SEASONAL AND DEcadAL-SCALE CHANNEL EVOLUTION ON THE DAMMED ELWHA RIVER, WASHINGTON

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INTRODUCTION

More than 75,000 dams exist in the continental United States to provide water storage, flood control, and hydropower generation (Graf, 1999). Many of these were built during the early twentieth century and are due for relicensing consideration now and in the near future. The cost of repairing aging dams, together with growing understanding of the ecologic effects of river regulation (Williams and Wolman, 1984; Dynesius and Nilsson, 1994; Graf, 1999, 2003; Yang et al., 2007), in some places have prompted dam removal, facilitating restoration of riparian habitat to a more natural state. In the Pacific Northwest region of the U.S., river-restoration efforts are commonly targeted to improve habitat quality for native salmonid fish species, many runs of which have declined precipitously from their historical conditions (owing, in part, to overfishing and habitat loss and degradation) and are now endangered (e.g., Nehlsen, 1997; Larsen et al., 2004; Pess et al., 2008). Removal of dams that block the upstream migration of anadromous fish is considered an important step toward any potential recovery of Pacific Northwest salmon and steelhead populations.

Two dams on the Elwha River (Fig. 1), which drains the north coast of the Olympic Peninsula, Wash., are scheduled for removal as part of a large-scale riparian restoration project. Elwha and Glines Canyon Dams, 12 km apart, were completed in 1913 and 1927 and reach 32 and 64 m high, respectively. Removal of both dams would allow unimpeded flow along ~70 km of the mainstem river in a nearly undeveloped watershed, most of which is within Olympic National Park. After dam removal, sediment in the two reservoirs will be transported downstream through the lower river to the ocean (Randle et al., 1996; Curran et al., 2009). Studying channel change downstream of these dams presents an unprecedented opportunity to understand fluvial adjustment to a large-scale loss (through damming) and restoration of sediment supply. Although researchers have had valuable opportunities to study fluvial response to removal of dams <15 m high (Bushaw-Newton et al., 2002; Pizzuto, 2002; Wildman and MacBroom, 2005), including Marmot Dam on the Sandy River, Oregon, in 2007 (Major et al., 2008), there is much still to be learned about channel response to dam removal, indicating the need for landscape-scale case studies (Grant, 2001; Pizzuto, 2002; Doyle et al., 2002; Graf, 2003).

Anticipating dam removal on the Elwha River, Federal, State, and local agencies are documenting conditions in the dammed ecosystem for eventual comparison with its state during and after dam removal. In addition to the research discussed here, studies by the U.S. Geological Survey (USGS), the Bureau of Reclamation, the Lower Elwha Klallam Tribe, the National Park Service, the National Oceanic and Atmospheric Administration, the University of Washington, and others will assess the effects of dam removal on floodplain vegetation, anadromous fish and nutrient cycling, large woody debris, and response of the marine environment to increased...
sediment supply, among other topics (Duda et al., 2008; Kloehn et al., 2008; McHenry and Pess, 2008; Morley et al., 2008; Shaffer et al., 2008). The USGS conducts biannual field surveys of channel topography and sediment grain size on the lower Elwha River (downstream of Elwha Dam; Draut et al., 2007). USGS scientists also survey topography and grain size on beaches of the Elwha delta, as well as nearshore bathymetry and habitat (Warrick et al., 2008, 2009).

To complement ongoing field studies of channel morphology, we evaluate decadal-scale evolution of the dammed lower Elwha River by using historical aerial photographs. Here, we revise an analysis published by Draut et al. (2008), which covered the interval 1939–2006, to include data collected after a major flood on December 3, 2007. That flood, which resulted from substantial rainfall on snow in the upper watershed, had instantaneous peak discharge of 1,016 m$^3$/s (35,900 ft$^3$/s), the second-highest recorded peak on the Elwha River since records began in 1898 and the largest since dam construction. A log-Pearson Type III flood-frequency analysis indicates that this flood would have a return interval of ~30 years (annual exceedence probability of ~0.03; C.S. Magirl, unpublished data). Observing channel change on the Elwha River from that event allows a more thorough characterization of the dammed channel’s response to flow over seasonal as well as annual and decadal time scales.
STUDY AREA

