Channel Evolution on the Lower Elwha River, Washington, 1939–2006

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Abstract

Analyses of historical aerial photographs of the lower Elwha River, Clallam County, Washington, reveal rates and patterns of channel change in this dammed, anabranching river between 1939 and 2006. Absolute positional changes of the active-floodplain margins, which commonly exceeded 50 m over that interval, have exceeded 400 m locally. Annualized rates of channel movement were typically ~2 to 10 m/yr; higher annualized rates over some time intervals are attributable to the formation of new channels by episodic avulsion. Channel movement by more gradual lateral meander migration was also common. Anthropogenic modification of the floodplain between the 1940s and 1980s substantially altered channel form and position.

This analysis of rates and patterns of channel change over nearly 70 years on the lower Elwha River is intended to characterize the evolution of the river throughout most of the time interval when two large dams have been in place upstream. Channel morphology and rates of channel movement are expected to change significantly in response to removal of the dams and re-establishment of the upstream sediment supply during a major river-restoration project.

Introduction

In the continental United States, >75,000 river-regulation structures have been built for water storage, flood control, and hydropower generation (Graf, 1999). Economic considerations of repairing aging dams that have fallen into disrepair, coupled with growing understanding of the ecologic effects of river regulation (Williams and Wolman, 1984; Dynesius and Nilsson, 1994; Graf, 1999, 2003; Yang and others, 2007), in some places have prompted dam removal and restoration of riparian habitat to a more natural condition. Although fluvial response to the removal of several small (<10 m high) dams has been studied (Bushaw-Newton and others, 2002; Pizzuto, 2002; Wildman and MacBroom, 2005), many important gaps remain, indicating the need for landscape-scale case studies of channel response to dam removal (Grant, 2001; Pizzuto, 2002; Doyle and others, 2002; Graf, 2003).

Two large dams on the Elwha River (fig. 1), which drains the north coast of the Olympic Peninsula in Clallam County, Wash., are scheduled for removal over the coming decade as part of the first riparian restoration project conducted on such a large scale. 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 mainstem riparian habitat in a nearly undeveloped watershed, most of which is within Olympic National Park (fig. 1). According to an interagency environmental-impact statement, dam removal is anticipated to improve habitat and spawning grounds for native fish populations, which have declined significantly since 1900 (Beechie and others, 2001). After dam removal, a substantial flux of sediment that is currently impounded in the two reservoirs will be transported downstream through the lower river to the ocean (Randle and others, 1996).

In anticipation of dam removal, Federal, State, and local agencies are documenting conditions in the dammed Elwha River for eventual comparison with the state of the river and its ecosystem during and after dam removal. In addition to the research discussed here, studies by the U.S. 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, populations of anadromous fish and related nutrient cycling, large woody debris, and response of the marine environment to increased sediment supply. The U.S. Geological Survey (USGS) is conducting biannual field surveys on the lower Elwha River (downstream of Elwha Dam) to monitor channel topography and sediment grain size (Draut and others, 2007). USGS scientists also conduct regular field surveys of topography and grain size on beaches of the Elwha delta (Warrick and others, 2007) and of nearshore bathymetry, habitat, and fluvial discharge into the coastal ocean (Warrick and others, 2008; Cochrane and others, in press).

To complement ongoing field studies, we have evaluated historical channel migration, using a series of aerial photographs of the lower Elwha River taken between 1939 and 2006. Because alluvial-channel geometry is partly controlled by the volume 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 effects of dam removal that would be measurable in aerial photographs of the lower section of the river could include changes in the rate of lateral channel migration, in the degree of channel braiding and sinuosity, and in the rates and patterns of braiding and new channel avulsion caused by increasing availability of large woody debris (Fetherston and others, 1995; Montgomery and others, 1995; Collins and others, 2002; O'Connor and others, 2003). Additional effects of sediment influx that would require field surveys include filling of pools (at least temporarily), bed aggradation, and fining of grain sizes in the lower river, where much of the channel bed presently consists of an armored cobble substrate (Randle and others, 1996; Randle, 2003; Pohl, 2004). Pohl (2004) evaluated the potential for bed-sediment mobility on the Elwha

