009a) studied topography and grain size on- and offshore of the Elwha delta. The coast has eroded downdrift of the Elwha River mouth since the dams were built, a consequence of lost fluvial sediment supply (Galster and Schwartz, 1990; Warrick et al., 2009a). The volume of sediment trapped in the upstream reservoirs (Lakes Aldwell and Mills) was estimated in 1996 to be $13.8 \times 10^6$ m$^3$ (Randle et al., 1996); the total volume now is likely more than $16 \times 10^6$ m$^3$ (Curran et al., 2009). At least $0.9–2.0 \times 10^6$ m$^3$ of sand and coarser sediment and approximately $3.7–4.3 \times 10^6$ m$^3$ of silt and clay will likely move downstream as the reservoir deltas erode after dam removal (Randle et al., 1996).

Previous studies of the Elwha floodplain include analysis of vegetation age in historical aerial photographs by Kloehn et al. (2008). Building on work by Beechie et al. (2006) on other forested Pacific Northwest floodplains, Kloehn et al. (2008) found that the proportion of floodplain surfaces older than 75 years increased through time downstream of the Elwha dams while the proportion of younger surfaces decreased. Because these trends differed from those in the nearby unregulated upper Quinault River, Kloehn et al. (2008) inferred that sediment-supply reduction through damming caused the lower Elwha floodplain to stabilize and transition toward more mature forests and channels undergoing less frequent disturbance. Their conclusion was based upon the finding that bed sediment below Elwha Dam includes armored cobble substrate, a result of lost upstream sediment supply (Randle et al., 1996; Randle, 2003; Pohl, 2004; Kloehn et al., 2008).

Work by Pohl (1999, 2004) provided a background for our investigation of channel and grain size evolution. Pohl evaluated the potential for bed sediment mobility on the Elwha River, using mean bed particle size measured along seven transects in summer 1998. Despite some bed armoring, sediment in the lowest 5 km of the river was fine enough to be mobile in a mean annual flood (considered to be 362 m$^3$/s by Pohl, 1999; using the longer gaging record now available, the recalculated mean annual flood is 446 m$^3$/s). Alluvial reaches of the upper river, unaffected by dams, had the finest, most mobile grain size (Pohl, 2004). This study builds upon those findings by greatly expanding the scope of previous grain-size studies, and by evaluating channel mobility in response to floods.

## 2. Methods

### 2.1. Topographic and grain size surveys

To examine modern spatial variability in bed-sediment grain size and channel mobility in response to floods, testing hypothesis (1) above, we conducted a four-year field study of channel topography and grain size. Three alluvial reaches of the lower Elwha River were selected, referred to as reaches 1, 2, and 3 in order from upstream to downstream (Fig. 1B), that represent a variety of geomorphic conditions and distance from the dams. Reach 1 (300 m long, centered 5.6 km above the river mouth and 1.3 km below Elwha dam), includes the first alluvial floodplain area downstream of the bedrock canyon where Elwha dam is located. Reach 2 (190 m long, 2.8 km above the river mouth) is in the eastern anabranch in an area where the flow occupies two channels separated by a vegetated island 400 m wide. During most of this field study, the anabranch containing reach 2 carried slightly more than half of the total river flow. Reach 2 includes an engineered log jam emplaced to provide fish habitat (McHenry et al., 2007) and the downstream end of a 12-m-wide side channel that maintains a groundwater connection to the river but receives surface flow only during floods. Reach 3 (250 m long) is centered 0.5 km above the river mouth in the intertidal zone. This reach includes the downstream end of a side channel that joins the main channel from the east and is downstream of a steep eroding bluff 310 m long by 38 m high.

A fourth area upstream of both reservoirs, within Olympic National Park, was studied as a control site (Fig. 1A). The control reach (190 m long) is within a 3.2-km-long alluvial valley below and above which the river is confined by bedrock canyons. Monitoring the control reach measures conditions in the undammed Elwha River for comparison with the dam-influenced lower river, recognizing that the steeper gradient of the control reach compared to reaches 1–3 (0.009 vs. 0.006) implies a somewhat more dynamic system above the dam sites.

Beginning in 2006, channel topography was surveyed twice annually on transects (21 in total) across the four river reaches described above. Spring and fall channel surveys were conducted between flood seasons to resolve changes caused by winter storm floods and those caused by spring snowmelt flows (Fig. 2B). Within each reach, four to six transects perpendicular to the river banks were spaced 5–15 m apart and spanned as great a cross-sectional width as safe access allowed. High-resolution topographic profiles were obtained using a survey rod and total-station instrument. Geodetic control points were established by coincident surveying of three Global Positioning System (GPS) receivers within each reach; GPS receivers were referenced back to a continuously operating base station, which in turn was referenced to a national network of continuously operating GPS receivers. Positional accuracy of topographic surveys is estimated to be within 2–4 cm.

Grain size was measured on selected transects by analyzing digital photographs of bed sediment. Referred to as the CobbleCam technique, this method uses an autocorrelation algorithm of pixels in digital images (Rubin, 2004) to calculate mean grain size of sediment ranging from sand to boulders (Warrick et al., 2009b). Photographs were taken along unvegetated, subaerially exposed parts of transects (3–4 transects per reach, depending on river flow at the time of each survey, with photographs spaced every 1 m) using a 6.0-megapixel Canon PowerShot S31S camera mounted on a tripod and facing directly downward from 0.8 to 1.2 m above the bed. CobbleCam grain size analyses, which have error of approximately 14% for grain sizes 1–200 mm in natural field lighting (Warrick et al., 2009b), provide a more rapid, efficient means to characterize bed sediment than traditional sieving or pebble-counting methods. Sampling spatial and temporal bed-sediment grain size trends using the CobbleCam thus provided useful information on sediment mobility and transport in each reach.

### 2.2. Aerial photographic analysis

To characterize longer term patterns of channel change on the Elwha River, addressing hypothesis (2) above, we analyzed lateral channel change evident from historical aerial photographs. This analysis focused on the lowermost 4 km of the channel and floodplain (the region for which the aerial photographic record is most complete), and we sought to differentiate between natural and human-caused change. We interpreted and digitized channel boundaries from orthorectified and manually georeferenced aerial photographs collected between 1939 and 2009. This aerial photographic analysis was discussed by Draut et al. (2008, 2010); without repeating the level of detail in those publications, the methods and findings are summarized and further analyzed here.

Channel boundaries were digitized from 14 sets of photographs taken in 1939, 1956, 1965, 1971, 1977, 1981, 1990, 1994, 2000, 2002, 2005, 2006, 2008, and 2009. River discharge was between 10 and 90 $m^3/s$ in all photographs except for those from 2006, when the flow was 186 $m^3/s$. Photographs from 1939 are the earliest known accurate representations of the Elwha River; pre-dam survey maps made in the late 1800s do not show channel morphology with spatial accuracy (Pohl, 1999) and were not used in this study (see Gaeuman et al., 2003, Hapke and Reid, 2007, and Draut et al., 2008, on spatial error determination for aerial photographs). On each set of photographs, the westernmost (left) and easternmost (right) margins of the recently active floodplain were digitized. “Recently active floodplain” was defined as the unvegetated (or only sparsely vegetated) part of the channel, including all wet and dry areas (Sear et al., 1995; Kondolf et al., 2002; O'Connor et al., 2003; Rapp and Abbe, 2003; Grams and Schmidt, 2005). By considering the entire unvegetated part of the floodplain to have been flooded recently, we assume vegetation would rapidly colonize areas not regularly or recently devegetated by floods. Use of the vegetated floodplain margins (as opposed to wetted channel) eliminates variation that would arise from using channel margins occupied at lower stage. Also included within the margins of the recently active floodplain were places where water was visible in small side channels with thick vegetation on either side but with an open connection to water in a larger channel.

Using the Digital Shoreline Analysis System ArcGIS™ software extension (Thieler et al., 2005), positions of the left and right margins at transects spaced 150 m apart were determined relative to a channel-parallel baseline. Rates of channel movement for the entire period of record (1939 to 2009) were calculated by using a linear-regression analysis of each transect's position through time. Over nearly all of the record, this analysis documented channel movement by meander migration; in rarer cases where channel movement occurred by new avulsion or by activation of small side channels, those processes are discussed in detail below (avulsion in the late 1990s, and effects of the 2007 flood, respectively).