The 833-km²-area Elwha River basin spans mostly steep, mountainous terrain. The river channel is confined in a bedrock canyon in some reaches, and forms an alluvial floodplain in others. The reservoirs behind Elwha and Glines Canyon Dams (Lakes Aldwell and Mills, respectively) are too small to provide flood control; dam-released flows are near “run of the river” except that they have included more rapid fluctuations and lower daily minima than is natural (Johnson, 1994; Pohl, 1999). Annual peak discharge as recorded at the USGS gaging station on the Elwha River at McDonald Bridge (station number 12045500) has always occurred during the months of October to March in response to fall and winter rain storms with three fourths of the peaks occurring in November, December and January. Secondary peaks with longer duration occur in late spring in response to snowmelt. June has the highest mean monthly discharge of 62.9 m³/s.

The sediment supply to the lower Elwha River has been virtually eliminated by the dams except during large floods. According to the environmental-impact statement (1996), fluvial sediment delivery to the coastal ocean is presently ~2 percent of the predam load. In 1996 an estimated 13.8x10⁶ m³ of sediment lay impounded in the reservoirs behind the two dams, forming deltas in Lakes Aldwell and Mills (Randle et al., 1996); the total volume now is likely more than 16x10⁶ m³ (Curran et al., 2009). An estimated 0.9–2.0x10⁶ m³ of sand and coarser sediment and ~3.7–4.3x10⁶ m³ of silt and clay will move downstream as these reservoir deltas erode after removal of the dams (Randle et al., 1996). The area expected to be most affected by the renewed sediment supply after dam removal (aside from the reservoir deltas) is the 7.8-km-long reach known as the lower river, downstream of Elwha Dam (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 consist of anabranching channels on a vegetated floodplain (Pohl, 2004). Anabranching rivers (Harwood and Brown, 1993; Knighton and Nanson, 1993), consist of multiple channels separated by bars and vegetated islands excised from the floodplain. The lower Elwha floodplain is heavily vegetated, dominated by hardwood and conifer trees (Beechie et al., 2006). Floodplain sediment is largely glacial, ranging from silt and clay to cobbles; bluffs along the lower floodplain represent virtually the only sediment input downstream of the dams (Draut et al., 2008).

ANALYSIS OF AERIAL PHOTOGRAPHS

To determine the extent and rate of lateral channel change on the lower Elwha River downstream of Elwha Dam, we interpreted and digitized channel boundaries from georeferenced aerial photographs collected in 13 different years between 1939 and 2008. Photographs taken in 1939 are the earliest known accurate representations of the Elwha River—survey maps made in the late 1800s do not show channel morphology with spatial accuracy (Pohl, 1999) and were not analyzed for this study. Sources, scale, and spatial error (based on registration error and digitizing error) of aerial photographs from 1939, 1956, 1965, 1971, 1977, 1981, 1990, 1994, 2000, 2002, 2005, and 2006 are as reported by Draut et al. (2008). For the analysis described here, we also studied a set of 1:12,000-scale aerial photographs taken on April 3, 2008, by the Washington Department of Transportation in which the total spatial error on digitized channel margins is estimated to be 14.2 m. Rates of channel change between 1939 and 2008, and annualized rates of change for the floodplain, have been recalculated for this present study after analysis of the 2008 photographs that followed the large flood of December 2007.
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 visible in the photographs (Sear et al., 1995), including all wet and dry areas, according to the methods of Kondolf et al. (2002), O’Connor et al. (2003), Rapp and Abbe (2003), and Grams and Schmidt (2005). By considering the entire unvegetated part of the Elwha floodplain to have been recently occupied by floods, we assume that vegetation would rapidly colonize parts of the floodplain that were 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 by lower stages; the flow varies from one set of photographs to another. Also included within the margins of the recently active floodplain were places where water was visible in a small side channel with thick vegetation on either side but with an open connection (at either or both of the upstream and downstream ends) to water in a larger channel. Digitization was performed while aerial photographs were viewed at a scale of 1:3,000. The personnel who georeferenced photographs (McCoy and Logan) and digitized channel margins (Draut) were also familiar with the terrain and channel geomorphology through fieldwork (see Rapp and Abbe, 2003).