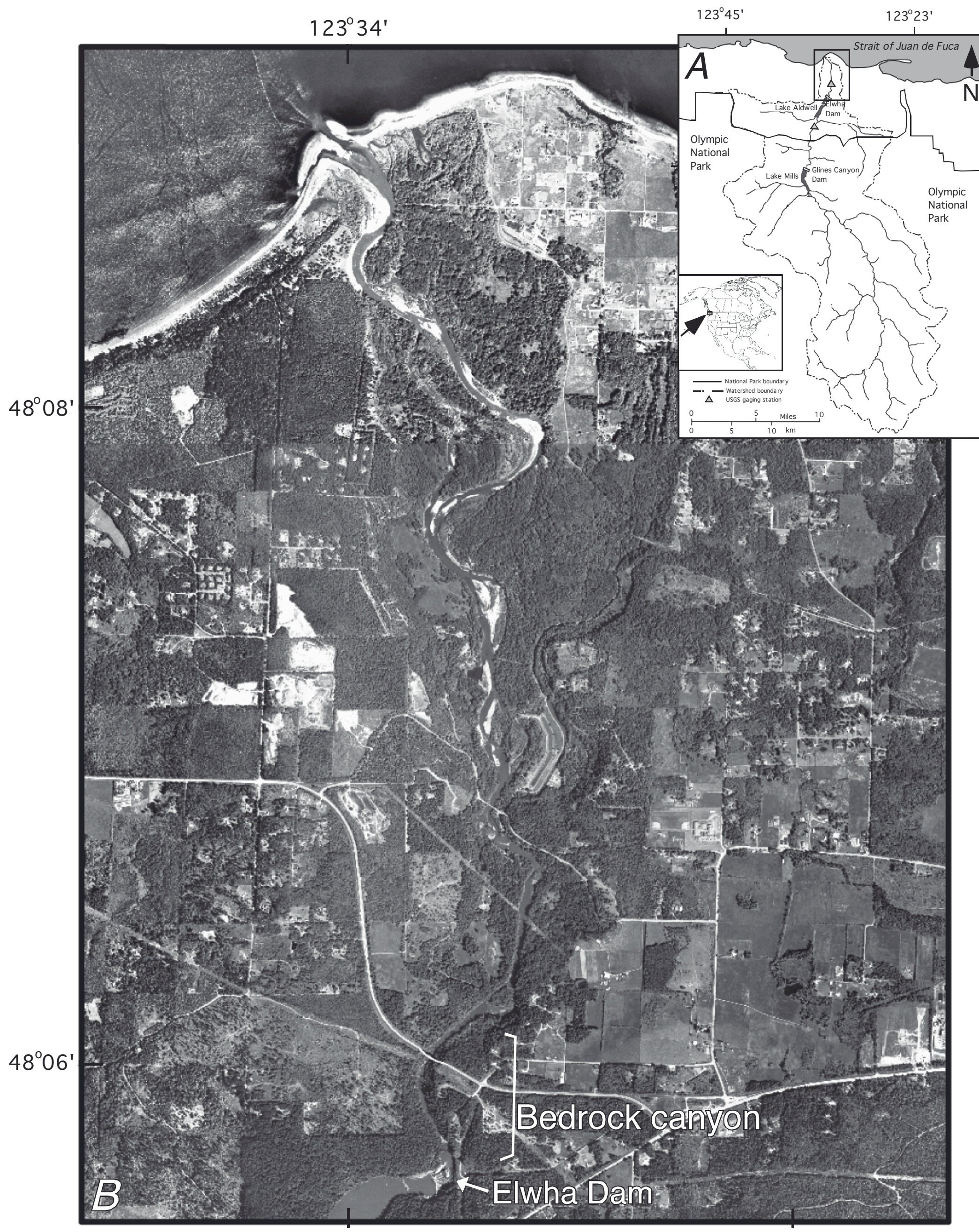

Figure 1. Elwha River watershed, Wash., showing locations of Elwha and Glines Canyon Dams and reservoirs, Lakes Aldwell and Mills. *A*, Index map. *B*, Aerial photograph taken in 2005 of the lower Elwha River, downstream of Elwha Dam. Immediately below dam is a 1.3-km-long reach where river is confined within a bedrock canyon. From downstream end of this canyon to delta (~6.5 km), river channel anastomoses across an alluvial floodplain.

River, using mean bed particle size. Her study indicated that although sediment-supply disruption by the dams had caused some armoring of the bed between the dams and in the lower river, sediment in the lowermost ~5 km of the river was fine enough to be mobile under mean-annual-flood-conditions (362 m^3/s). Her results imply that the dammed lower-river channel would be more capable of geomorphic adjustment to annual floods than the channel between the dams or in a confined (canyon) reach immediately above Lake Mills (fig. 1*A*). Alluvial reaches of the upper section of the river, unaffected by damming and with the finest mean grain size, displayed the greatest potential for bed-sediment mobility (Pohl, 2004).

To allow accurate detection of the changes in fluvial processes that will occur after dam removal, the rates and patterns of channel evolution in the dammed river system need to be quantified. The decadal-scale aerial-photographic analysis presented in this study attempts to define those parameters. However, whether this analysis 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.