Channel sinuosity and braiding index were determined for each of the 14 years represented in aerial photographs. Main channel sinuosity is calculated as the length of the route carrying the most water, divided by downvalley distance. We determined channel braiding index both in terms of total channel length (sum of mid-channel lengths of all channels, divided by length of the widest channel's mid-line; Friend and Sinha, 1993) and in terms of the number of channels—the average number of anabranches crossed by transects spaced 150 m apart on photographs (after Howard et al., 1970). These two methods independently evaluate different aspects of braiding (total sinuosity of all channels vs. intensity of flow division; Bridge, 1993; Egozi and Ashmore, 2008).

It is important to note that variable timing of aerial photographs affects the inferred rates of channel change. Estimating long term rates of change and resolving effects of floods are complicated by photographic intervals that are sometimes, but not always, dictated by the timing of floods—the 2006 and 2008 sets of photographs were collected deliberately to evaluate the effects of recent floods, and therefore recorded channel change that happened at rates much faster than the long term average (Draut et al., 2010). If intervals between photographs are longer and encompass other years without large floods, the effects of floods such as those in 2006 and 2008 become less apparent (see Appendix). Similar complications commonly arise in other earth science studies, as observation intervals may not sufficiently resolve true rates, frequencies, and effects of rare, large magnitude events. In interpreting channel evolution on the Elwha River, another complication is introduced by variations in photographic quality: visibility of narrow side channels is a function not only of how recently floods have moved through and widened them but also of photograph resolution. Small anabranches are more readily identifiable in recent, high resolution images than in older, lower quality photographs, potentially affecting inferred braiding index and positions of active channel margins.

## 3. Results

### 3.1. Topographic and grain size surveys

Nine biannual field surveys revealed spatial variations in Elwha River bed sediment and spatial variations in the modern channel response to floods. Topographic profiles are shown for the four reaches, in order from upstream (control reach) to downstream (reach 3), in Figs. 3–6. Fig. 7 summarizes all topographic and grain size data.

Channel profiles in the lower river between 2006 and 2010 displayed increasing mobility and greater topographic change with distance below the dams. The greatest magnitude of topographic variation occurred in the control reach above the dams, which underwent vertical bed-elevation changes commonly greater than 1 m and locally more than 3 m (Figs. 3 and 7A). Riverbanks eroded tens of meters in parts of the control reach, especially as the channel responded to a large flood in 2007 (discussed below; Fig. 3B). In contrast, bed elevation changed much less in reach 1 (20 cm or less, excluding bulldozer disturbance; Fig. 4) and no bank erosion or channel widening occurred there (Fig. 7). The greatest bed elevation changes in reach 2 measured 0.5 m in the primary anabranch and in the side channel (Fig. 5A); bank erosion was negligible in reach 2 (Fig. 7). Reach 3, the farthest downstream study area, underwent bed aggradation and degradation on a scale approaching that of the control reach (1–3 m; Figs. 6 and 7A). Bank erosion and widening of 15–20 m occurred throughout reach 3 between 2006 and 2010, though the channel widened as much as 50 m where the mouth of a side channel shifted eastward (Fig. 6A).

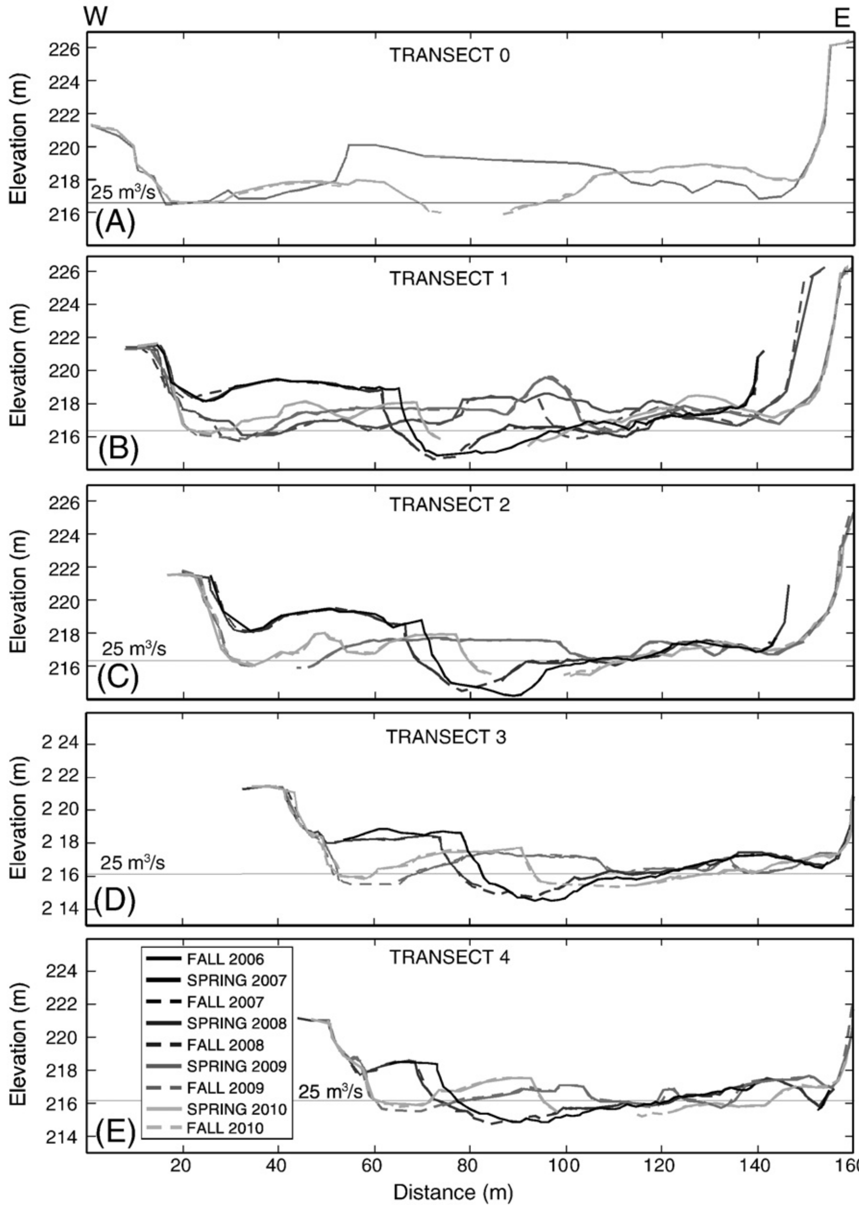


**Fig. 3.** Channel-perpendicular topographic profiles surveyed in the control reach, upstream of Elwha and Glines Canyon dams, in Olympic National Park, between fall 2006 and fall 2010. Five transects, numbered 0 through 4 in order from upstream to downstream, are plotted in (A) through (E), respectively. River stage elevation at a discharge of 25 $m^3/s$ (as of April 2010) is shown. Surveys of the control reach in spring and fall 2008 were affected by substantial errors in survey control after geodetic control points were lost in a December 2007 flood. For transect 1 (B), the positional accuracy of both 2008 surveys is estimated to be within 3 m. The 2008 surveys on other transects in this reach had positional error > 3 m and are not shown. Accuracy of surveys made at other times is estimated to be 2–4 cm. Elevation is referenced to the NAVD88 datum. Data gaps within profiles occur where fast current prevented data collection.

Bed grain size differed among the three reaches below the dams and between those and the control reach (Fig. 7C). Sediment in the control reach was much more poorly sorted than that of reaches 1–3, ranging from boulders larger than 400 mm to extensive patches of coarse sand and granules; one continuous sand patch within the control reach in 2010 measured 83 by 33 m, larger than any sand patches seen during this study in reaches 1, 2, or 3. The median value of 799 CobbleCam mean-grain size measurements in the control reach was 38.5 mm. Below the dams, grain size was better sorted and decreased with distance downstream (Fig. 7C). A subaerial bar in reach 1 contained mainly 80–200 mm cobbles (the median value of 265 grain size measurements in reach 1 was 119.3 mm), whereas sediment in reach 2 was generally 30–150 mm (the median value of 585 grain size measurements in reach 2 was 71.4 mm), and sediment in reach 3 was dominated by grains 20–80 mm, with extensive areas finer than 30 mm (Fig. 7C). The median value of 1020 grain size measurements in reach 3 was 26.3 mm.