Digital coverages of floodplain margins were imported into a GIS database for spatial analysis. Using the Digital Shoreline Analysis System (DSAS) ArcGIS software extension (Thieler et al., 2005), the historical positions of the left and right margins were determined relative to a channel-parallel baseline along transects between Elwha Dam and the river mouth (Draut et al., 2008). Because not all sets of photographs span all of that distance, here we discuss only the region common to all 13 sets of photographs: the lowermost ~4 km of the channel, in which we studied 26 transects using DSAS. In areas where the orientation of the river margins had changed substantially over time, such as on the outer bend of a meander, transect orientations were adjusted to be orthogonal to the general direction of channel movement. Distances between the baseline and each channel margin were calculated using DSAS. This time series of successive distances was then used to calculate annualized rates of change in channel position over each time interval covered by the historical imagery (“end-point rates”). Finally, annualized rates of change in channel position for the entire study interval (1939–2008) were calculated by using a linear-regression analysis of each transect’s position in each of the 13 time steps studied. The error in estimated annualized rates of change ($E_a$) between two sets of aerial photographs taken in different years ($E_{total,1}, E_{total,2}$) was calculated assuming that the error margins estimated for each set of photographs (in Draut et al., 2008) are independent of each other, and dividing by the time interval $t$ (in years) represented by the two sets of photographs (Hapke and Reid, 2007):

$$E_a = \frac{\sqrt{E_{total,1}^2 + E_{total,2}^2}}{t}.$$  \hspace{1cm} (1)

Where the absolute change and annualized rates of change in channel position exceeded the composite estimated error from both sets of photographs, the change in channel position was considered to be measurable.
SEASONAL TO DEcadal-SCALE CHANNEL CHANGE

On the lower Elwha River floodplain, net lateral channel movement by tens to hundreds of meters occurred between 1939 and 2008 (Table 1; Fig. 2). Some areas of the floodplain, particularly in a region 2 to 3 km upstream of the river mouth, showed lateral channel movement of more than 400 m. Channel movement occurred by meander migration, avulsion of new channels, and, in the 1940s–1980s, human alteration of the floodplain. The largest single artificial channel change was caused by a meander cutoff excavated by Clallam County in 1947 (Johnson, 1994; location marked by the arrow in the 1956 diagram in Fig. 2). Other anthropogenic alterations included dike construction in 1950 that shifted the river mouth into only the western of two natural distributary channels, flood-protection dikes built in 1985 at the eastern edge of the floodplain, and private-party bulldozing (1950s–1980s) that focused primarily on the region 2–3 km upstream of the river mouth (Johnson, 1994; Draut et al., 2008).

Table 1 Movement of river-left (western) and river-right (eastern) active-floodplain margins for each time step analyzed for the lower Elwha River, Washington. Values were calculated by using only the part of the floodplain common to all sets of photographs (26 cross-channel transects along the lowermost ~4 km of the channel). Asterisks indicate values that are less than the error calculated for that time step (for details of error calculations, see Draut et al., 2008). Last row lists channel change for the interval 1939–2008, including annualized rates calculated from a linear-regression analysis of transect positions in each of the time steps; annualized rates of change for other time steps (other rows) were calculated as end-point rates of change. Average annualized movement over long time steps (such as 1939–2008) can be substantially less than over shorter time steps, because the channel in many places moves in one direction and then back toward its earlier position, appearing over longer time scales not to have moved as far as shorter-time-scale analyses show that it did. The same process (channel movement in one direction followed by later movement in the opposite direction) also causes greater average absolute movement of the left margin than the right over the time step 1939–2008, even though average annualized movements of the left and right channel margin were equivalent over that longest time step.