Project Objectives

The objectives of this study were to compile a temporal dataset of georeferenced historical aerial photographs of the lower Elwha River and to quantify river-channel position

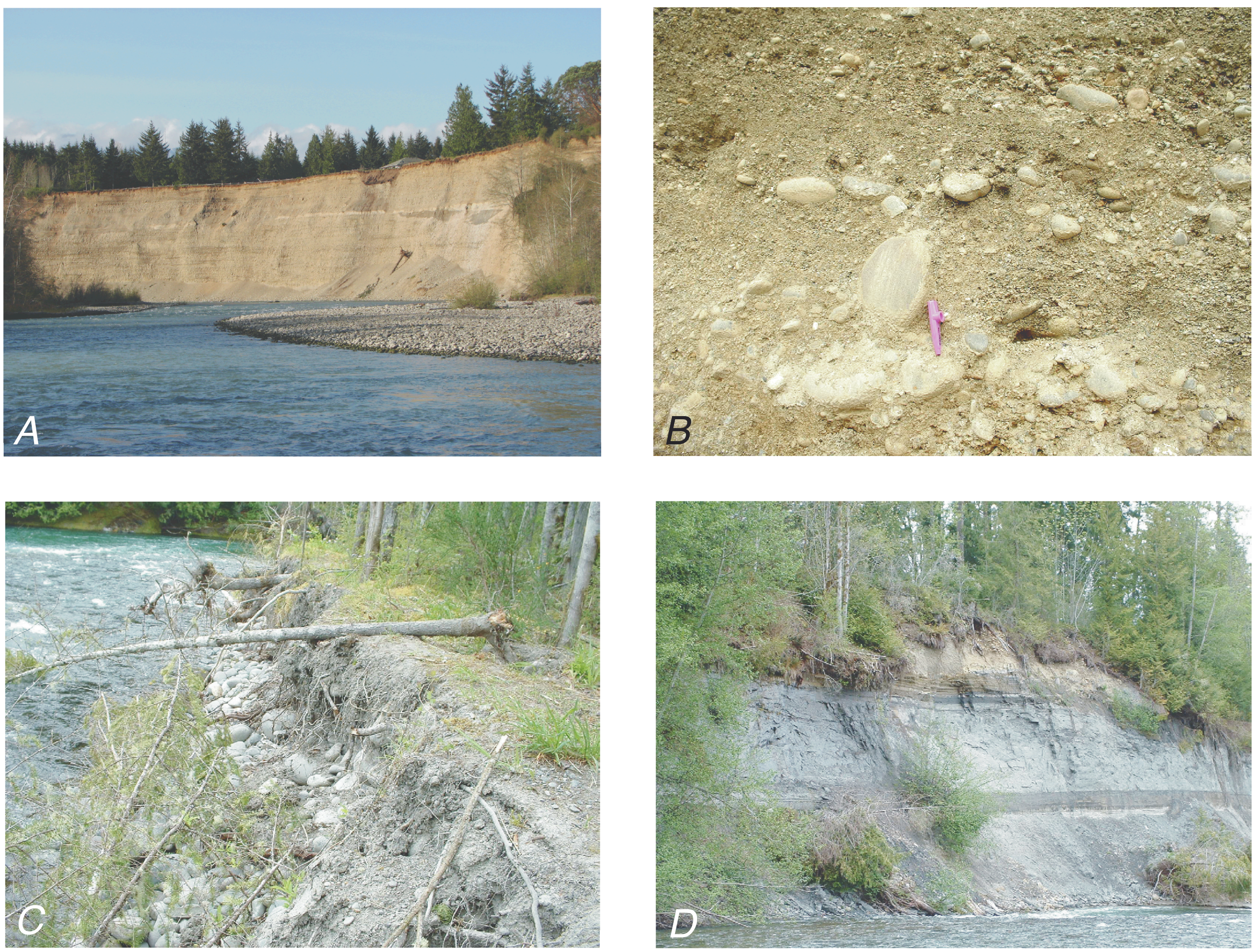

Figure 2. Sediment-producing bluffs on the lower Elwha River, Wash. (fig. 1). *A*, Largest bluff on lower river, at western margin of channel 0.5 km upstream of river mouth, is 38 m high and 310 m long. Slope failures here supply sediment to channel. *B*, Unconsolidated sediment in same bluff as in figure 2*A*, showing absence of grain-size sorting or imbrication that is characteristic of glacial till. Purple kazoo for scale is 12 cm long. *C*, Smaller (1 m high) bluff ~5.5 km upstream of river mouth. Bluffs of this scale, which are common on lower river, supply poorly consolidated, poorly sorted sediment to channel with grain sizes ranging from clay to cobbles. *D*, Lower river's second-tallest bluff, ~5 km upstream of river mouth, exposes well sorted, fine-grained strata. Gray, clay-rich unit in center of exposure may be a glacial-lake deposit. Bluff is ~4 m high.

at each time shown in the photographs. Those objectives were achieved by delineating active-floodplain margins in a geographic-information-system (GIS) database and measuring the changes in their position over time. Rates and patterns of channel movement obtained in this analysis will represent the response of the dammed lower Elwha River to the combined influences of flow and floodplain engineering between 1939 and 2006.