Greater channel change occurred during winter than during spring flood seasons (the field study spanned four winter flood seasons and four spring snowmelt flood seasons; Fig. 7A, B). The largest and most significant channel-changing event between 2006 and 2010 was a flood peak of 1016 $m^3/s$ on 3 December 2007 (Fig. 2B). This was the second highest discharge recorded on the Elwha River (the highest being 1177 $m^3/s$, measured in November 1897), and the highest since the dams were built. A log-Pearson type III flood-frequency analysis using all annual flood peaks measured at USGS gaging station 12045500 (Fig. 1A) indicates that the December 2007 flood magnitude would have an expected return interval of about 40 years. This flood reorganized the control reach such that the one principal pre-flood channel was replaced by three to four smaller anabranches carrying water. The December

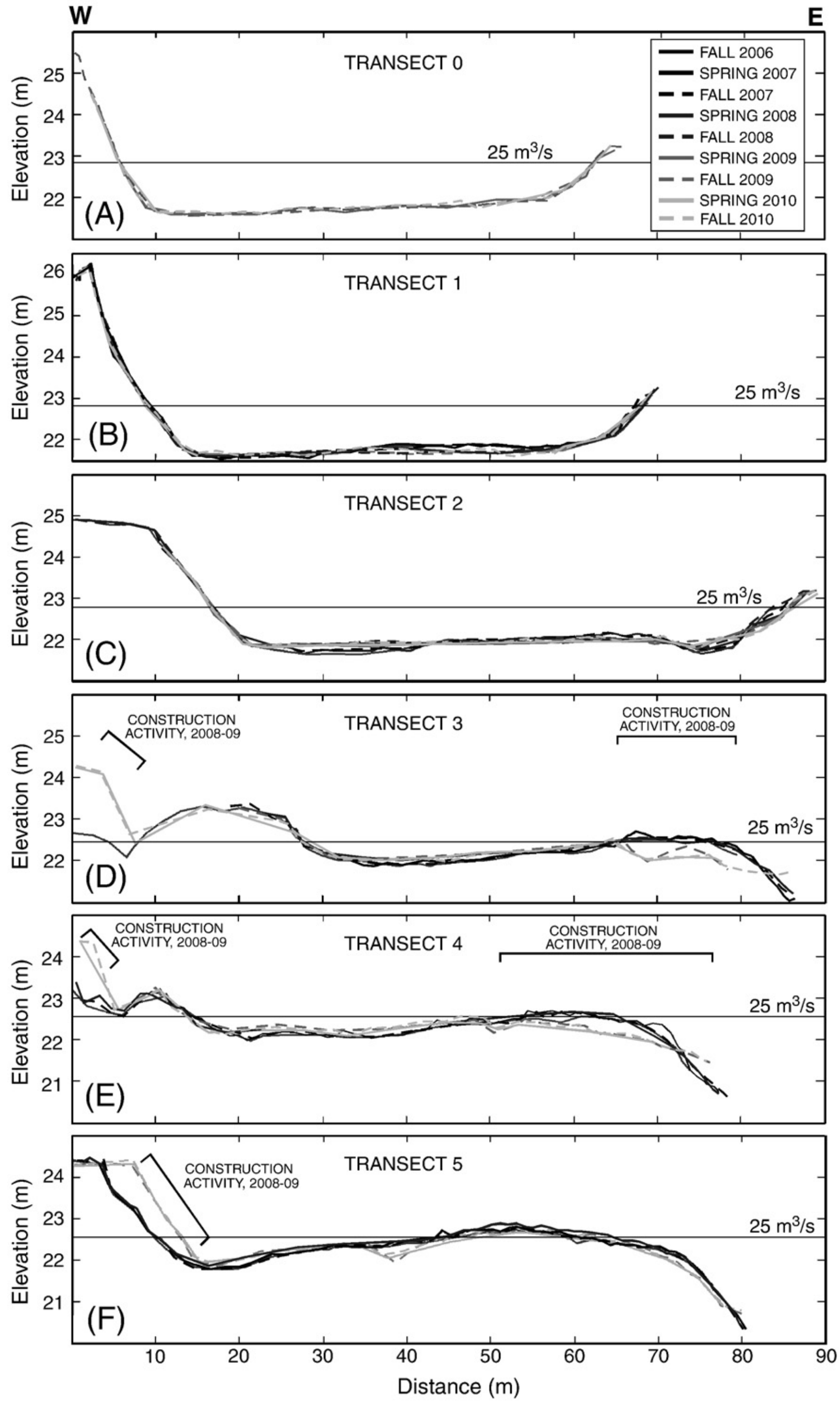


**Fig. 4.** Channel-perpendicular topographic profiles surveyed in reach 1. Six transects, numbered 0 through 5 in order from upstream to downstream, are plotted in (A) through (F), respectively. Topography around transects 3, 4, and 5 was affected by construction activity during 2008 and early 2009; surveys of those transects were omitted then, but resumed after construction activity ceased in mid-2009. Transects 3–5 (D–F) end within the active channel, at the easternmost accessible part of the cross section; the thalweg and right bank are inaccessible, east of where the cross sections end.

2007 flood widened the channel in the control reach by 52 m, eroding the eastern bank by 7 m and removing a 45-m-wide vegetated bench at the western channel margin (Fig. 3B). Downstream of the dams, effects of the December 2007 flood were less severe, though still notable (Fig. 8). Reach 1 underwent its greatest bed elevation changes then, and the mean grain size of its central bar coarsened by 20–40 mm. In reach 2, bed elevation changed more between fall 2007 and spring 2008 than during any other interval—as much as 50 cm of erosion and 70 cm of gravel deposition locally. The eastern bank of the channel in reach 3 eroded 7–8 m in the December 2007 flood and locally shifted as much as 50 m eastward as a side-channel mouth widened; the bed aggraded and degraded locally 1.5 m in reach 3 that winter (Fig. 6). Channel adjustment after the 2007 flood continued through the following summer, inferred from bed elevation changes between spring and fall 2008 in reach 3 (0.5 m) and the control reach (1.5 m) that were greater than any other summertime change in this field study.

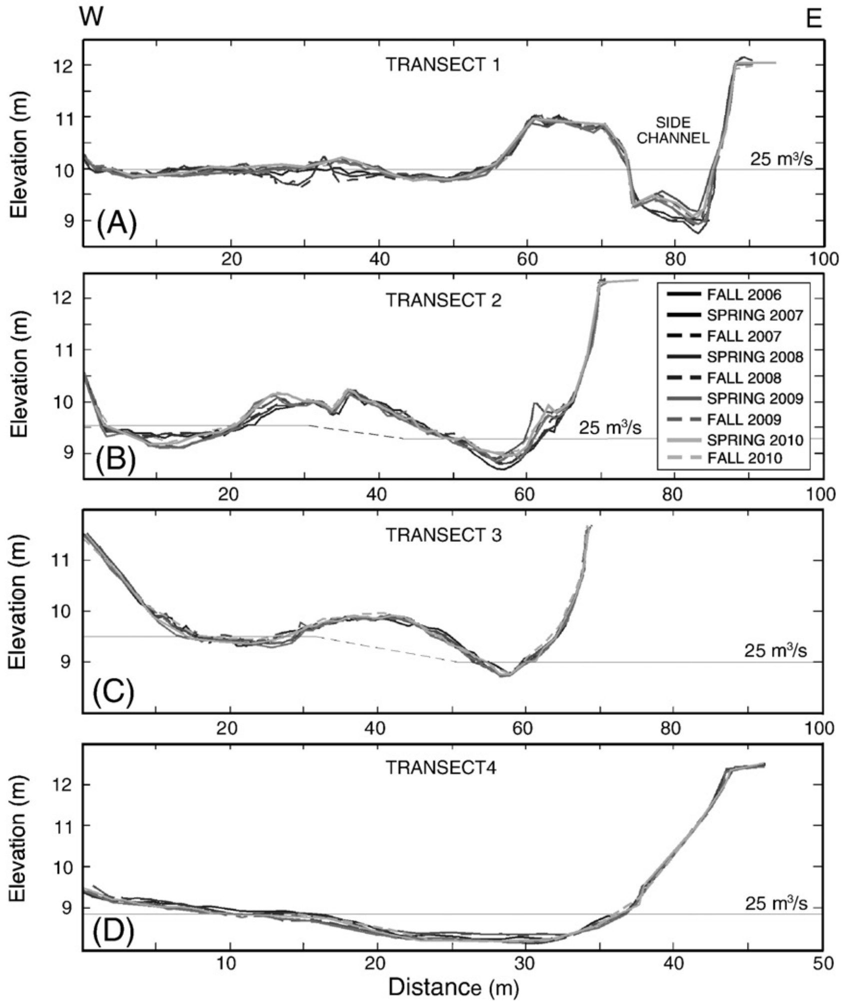


**Fig. 5.** Channel-perpendicular topographic profiles surveyed in reach 2. Four transects, numbered 1 through 4 in order from upstream to downstream, are plotted in (A) through (D), respectively. An engineered log jam (McHenry et al., 2007) is situated on a cobble bar within the channel between transects 1 and 2.