<table>
<thead>
<tr>
<th>Time step</th>
<th>Average absolute movement of left margin (m)</th>
<th>Average absolute movement of right margin (m)</th>
<th>Average annualized movement of left margin (m/yr)</th>
<th>Average annualized movement of right margin (m/yr)</th>
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<td>130</td>
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<td>15</td>
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<td>24</td>
<td>64</td>
<td>4*</td>
<td>10</td>
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<tr>
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<td>8</td>
</tr>
<tr>
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<td>56</td>
<td>24*</td>
<td>14</td>
<td>6*</td>
</tr>
<tr>
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<td>16*</td>
<td>25</td>
<td>2*</td>
<td>3</td>
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<td>15</td>
<td>26</td>
<td>4</td>
<td>7</td>
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<td><strong>116</strong></td>
<td><strong>2.2</strong></td>
<td><strong>2.2</strong></td>
</tr>
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</table>
Figure 2 Outlines of channel features on the lower Elwha River (downstream of Elwha Dam) digitized from aerial photographs taken between 1939 and 2008. Length of channel digitized varies because 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 and anabranches. Red is the center line of the main channel (the channel apparently carrying the most water).
Annualized rates of change were typically less than 10 m/yr in each time step, averaged over the lowermost 4 km of the river channel (with an average of 2.2 m/yr; Table 1). Greater rates of change occurred in response both to human alteration of the floodplain and to floods. Human alteration, as discussed above, was the cause of 10–15 m/yr movement of the right channel margin between 1956 and 1971 as water was diverted artificially away from the right (eastern) delta distributary and the former channel there became vegetated. High rates of channel change over other time intervals were most likely caused by winter floods. Between 1977 and 1981, when the left channel margin moved an average of 14 m/yr, those four years included the largest two floods to have occurred between 1955 and 1990, with peak discharges of 739 m$^3$/s (26,100 ft$^3$/s) on December 17, 1979, and 784 m$^3$/s (27,700 ft$^3$/s) on December 26, 1980. Channel change between 1977 and 1981 included left and right migration of two successive meanders centered ~2.5 km upstream of the river mouth, and an right (eastward) shift (avulsion) of the left channel margin by >160 m along nearly 1 km of river length (Fig. 2; see also Draut et al., 2008). Between 1994 and 2000, an interval in which a 1.5-km-long new avulsion, the so-called Hunt’s Road Channel, formed along the left side of the channel (marked by a black arrow next to 2008 diagram in Fig. 2), were flood peaks of 676 m$^3$/s (23,900 ft$^3$/s) on November 8, 1995, and 654 m$^3$/s (23,100 ft$^3$/s) on March 19, 1997 (at USGS gaging station 12045500). Channel change between 2005 and 2006, which included 30 m movement of the right channel margin as a new side channel near the river mouth became visible in aerial photographs, was largely due to a flood that peaked on November 6, 2006, at 592 m$^3$/s (20,900 ft$^3$/s), a flow with a return frequency of less than 5 years (C.S. Magirl, unpublished data). The 2006 aerial photographs were taken on the day after that flood peak (November 7, 2006).

As mentioned above, the most notable flood during the 69 years covered by aerial photographs (and second-highest recorded Elwha River discharge), happened in the winter of 2007–08: the 1,016 m$^3$/s (35,900 ft$^3$/s) peak on December 3, 2007. Channel change apparent between the 2006 and 2008 photographs is largely attributable to that flood. Mean annualized rates of channel change on the lowermost 4 km of the floodplain over the 2006–2008 time step were 28 m/yr for the left channel margin, and 61 m/yr for the right channel margin. These were the highest annualized rates measured for any time step in this study, and exceeded the mean annualized channel-margin movement for 1939–2008 (based on linear regression rate of change) by factors of 13 and 28, for the left and right margins, respectively (Table 1). The most substantial changes on the lower Elwha floodplain between 2006 and 2008 were 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 maintain only groundwater connection to the main channel (known from field observations); some of those side channels lengthened or were otherwise reconfigured between 2006 and 2008. Another major change apparent in the 2008 photographs was the shifting of the main channel (carrying the most water) to the west at the location of the 1.5-km-long Hunt’s Road Channel anabranch that first avulsed some time between 1994 and 2000 (black arrow next to 2008 diagram in Fig. 2). The 2008 photographs are the first that show a greater proportion of the flow in that left (western) channel than in the right (eastern) anabranch that was formerly the “main” route. We infer that the December 2007 flood probably eroded the outside of the convex-westward meander bend situated immediately upstream of that avulsion point enough to direct more flow through the left than through the right channel.
We can use field surveys of channel topography to refine the substantial channel change during 2006–2008 from annualized rates (Table 1) to more precise seasonal rates of change locally. Topographic (rod and total-station) surveys made 0.5 km upstream of the river mouth at biannual intervals, part of a larger field study still in progress, show that each of the winter seasons 2006–07 and 2007–08 was accompanied by 5 m of eastward migration of the river channel, for total bank erosion of ~10 m between September 2006 and April 2008 (Fig. 3). Vertical bed-elevation changes also occurred over both winters. Approximately 0.5 m of local erosion and aggradation occurred between September 2006 and April 2007; greater change in bed elevation occurred between the September 2007 and April 2008 field surveys, with 0.5–1 m of aggradation and as much as 2 m of erosion locally (Fig. 3). Essentially all of the measured channel change between 2006 and 2008 can be attributed to the action of winter floods, as field surveys showed negligible channel change over the spring snowmelt season (e.g., no change between April 2007 and September 2007 surveys in Fig. 3).