Study Area

The 833-km^2-area drainage basin of the Elwha River is situated predominantly in steep, mountainous terrain, draining a glaciated landscape of uplifted low-grade-metamorphosed marine sandstone and slate. The river channel is confined in a bedrock canyon in some reaches, and forms an alluvial floodplain in others. Because of the relatively small size of their reservoirs, Elwha and Glines Canyon Dams have little effect on the magnitude and duration of high flows and are not used for flood control. Throughout most of the dams' history, however, the flows have included more rapid fluctuations and lower daily minima than is natural, in response to hydropower production (Johnson, 1994; Pohl, 1999). Typical annual discharge has two peaks corresponding to winter rain-on-snow events and late-spring snowmelt. Monthly mean discharge of the two peaks is similar, near 60 m^3/s in June and December, although the largest floods occur in winter (see URL http://waterdata.usgs.gov/nwis/).

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, fluvial sediment delivery to the coastal ocean is presently ~2 percent of the predam load. An estimated 13.8x10^6 m^3 of sediment is impounded in the reservoirs behind the two dams, forming deltas in Lakes Aldwell and Mills (Randle and others, 1996). An estimated 0.9–2.0x10^6 m^3 of sand and coarser sediment and ~3.7–4.3x10^6 m^3 of silt and clay will be transported downstream by erosion of these two reservoir deltas (Randle and others, 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. 1*B*). Within the upper 1.3 km of this reach, the river is confined to a narrow bedrock gorge, whereas the lowermost 6.5 km consists of anabranching channels on a vegetated floodplain (Pohl, 1999, 2004). Anabranching rivers, also referred to as "anastomosing" (Smith and Smith, 1980; Harwood and Brown, 1993; Knighton and Nanson, 1993), consist of multiple channels separated by bars and vegetated islands excised from the floodplain. Islands in anabranching rivers can be large relative to the width of the channel and are commonly stable on decadal to even centennial time scales. Individual channels meander or may exhibit smaller-scale braiding but eventually rejoin (Knighton, 1998). Anabranching fluvial systems can be classified within order B2 of the genetic floodplain-classification scheme of Nanson and Croke (1992)—wandering gravel-bed river floodplains—although processes that cause anastomosis remain incompletely understood.

The floodplain of the lower Elwha River is heavily vegetated, dominated by hardwood and conifer trees; in Pacific coastal forest areas of the Olympic Peninsula, young floodplain areas are commonly colonized first by alder and cottonwood, to be replaced over time by spruce, hemlock, and cedar (Beechie and others, 2006). Sediment composing the Elwha floodplain is largely glacial in origin, including poorly sorted and poorly consolidated diamicton (figs. 2*A–C*) with grain sizes ranging from silt and clay to cobbles (Draut and others, 2007). Clay-rich strata suggestive of glaciolacustrine deposits are exposed in a ~4-m-high bluff along the river channel (fig. 2*D*). The largest sediment-producing bluff is 38 m high, 0.5 km upstream of the river mouth (fig. 2*A*); most other bluffs are 1 to 3 m high. These bluffs represent virtually the only sediment input to the Elwha River downstream of the dams.

The expected response of the lower Elwha River to post-dam-removal sediment influx (lateral migration of the channel, changes in bed elevation and sediment composition) will likely increase the flood risk on private and State-owned property and the Lower Elwha Klallam tribal reservation on the floodplain (Randle, 2003). On the basis of previous hydrologic modeling, downstream sediment transport will approach natural, predam conditions within an estimated 1–3 years after dam removal. 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.

Methods

Compilation and Spatial Referencing of Aerial Photographs

To determine the extent and rate of lateral channel change, historical channel boundaries were interpreted and digitized from georeferenced aerial photographs collected in 12 different years between 1939 and 2006. The 1939 photographs are believed to be the earliest accurate representations of the Elwha River; survey maps from 1878 and 1892 show the lower river but are not considered to be spatially accurate with respect to channel morphology (Pohl, 1999) and were not consulted in this study. A timeline from 1918 to early 2007 (fig. 3) shows the temporal spacing of available aerial photographs and the river-discharge history between time steps represented in the photographs. The sources and specifications of each set of aerial photographs, with the estimated error associated with their spatial rectification, are listed in table 1.