### *3.2. Aerial photographic analysis*

Active floodplain margins digitized from aerial photographs showed net lateral channel movement by tens to hundreds of meters on the lower Elwha River between 1939 and 2009 (Fig. 9; Draut et al., 2008, 2010). Some areas, particularly a region 2 to 3 km upstream of the river mouth, showed net lateral channel movement of more than 400 m, though 150–200 m was more common. Along the lowermost 4 km of the alluvial floodplain (the region common to all sets of aerial photographs), annualized rates of change were typically less than 10 m/year (average of 2.1 m/year with standard deviation 1.7 m/year).

The most rapid channel change evident from the 70-year aerial photographic record corresponded to the largest flood during that time, the 1016 $m^3$/s peak in December 2007. Channel change apparent between photographs taken in November 2006 and April 2008 is largely attributable to that flood (Figs. 8 and 9). Mean annualized rates of channel change over that time step, averaged over 150-m-spaced transects on the lowest 4 km of the floodplain, were 28 m/year for the left channel margin and 61 m/year for the right channel margin, caused partly by bank erosion and partly by widening of the recently active floodplain as small side channels became active (discussed below). These were the highest annualized rates measured for any time interval and exceeded the mean annualized channel-margin movement for 1939–2009 by factors of 13 and 28 for the left and right margins, respectively.

Changes on the lower Elwha floodplain between 2006 and 2008 included the formation or enlargement of side channels that carried surface flow during the December 2007 flood. Some of those narrow channels through wooded areas of the floodplain existed before that flood but usually maintained only groundwater connection to the main channel (known from field observations; e.g., the side channel in Fig. 5A); some of those side channels lengthened or were otherwise reconfigured between 2006 and 2008 (Fig. 8). Also apparent in the 2008 photographs was that the main channel (carrying the most water) had shifted westward into a 1.5-km-long anabranch known as the Hunt's Road channel, which first avulsed sometime in the late 1990s (Figs. 8 and 9). We infer that the December 2007 flood probably eroded the outside of the convex-westward meander bend immediately upstream of that avulsion point enough to direct more flow through the western than through the eastern channel.

Several other notable high flows preceded the 40-year event of December 2007. Much channel change is apparent between aerial photographs taken in 1977 and 1981, an interval that included the largest two floods to have occurred between 1955 and 1990 (in December 1979 and December 1980; Fig. 2A). Aerial photographs and this field study also documented channel response to a winter flood peak with a 5-year return interval (592 $m^3$/s on 6 November 2006; Fig. 2B), which included a 30-m movement of the right margin as a new side channel near the river mouth became visible from the air; the banks in reach 3 eroded 2–8 m in that flood (Fig. 6).

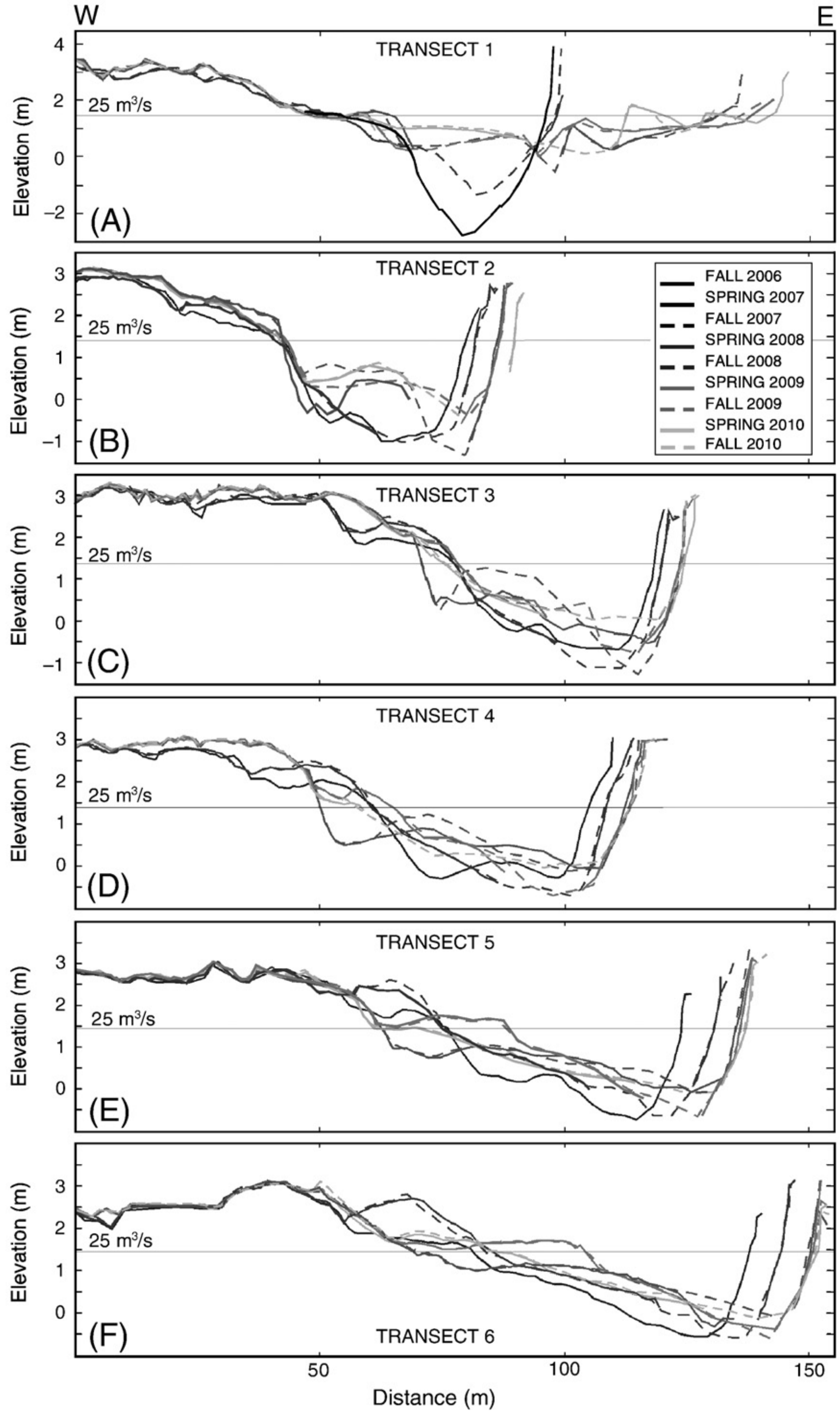


**Fig. 6.** Channel-perpendicular topographic profiles surveyed in reach 3. Six transects, numbered 1 through 6 in order from upstream to downstream, are plotted in (A) through (F), respectively. Vertical scale in (A) differs from that in (B) through (F). Data gaps within profiles occur where fast current prevented data collection.

Although most of the channel change on the lower river has been attributed to floods, human activity also altered the Elwha floodplain substantially between the 1940s and 1980s. One of the largest artificial alterations was a meander cutoff excavated in 1947, which the Hunt's Road channel may have later reoccupied (Johnson, 1994; black arrow in Fig. 9B). Other anthropogenic changes included dike construction in 1950 that closed the eastern of two natural distributary channels (red arrow in Fig. 9B); the eastern distributary became vegetated and its remnants are coastal ponds today. Flood-protection dikes were built in 1985 at the eastern edge of the floodplain, and private-party bulldozing took place repeatedly 2–3 km upstream of the river mouth between the 1950s and 1980s (Johnson, 1994; M. McHenry, Lower Elwha Klallam Tribe, personal communication, 2008).