It is important to note that a nonrandom sampling interval (temporal spacing of aerial photographs) affects the calculated rates of channel change. Resources have been available in recent years for aerial photography in response to floods, increasing our ability to detect rapid, episodic channel change. If the interval between aerial photographs had been longer and encompassed other years without major floods, the geomorphic effects of individual floods would be less apparent in this analysis, and annualized rates of change in channel position would be lower. Therefore, calculating truly representative long-term rates of change, and resolving effects of individual floods, are complicated by sampling (aerial photographic) intervals that are sometimes, but not always, dictated by the timing of floods. Our assessment of channel response to the December 2007 flood uses 2008 photographs taken at such high resolution that individual branches on trees are clearly visible. This is a substantial improvement in resolution compared with previous photographs, but it adds an additional complication to the sampling technique. Such advances in photographic technology allowed us to see water in narrow side channels that were not visible in older, lower-resolution photographs; visibility of open side channels affects our identification of channel margins and anabranches (Fig. 2). In some cases, field observations confirmed that side channels appeared open in the 2008 photographs because a large volume of water had recently moved through them during the December 2007 flood. It is possible, though, that the channel margins and anabranches identified, and the resulting rates of change calculated, were affected not only by recent flood activity but also by small channels’ improved visibility as photographic quality improves in successive sets of photographs.

Because alluvial-channel geometry is controlled partly by the amount and grain size of available sediment, channel morphology on the lower Elwha River may change substantially as a result of new sediment influx after dam removal. Geomorphic adjustments that could accompany dam removal that are measurable from aerial surveys include changes in the rate of lateral channel migration, in the degree of braiding and sinuosity, and in the rates and patterns of braiding and avulsion caused by newly available large woody debris from upstream (Fetherston et al., 1995; Montgomery et al., 1995; Collins et al., 2002; O’Connor et al., 2003). Additional effects of sediment influx that would require field surveys to monitor the changes include filling of pools, bed aggradation, and fining of grain sizes in the lower river, where much of the channel bed has been winnowed to a dominantly cobble size (EIS, 1996; Randle et al., 1996; Randle, 2003; Pohl, 2004).
The expected response of the lower Elwha River to post-dam-removal sediment influx, especially by lateral channel movement and bed aggradation, could increase the flood risk on state, private, and tribal lands on the floodplain (Randle, 2003). The local magnitude and spatial distribution of future changes is uncertain, and is particularly difficult to predict in reaches with multiple channel anabranches, as in most of the lower river (Konrad, 2009). According to the environmental-impact statement, however, aggradation of coarse sediment in the lower river channel could increase the 100-year flood stage there by 0.3 to 1.2 m. On the basis of hydraulic modeling, downstream sediment transport will have completed a substantial proportion of its adjustment to dam removal within 1–4 years after dam removal (Randle, 2003; Konrad, 2009).

**SUMMARY**

The analysis presented here of historical channel change on the lower Elwha River is intended to serve as a basis against which to compare channel behavior after dam removal. Channel change on the lower river occurs by meander migration, avulsion of new channels, and episodic flood flow through side channels that, in non-flood stage, have only groundwater connection to larger anabranches. In the dammed system, average positional changes of the river across its lower floodplain exceeded 100 m over the interval 1939–2008, and exceeded 400 m locally. Annualized rates of change in channel position were commonly <10 m/yr, but can be much higher over intervals with major winter floods, e.g., an average positional change of 28 m/yr on the left channel margin and 61 m/yr on the right margin between 2006 and 2008, attributable to a 30-year flood event. Rates of change on the lower Elwha River were generally similar to decadal
rates of channel movement on the undammed Queets and Quinault Rivers (O’Connor et al., 2003), basins on the west side of the Olympic Peninsula that have been considered possible “control” areas with general setting similar to the Elwha (although with wider floodplains and higher rainfall). Whether our analysis of Elwha River channel change reflects true equilibrium conditions of the dammed river channel is unknown, because the river might still be adjusting to the presence of the dams when dam removal begins.

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REFERENCES