Digital orthophotographs (spatially referenced by adjustment relative to a digital elevation model and based on camera

Table 1. Sets of aerial photographs used in channel analysis for the Elwha River, Washington.

[For digitally orthorectified photographs, registration error is the rms error stated by the agency releasing the photographs. For georeferenced photographs, registration error is estimated by comparison with the 1990/94 orthophotographs, added to the 7-m rms error of those orthophotographs. Total error on digitized channel margins was calculated for each set of aerial photographs by combining registration error with 5-m digitizing error, using equation 1 (see text)]

Year	Date	Source	River discharge (m^3/s)	Scale	Spatial-registration method	Estimated registration error (m)	Total error on digitized channel margins (m)
1939	8/1/1939	Puget Sound River History Project, University of Washington	29.7	~1:30,000	Orthorectified	10.6	11.7
1956	8/8/1956	Clallam County Assessor	39.1	1:12,000	Georeferenced to 1990/1994 orthophoto	18.7	19.4
1965	5/7/1965	Washington Department of Natural Resources	34.5	1:12,000	Georeferenced to 1990/1994 orthophoto	14.9	15.7
1971	7/17/1971	Washington Department of Natural Resources	87.4	1:12,000	Georeferenced to 1990/1994 orthophoto	16.7	17.4
1977	7/23/1977	Washington Department of Natural Resources	18.4	1:12,000	Georeferenced to 1990/1994 orthophoto	15.6	16.4
1981	7/27/1981	Washington Department of Natural Resources	21.9	1:12,000	Georeferenced to 1990/1994 orthophoto	18.4	19.1
1990	7/9/1990	Washington Department of Natural Resources	37.9	1:12,500	Georeferenced to 1990/1994 orthophoto	13.0	13.9
1990	7/19/1990	U.S. Geological Survey	29.1	1:12,500	Orthorectified	7.0	8.6
1990	9/4/1990	U.S. Geological Survey	10.6	1:12,500	Orthorectified	7.0	8.6
1994	3/26/1994	Washington Department of Natural Resources	32.0	1:12,000	Georeferenced to 1990/1994 orthophoto	24.0	24.5
1994	9/21/1994	U.S. Geological Survey	9.9	1:12,000	Orthorectified	7.0	8.6
2000	unavailable	Washington Department of Natural Resources	unavailable	unavailable	Georeferenced to 1990/1994 orthophoto	13.0	13.9
2002	6/21/2002	Washington Department of Natural Resources	71.3	1:12,000	Georeferenced to 1990/1994 orthophoto	21.5	22.1
2005	unavailable	Washington Department of Natural Resources	unavailable	1:32,000	Orthorectified	3.1	5.9
2006	11/7/2006	U.S. Department of Agriculture	186	unavailable	Orthorectified	5.0	7.1