We can evaluate the capacity of the river to adjust to natural and human forcing by analyzing temporal variations in channel sinuosity and degree of braiding. Sinuosity of the main channel decreased markedly from 1.42 in 1939 to 1.18 in 1956 as a result of the artificial channel cutoff (straightening) in 1947 (Figs. 9 and 10A). Main-channel sinuosity then increased incrementally over several decades, recovering to near its 1939 value. Sinuosity remained around 1.4 from 2000 until at least 2006 before decreasing to 1.18 again after the

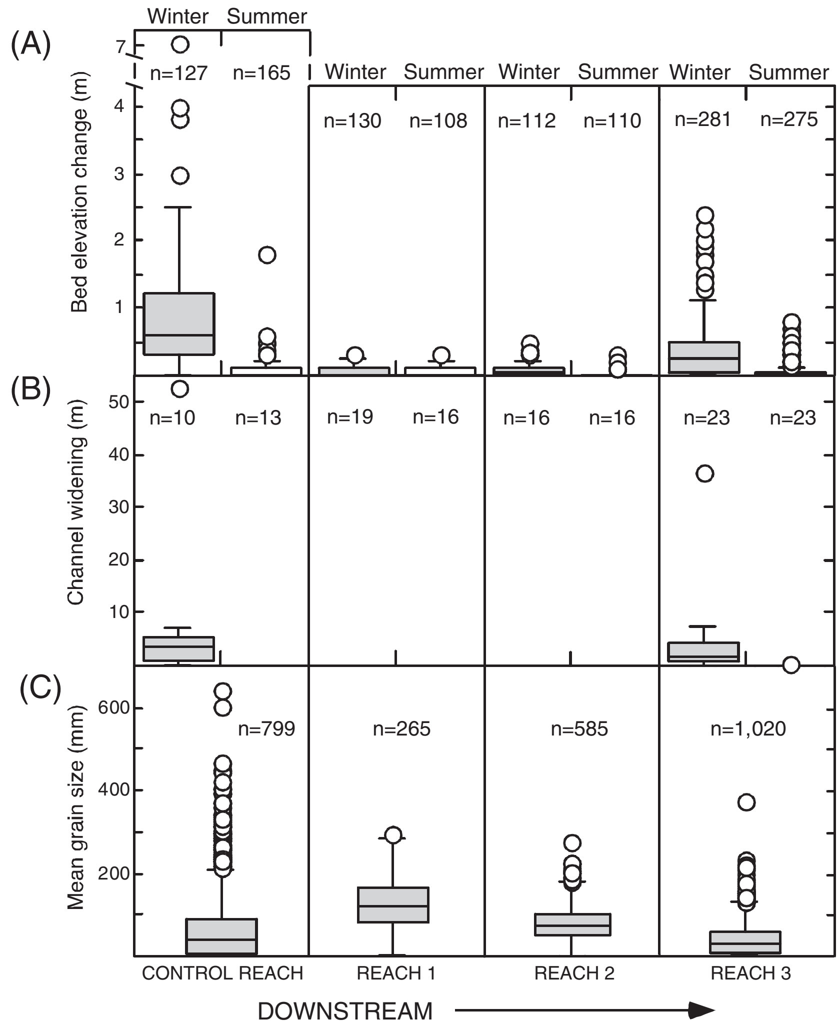


**Fig. 7.** Summary of seasonal topographic change and bed-sediment grain size in four reaches of the Elwha River between fall 2006 and fall 2010. In the box-and-whisker plots, box height spans the first to third quartile (interquartile range) of the data sample, horizontal line through the box represents the median, and whiskers extend to highest and lowest non-outlier data points; outliers (circles) are more than 1.5 times the interquartile range. (A) Absolute value of measured change in bed elevation over winter (difference between spring and previous fall surveys) and summer (difference between fall and previous spring surveys). Values were obtained using bed elevation change over each survey time step in bins 10 m wide across each transect. (B) Magnitude of increase in channel width over winter and summer seasons. Values were obtained by measuring width of the recently active channel at each channel-perpendicular transect. (C) Mean grain size of subaerial, unvegetated bed sediment, analyzed using the CobbleCam algorithm on digital photographs. All data collected between fall 2006 and fall 2010 are shown (2651 measurements in total).

December 2007 flood (because the shorter Hunt's Road channel became the main route after that flood).

Two methods of evaluating braiding index (Howard et al., 1970; Friend and Sinha, 1993) yielded similar results on the lower Elwha River (Fig. 10), showing increased braiding between 1939 and 1956 (a result of the artificial cut in 1947), followed by a decrease to quasi-steady values maintained between the mid-1960s and mid-2000s, then an abrupt increase after the large December 2007 flood, reflecting recent flow in numerous small side channels. The high braiding index evident in aerial photographs taken in April 2008, four months after the flood, had decreased markedly by August 2009, 20 months after the flood (Fig. 10), as regrowth of vegetation obscured many side channels that no longer carried surface water during non-flood flows.

## 4. Discussion

Like most rivers in the western U.S., the Elwha River has responded to both natural and human forcing over the past century. This river channel adjusts to forcing events in some ways that characterize its geomorphic class – anabranching gravel-bed rivers – but that would not occur in other systems for which channel behavior and effects of dams have been described more widely in the literature. An example is the evolution of channel braiding index (Fig. 10) as this system accommodates floods by expanding the flow into pre-existing or newly avulsed gravel-bed side-channels. Though some of those braids may become new major flow routes after a flood, most quickly lose surface-water flow as the flood recedes; between floods, they may carry only groundwater, and become vegetated. Bed armoring and sediment winnowing in a system such as the Elwha River also differ importantly from some other dammed channels where those processes have been described. Unlike a dammed channel in a bedrock canyon (e.g., Hazel et al., 2006) or one meandering through cohesive fine-grained banks (several case studies in Galay, 1983), the Elwha River can recruit abundant unconsolidated sediment of mixed grain sizes from its banks and broad floodplain below the dams. As discussed below, fine-sediment recruitment from the floodplain allows channel mobility (avulsion and bank migration) to operate somewhat independently of armored conditions on the beds of large anabranches and thus plays an important role in post-dam evolution of the Elwha channel.

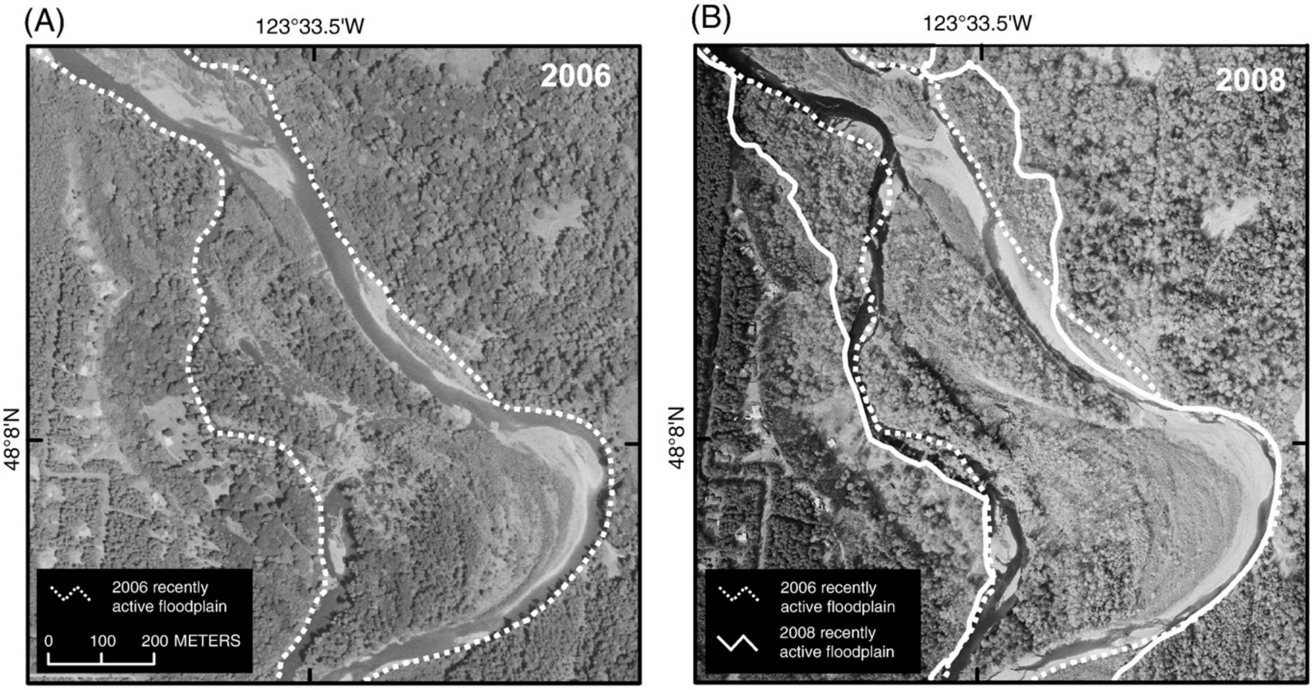


**Fig. 8.** Aerial photographs of part of the lower Elwha River before and after the 1016 $m^3/s$, 40-year flood of 3 December 2007. (A) Photographs taken on 7 November 2006 by the U.S. Department of Agriculture. Dashed white lines show interpreted margins of the recently active floodplain. (B) Photographs taken on 3 April 2008 by the Washington Department of Transportation. Dashed white lines show the recently active floodplain margins of 2006; solid white lines show margins of the recently active floodplain interpreted from the 2008 photographs. Margins in the northern part of (B) follow narrow channels through vegetated areas. The large channel shown in the western part of the floodplain is known as the Hunt's Road channel.