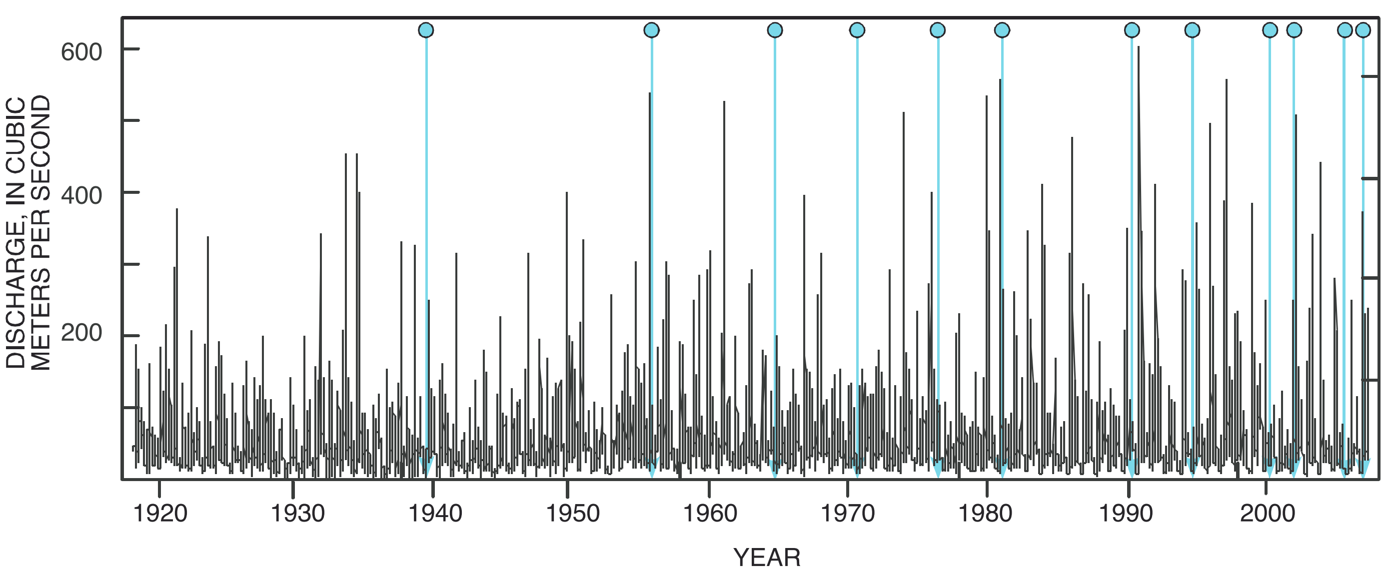

Figure 3. Hydrograph of the Elwha River (fig. 1) recorded at U.S. Geological Survey gaging station 12045500 (at McDonald Bridge, above Lake Aldwell) from October 1, 1918, to January 30, 2007. Blue dots and arrows indicate times from which aerial photographs were analyzed for this study.

position and lens specifications) are available from 1939, 1990, 1994, 2005, and 2006 (table 1). Other photographs, from 1956, 1965, 1971, 1977, 1981, 1990, 1994, 2000, and 2002, were georeferenced by R. McCoy, using ground-control points to adjust the spatial distortion of photographs. The spatial (registration) error for the five sets of digital orthophotographs is taken to be the rms error stated by the agency releasing the photographs (table 1). The registration error on the georeferenced photographs was estimated by comparing the positions of photoidentifiable features with those in the 1990 and 1994 orthophotographs, and adding the average of the offsets to the 7 m rms error of the 1990 and 1994 orthophotographs (table 1). (The 1990 and 1994 orthophotographs each contained only partial coverage of the lower river.)

In addition to the registration error associated with georeferencing or orthorectification, analysis of channel parameters from aerial photographs is also subject to a digitizing error (inaccuracy in picking the exact channel margin), which is affected by the scale and resolution of the photographs and the effects of shadows that may obscure the channel margin. The digitizing error was conservatively estimated at 5 m for each set of photographs analyzed (after Hapke and Reid, 2007). Because registration error (E_{reg}) and digitizing error (E_{dig}) are two independent sources of error that contribute to the total error in channel analysis, the total error in channel position (E_{total}) inferred from each set of aerial photographs was calculated as (Gaeuman and others, 2003; Hapke and Reid, 2007):

$$E_{total} = \sqrt{E_{reg}^{\ 2} + E_{dig}^{\ 2}} \qquad (1)$$

Delineation of Channel Boundaries in ArcGIS

On each set of aerial photographs, the westernmost and easternmost margins of the apparent recently active floodplain were digitized, where the “recently active floodplain” was defined as the unvegetated (or only sparsely vegetated) part of the channel (see Sear and others, 1995), including all wet and dry areas, according to the methods of Kondolf and others (2002), O’Connor and others (2003; see Osterkamp and Hedman, 1982), Rapp and Abbe (2003), and Grams and Schmidt (2005). Grams and Schmidt analyzed channel morphology on georeferenced aerial photographs of the Green River in Utah and Colorado and inferred that bare or sparsely vegetated sand and gravel deposits were “active” because they were below the (recent) mean-annual-flood stage, that is, flows frequent enough with sufficient bed shear stress to transport sediment and remove small plants (Montgomery and MacDonald, 2002; Rapp and Abbe, 2003). Consideration of the entire unvegetated part of the Elwha floodplain as having been recently occupied by floods assumes that vegetation would rapidly colonize parts of the floodplain that were not regularly devegetated by floods. Use of the absolute floodplain margins eliminates bias and variation that would arise from using channel margins occupied by lower stages; the flow varies from one set of aerial photographs to another. Also included within the margins of the recently active floodplain were rare places where water was visible in a small side channel with thick vegetation on either side but with an open connection (at both 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. All of the project staff who georeferenced photographs and digitized channel margins were also familiar with the lower Elwha River terrain and channel geomorphology through fieldwork (see Rapp and Abbe, 2003).

The resulting 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 and others, 2005), the historical positions of the western (river left) and eastern (river right) margins were determined relative to an arbitrary channel-parallel baseline along 64 transects spaced at ~100-m intervals between the base of Elwha Dam and the river mouth. In areas where the orientation of the river margins had changed significantly over time, such as on the outer bend of a meander, the orientations of transects were adjusted to be as orthogonal as possible to the general direction of channel movement (see Hapke and Reid, 2007). Using the DSAS, the distances between the baseline and each channel margin were calculated. 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 (1939–2006) were calculated by using a linear-regression analysis of each transect’s position in each of the 12 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 by assuming that the error margins estimated with Equation 1 for each set of aerial photographs are independent of each other, and dividing by the time interval t (in years) represented by the two sets of aerial photographs (Hapke and Reid, 2007):

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

Where the annualized rates of change in channel position for each transect exceeded the composite estimated error from both sets of aerial photographs, the change in channel position was considered to be measurable.

Results

Figures 4 through 14 show end-point rates of change in channel position on the lower Elwha River between successive sets of aerial photographs. The annualized rate of change over the entire study interval (1939–2006) determined by linear regression of transect position at each time step is mapped in figure 15. Net changes in active-floodplain position between 1939 and 2006 are plotted in figure 16. Net

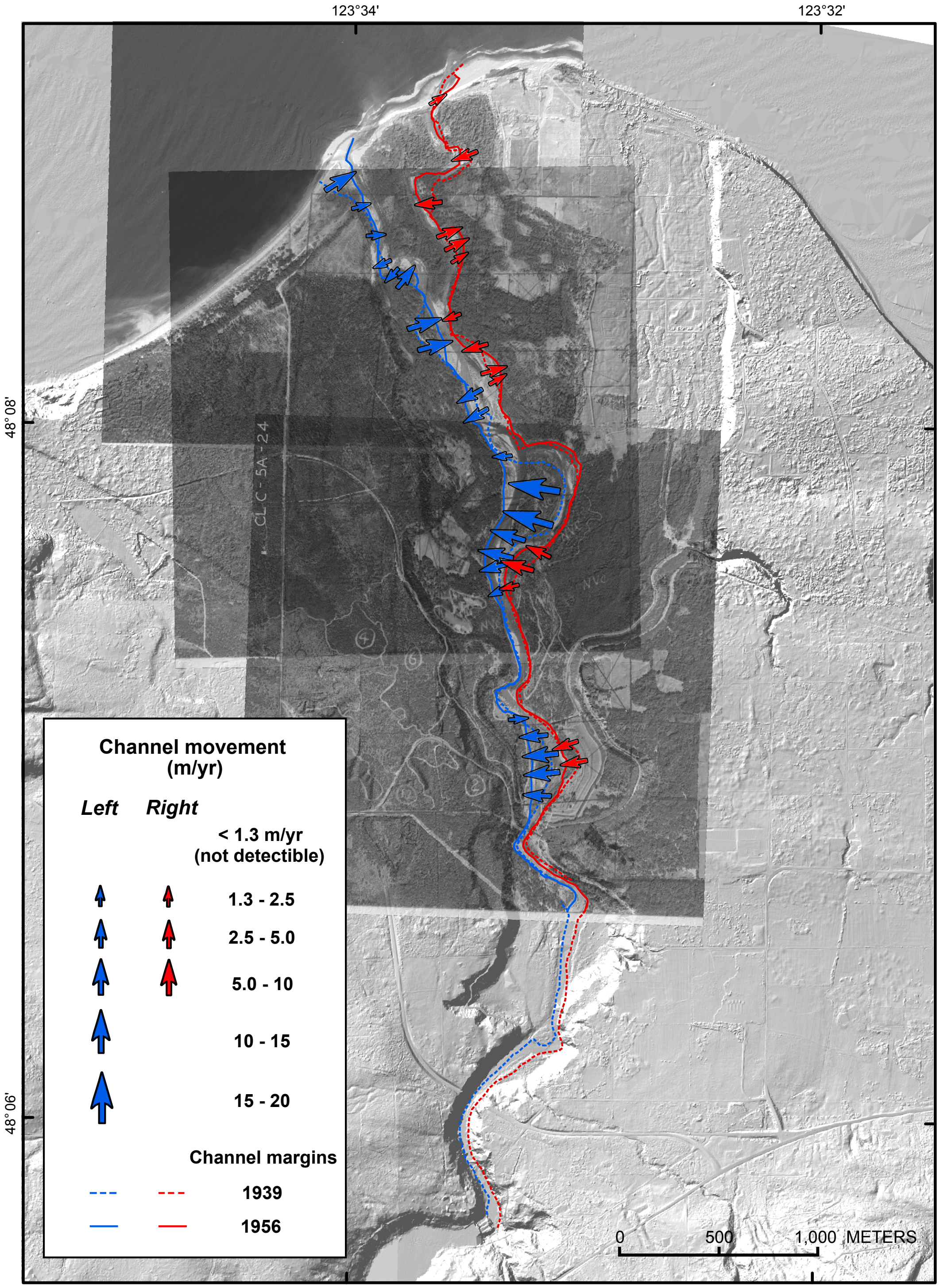

Figure 4. Channel change on the lower Elwha River, Wash. (fig. 1), between 1939 and 1956. Blue and red arrows indicate net movement in position of river-left (western) and river-right (eastern) active-floodplain margins, respectively, with size of arrows indicating magnitude and direction of channel movement. Channel movement of <1.3 m/yr is within error margin of analysis and so is not represented by arrows. Photographs taken in 1956, superimposed on airborne lidar image obtained in 2000 by the Puget Sound Lidar Consortium. Channel segment denoted by black bracket was straightened artificially (a meander cutoff was excavated) in 1947.