### *4.1. Influence of dams on modern bed sediment and topographic flood response*

We attribute some important characteristics of the lower river to a century of lost upstream sediment supply caused by the dams. The data presented here support hypothesis (1); spatial variation is apparent both in bed-sediment grain-size patterns and in topographic response of the channel to floods. Bed sediment shows armoring that is characteristic of river reaches below dams (sediment fining progressively downstream from reach 1), and lacks the poorly sorted quality of the naturally evolving bed above the reservoirs (Fig. 7C). On seasonal scales, the channel is relatively stable immediately downstream of the dams (reach 1), progressing toward a more mobile channel downstream such that reach 3 responded to the 40-year flood with bank erosion, bed accretion, and degradation on a scale approaching that of the natural (and steeper gradient) channel above the dams.

The December 2007 flood caused the greatest changes during this field study and some of the largest non-anthropogenic changes in the past 70 years. Widening of the active channel in reach 3 that winter by 14 m, or 24%, was comparable to the 30% widening measured on the Powder River, Montana, from a 35-year flood (Pizzuto, 1994), though the Powder River floodplain comprises finer sediment and a more meandering planform than does that of the Elwha (Pizzuto et al., 2008). The channel in our control reach widened substantially more than did reach 3 as a result of the 2007 flood, adding as much as 52 m (68%) to its recently active width (Fig. 3B). The spatial trends in grain size and channel mobility documented after the 40-year flood are thus consistent with predictions of sediment mobility in the dammed river made by Pohl (2004), although her field study did not span any flood events.

### *4.2. Channel mobility through time*

To evaluate whether channel mobility changes over decadal time scales within a given reach, it is informative to normalize a measure of channel movement in various time steps against a measure of the river's transport capacity in each of those intervals. Fig. 11 shows annualized channel movement of the lowermost 4 km of the Elwha River calculated for each time step in the 70-year aerial photographic record, normalized against cumulative, dimensionless shear stress estimated for the Elwha River flow over each time step. To obtain dimensionless shear stress ($\tau_*$), we first calculated bed shear stress ($\tau_b$) by the standard method ($\tau_b = \rho g h S$, where $\rho$ is the density of water [1000 $kg/m^3$], $g$ is gravitational acceleration, $h$ is flow height, and $S$ is slope [0.006 for the lower Elwha River]). Flow height was obtained by fitting a stage-discharge curve using the record of daily average discharge from USGS gaging station 12045500 (Fig. 1A), and using the curve-fit equation to hindcast flow height (at the gage) for each day as far back as 1 August 1939, the date of the first aerial photographs. Bed shear stress was made dimensionless by dividing $\tau_b$ by $(\rho_s - \rho)gD$, where $\rho_s$ is the density of quartz sediment (2650 $kg/m^3$) and $D$ is a reference grain diameter for the lower river, taken to be 71 mm (the median grain size in reach 2, from our field study). By summing the daily values, we obtained a cumulative value of dimensionless shear stress for each time step in the aerial photographic record (see Appendix for further details).

If the channel's capacity to move in response to flood forcing (represented by shear stress) had been reduced over time, then Fig. 11 would be expected to show a decreasing progression of normalized channel movement. No decreasing trend exists in Fig. 11. Even after human manipulation of channel margins ceased in the 1980s, channel mobility remained comparable to or greater than during the earlier years when bulldozers affected the data in Fig. 11. Hypothesis (2) is therefore not supported; loss of upstream sediment supply over a century with dams in place apparently has not reduced channel mobility per unit of flow forcing on the lowermost 4 km of the Elwha River.

The lack of a trend in our data toward decreasing mobility in the lowest 4 km of the Elwha channel contrasts with vegetation ages interpreted from aerial photographs by Kloehn et al. (2008). Kloehn

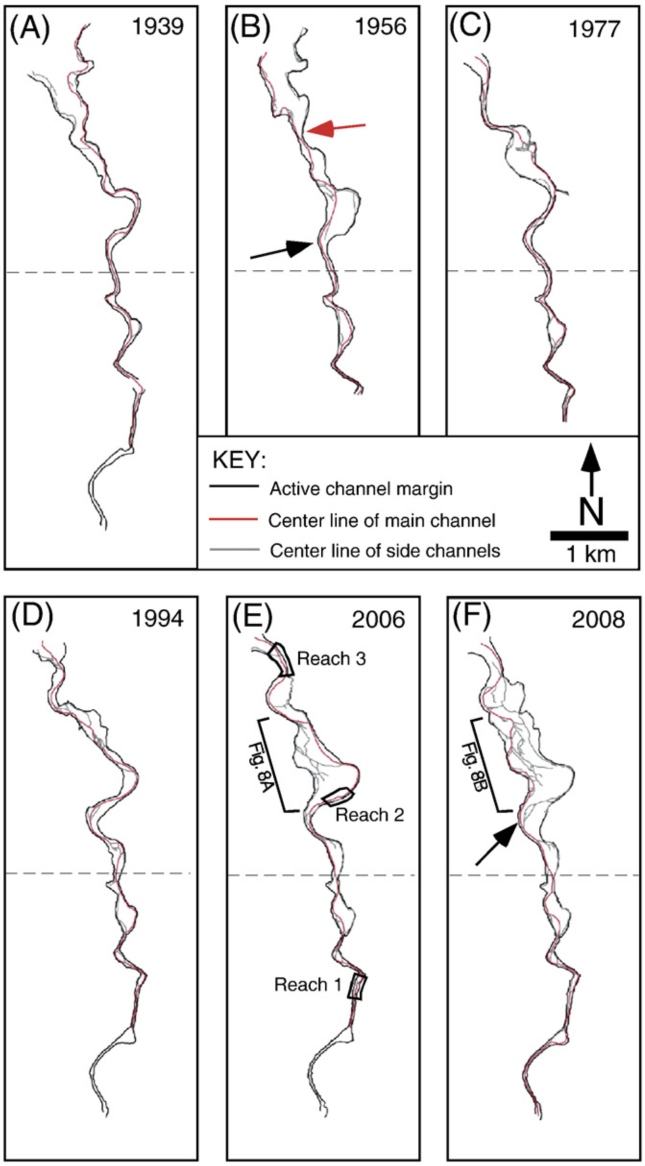


**Fig. 9.** Diagrams of channel morphology on the lower Elwha River below Elwha dam in selected years, showing margins of active (unvegetated) channels digitized from aerial photographs taken in (A) 1939, (B), 1956, (C) 1977, (D), 1994, (E) 2006, and (F) 2008. Size of digitized area varies because the extent of photographic coverage differs from year to year. Black lines are western (left) and eastern (right) margins of recently active floodplain. Gray lines are center lines of recently active channels. Red is the center line of the main channel (the channel apparently carrying the most water). Region north (downstream) of the horizontal dashed line defines the lowermost 4 km of the floodplain, the area common to all 14 sets of available photographs, on which more-detailed analyses were made in Figs. 10 and 11. Diagrams from years other than those shown here can be found in Draut et al. (2010). Reaches 1, 2, and 3 are outlined in (E). Arrows in (B) indicate anthropogenic channel alterations: artificial channel straightening in 1947 at the location of the black arrow and closure of the eastern distributary channel in 1950 at the location of the red arrow. Black arrow in (F) shows the bifurcation point below (north of) which the Hunt's Road channel anabranch became the main channel after a major flood in December 2007. The region shown in Fig. 8 is indicated in (F).

et al. concluded that because the proportion of older floodplain surfaces increased through time on the lower Elwha River sediment-supply reduction through damming had stabilized the floodplain, promoting more mature forests and less frequent channel disturbance. Although this study focused on different processes than did Kloehn et al., one explanation for the difference between our interpretation and that of Kloehn et al. (2008) is that a flood large enough to reset vegetation ages significantly had not yet occurred by the time the Kloehn et al. study was completed. Their analysis used photographs taken between 1939 and 2000 and therefore did not include the floodplain response to the major floods in 2006 and especially the 40-year event of 2007. Although reanalyzing vegetation patch ages is beyond the scope of our study, the channel widening, increased braiding, and anabranch migrations forced by the 2007 flood likely affected vegetated areas enough to reset some patch ages.

To reconcile the finding that hypothesis (1) (spatial effects of the dams on bed grain size and channel mobility) was supported by our data whereas hypothesis (2) (temporal changes in mobility of the lowermost channel) was not, it is necessary to consider where sediment supply becomes available below the dams. Immediately below Elwha dam, where bed armoring is most pronounced, the river flows through a bedrock canyon nearly 1 km long from which it gains essentially no new sediment. Reach 1, similarly, is still relatively sediment-starved because alluvial material in channel banks first becomes available only a few hundred meters above this reach as the canyon ends (Fig. 1B). The bed fines substantially over the 2–3 km between reaches 1 and 2 (Fig. 7C) and channel mobility increases, attributable to greater availability of fine, unconsolidated sediment in channel-margin bluffs and floodplain area that is accessed during high flows. Fine sediment is also available beneath the armor layer—if flows generate enough shear stress to mobilize bed-armoring cobbles, the sediment beneath is much finer and more easily transported (Fig. 12; cf. Rodrigues et al., 2006). Therefore, although the upstream-most alluvial regions of the river below Elwha dam probably have become less mobile (such as reach 1), the lowermost 4 km of the channel (including reaches 2 and 3) have recruited enough new fine sediment to effectively counteract the dam-imposed upstream sediment loss and to maintain channel mobility, at least over the one century that has elapsed since dam construction (cf. Kloehn et al., 2008). This sediment source would gradually deplete over time if the dams were not removed, until eventually channel mobility in the lowermost river would decrease.

### *4.3. Anticipated response to dam removal*

Because alluvial-channel geometry is controlled partly by the amount and grain size of available sediment, channel morphology on the lower Elwha River could change substantially as a result of new sediment influx after dam removal. At least $0.9–2.0 \times 10^6$ m$^3$ of sand and coarser sediment and ~$3.7–4.3 \times 10^6$ m$^3$ of silt and clay are expected to move downstream during erosion of the two reservoir deltas (Randle et al., 1996). Geomorphic adjustments after dam removal could include increases in the rate of lateral channel migration, degree of braiding, and sinuosity, with increased braiding and avulsion caused by newly available sediment (bed aggradation) and large woody debris from upstream (Bryant et al., 1995; Fetherston et al., 1995; Montgomery et al., 1995; Collins et al., 2002; O'Connor et al., 2003). Additional effects of sediment influx could include filling of pools, bed aggradation, and fining of grain sizes in the lower river (EIS, 1996; Randle et al., 1996; Pizzuto, 2002; Randle, 2003).

Such changes would be consistent with observations after dam removals and reservoir-sediment releases on other rivers, provided that sufficient flows occur soon after dam removal to transport substantial fine sediment downstream (cf. Wohl and Cenderelli, 2000; Doyle et al., 2002; Rathburn and Wohl, 2003a,b; Cheng and Granata, 2007), although the two dams on the Elwha River are substantially larger than any whose removal has been studied previously. Removal of the 14-m-high Marmot dam on the Sandy River, Oregon – subsequent downstream transport of 750,000 m$^3$ of sand and gravel – prompted growth of new bars and enlargement of existing ones as 350,000 m$^3$ were deposited over several months in the first 2 km below the dam site (Major et al., 2008; Podolak and Wilcock, 2009). Given that the Sandy

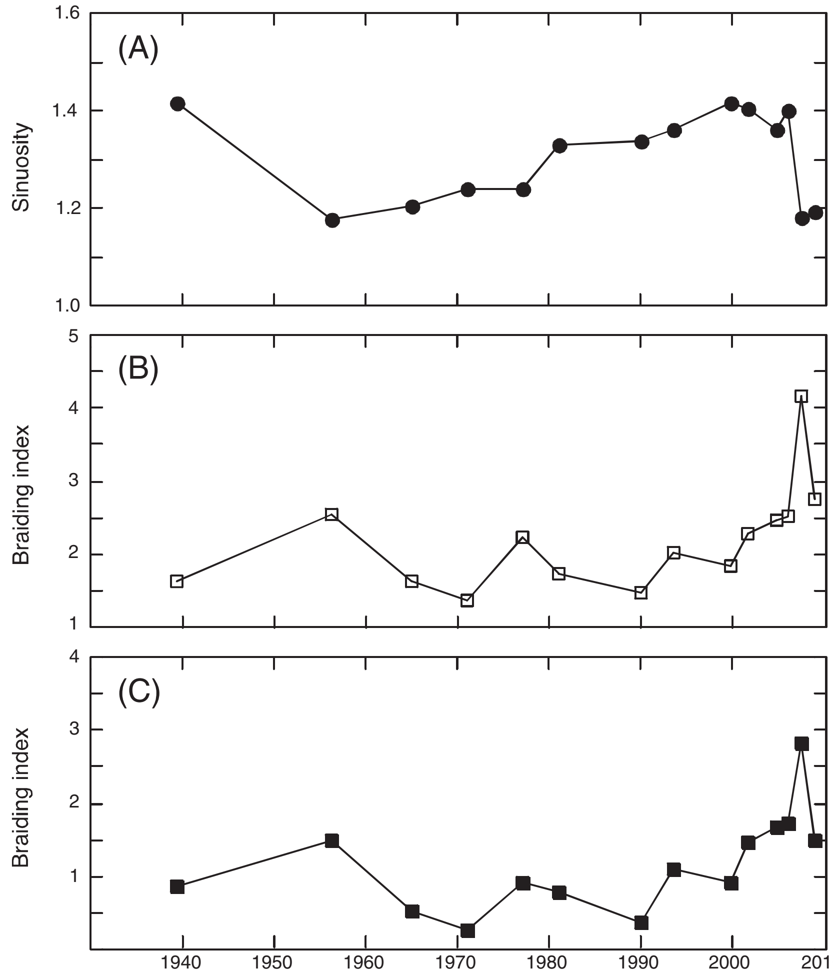


**Fig. 10.** Sinuosity and braiding index on the lowermost 4 km of the Elwha River calculated using channel form digitized from aerial photographs. (A) Sinuosity of the main channel; (B) braiding index calculated using the method of Friend and Sinha (1993) based on total lengths of channels; (C) braiding index calculated using the method of Howard et al. (1970) based on the number of channels crossed by transects spaced 150 m apart on photographs.

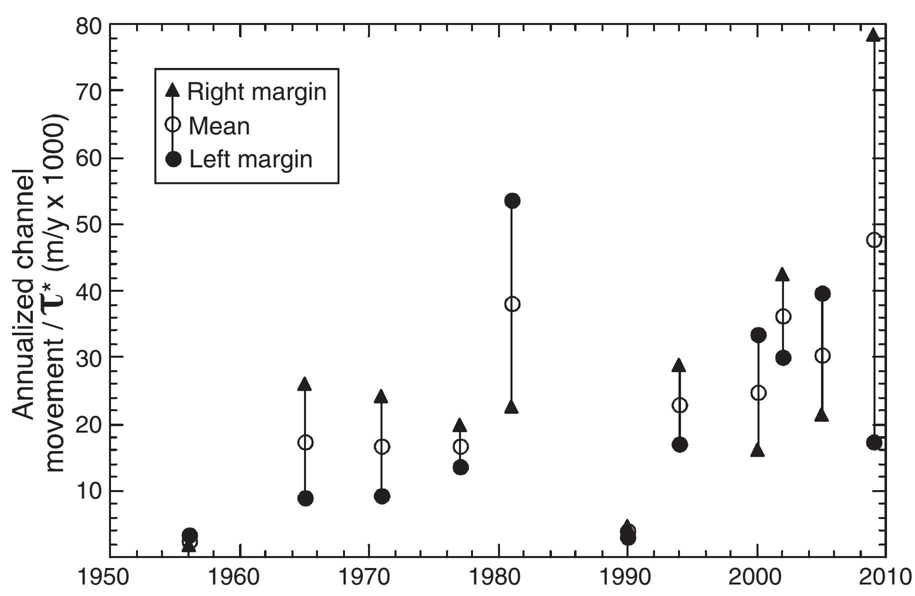


**Fig. 11.** Temporal trends in channel mobility of the lowest 4 km of the Elwha River. Annualized channel movement was calculated for time steps in the aerial photographic record (movement of the left and right margins of the recently active floodplain, divided by the number of years between photograph sets), normalized against cumulative, dimensionless shear stress estimated for the Elwha River discharge over each time step. Resulting normalized measurements of annual channel movement are plotted for each year that marks the end of a time step in the photographic record, e.g., the time step from 1939 to 1956 is represented by the data point at 1956. This figure treats the interval from 2005 to 2009 as one time step, omitting photographs that were intentionally taken shortly after floods in 2006 and 2008 and that therefore yield anomalously high rates of channel change (see Appendix).

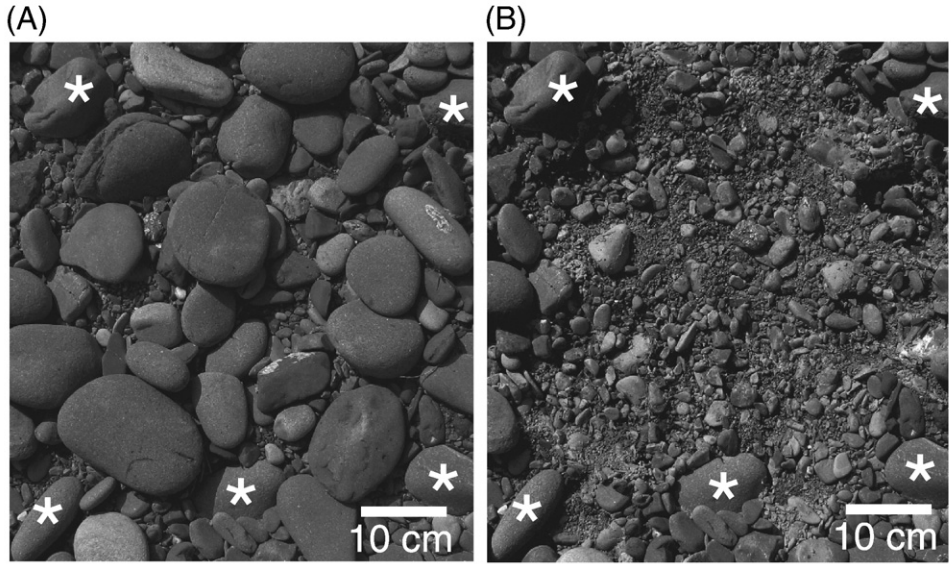


**Fig. 12.** Photographs of armor and subarmor bed sediment in reach 2 (two photographs taken several minutes apart at the same location; for reference, white asterisks indicate surface cobbles that appear in both images). Analysis of the CobbleCam digital photograph in (A) yields a mean grain size of 67.4 mm. (B) After the uppermost layer 1 grain thick was removed manually, a subsequent photograph of the underlying finer sediment yields a mean grain size of 11.8 mm.

River near the Marmot dam site has similar gradient, channel width, and geologic setting to that of the Elwha River (Keith et al., 2009), comparable bed aggradation and bar formation may follow dam removal in areas of the lower Elwha River near our reach 1. Similar changes occurred after dam removal on the Clark Fork River, Montana – where the bed aggraded ~1 m on main and side channels and new fine sediment infiltrated into a gravel and cobble bed (Brinkerhoff and Wilcox, 2009; Wilcox et al., 2009) – and on the Souhegan River, New Hampshire, where the bed aggraded 1.0–3.5 m below a former dam site (Pearson et al., 2009). Along with bed aggradation, bar enlargement, and increased braiding, new sedimentation below a dam removal can thereby increase the width/depth ratio of the channel (Burroughs et al., 2009). The lower Elwha River will likely require decades to adjust fully to renewed upstream sediment supply, just as, long after dam construction, it is still equilibrating to the loss of that supply.

Aggradation on the lower Elwha River after dam removal could raise the 100-year flood stage by 0.3–1.2 m (Stoker and Harbor, 1991; Randle, 2003), though recent estimates have been somewhat lower (less than 0.8 m; Entrix, 2009). The local magnitude and spatial distribution of future changes is uncertain and is particularly difficult to predict in reaches with multiple anabranches, as in most of the lower river (Konrad, 2009). Hydraulic modeling indicates that downstream fine-sediment transport likely will have completed a substantial proportion of its initial adjustment within 1–4 years after dam removal (Randle, 2003; Konrad, 2009).

In anticipating possible effects of dam removal on the Elwha River, it is often suggested that the Elwha may come to resemble more closely some nearby undammed rivers such as the Quinault (e.g., Kloehn et al., 2008), Queets, Hoh, or Dungeness Rivers. A brief comparison of Elwha channel evolution with the Queets and Quinault Rivers on the western Olympic Peninsula is therefore in order (detailed measurements of long-term change are not available for other nearby rivers). Rates of channel movement on the lower Elwha River (on average, 2.1 ± 1.7 m/year between 1939 and 2009) are generally lower than those on the Queets and Quinault (O'Connor et al., 2003). The lower Quinault River margins moved 5.0 ± 3.9 m/year between 1902 and 1997; rates on the upper Quinault River were 8.8 ± 4.1 m/year between 1902 and 1994 (O'Connor et al., 2003). The Queets River yielded similar rates, 5.6 ± 4.5 m/year between 1900 and 1994 (O'Connor et al., 2003). We propose that lower rates of channel movement on the Elwha are not necessarily attributable to the Elwha being dammed and that dam removal may not cause the Elwha to behave more like those rivers in terms of long-term geomorphic evolution. Both the Queets and Quinault are wider than the Elwha – mean floodplain width is ~1250 m on the Queets and lower Quinault and ~2470 m on the upper Quinault River, compared with 50–720 m on the lower Elwha River – and both receive more runoff than the Elwha, owing to higher rainfall in the western Olympic Mountains. Therefore, although the Elwha floodplain may become more active temporarily in response to an initial pulse of upstream sediment after dam removal, it is unlikely that channel mobility of the lower Elwha River decades after dam removal will have accelerated to the rates seen on the Queets and Quinault Rivers.

In addition to increasing the sediment supply to the lower Elwha River, removal of Elwha and Glines Canyon dams will have ecological consequences (e.g., Duda et al., 2008; McHenry and Pess, 2008; Pess et al., 2008). Scientists anticipate possible short-term negative impact to biota below the dam sites owing to initial large pulses of fine-sediment transport (Bednarek, 2001; Konrad, 2009). Over years to decades, the lower river is expected to benefit from greater supply of upstream nutrients and wood, transitioning toward greater biodiversity, while the upper-river ecosystem receives a renewed supply of marine nutrients as anadromous fish migrate upstream (Riggsbee et al., 2007; Brenkman et al., 2008; Morley et al., 2008; Pess et al., 2008; Sager-Fradkin et al., 2008; Duda et al., 2010).

## 5. Conclusions

This represents the first such comprehensive study of dam influence on sedimentary and geomorphic evolution of an anabranching, gravel-bed river. Over the past century with two dams obstructing the upstream sediment supply, the channel position, sinuosity, and braiding on the Elwha River have adjusted substantially in response to anthropogenic and natural forcing. Bed sediment shows armoring that is characteristic of river reaches below dams and is better sorted than the naturally evolving bed upstream of the dams. On timescales of flood seasons, the channel immediately below the lower dam is fairly stable but progresses toward greater mobility downstream such that the lowermost portion of the river responded to a recent 40-year flood with bank erosion and bed elevation changes on a scale approaching that of the natural channel above the dams.

Although dam influence is apparent in those spatial patterns of grain size and channel mobility along the first few kilometers below the dams, channel mobility in the lowest 4 km of the Elwha River has not decreased substantially with time. This region of the dammed channel is far from stable, even after a century without upstream sediment supply. Enough fine sediment remains in the glacial outwash floodplain and channel-margin bluffs that, given sufficient flood forcing, the channel margins can shift tens of meters per year, the bed can aggrade and degrade on the order of 1 m, and new avulsions can form. Unconsolidated sediment of mixed grain size is available to the lower river from bluffs, on parts of the floodplain accessed by high flows, and just beneath the armor layer—if floods mobilize bed-armoring cobbles. The fine sediment supply increases with distance downstream of Elwha Dam and would gradually deplete, eventually stabilizing the lower channel, over more time if the dams remained in place. The processes by which this anabranching gravel-bed river accesses new fine sediment below the dams (rapid migration into noncohesive banks, and avulsion of new channels) allow it to compensate for loss of upstream sediment supply more readily than would a dammed river with fine, cohesive alluvial deposits or a more limited supply of alluvium (such as in a canyon). The planned removal of both dams on the Elwha River will provide a valuable opportunity to evaluate large-scale channel response to restoration of natural upstream sediment supply.

## Acknowledgements

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.geomorph.2010.12.008.

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