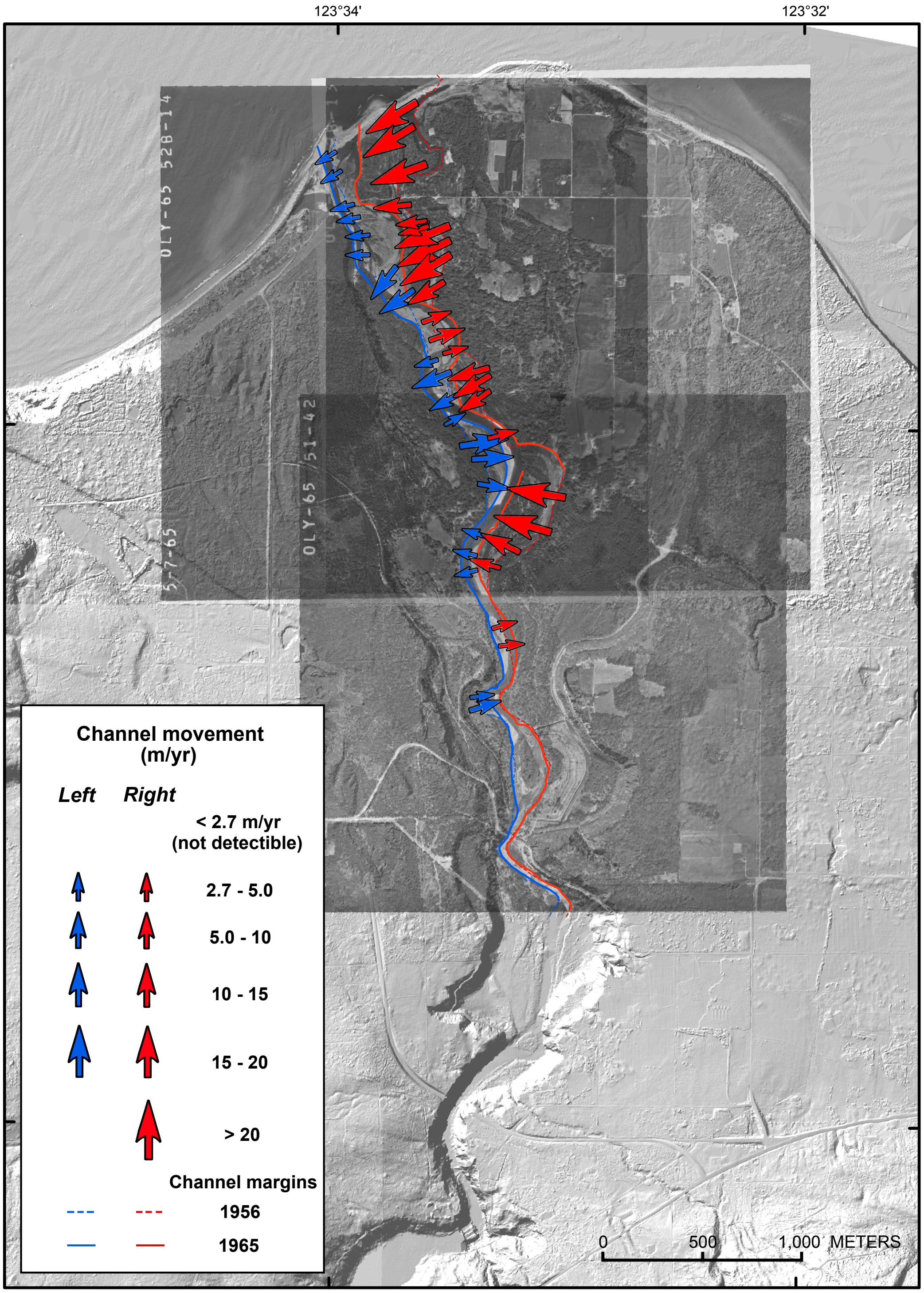

Figure 5. Channel change on the lower Elwha River, Wash. (fig. 1), between 1956 and 1965. Blue and red arrows indicate net movement in position of river-left (western) and river-right (eastern) active-floodplain margins, respectively, with size of arrows indicating magnitude and direction of channel movement. Channel movement of <2.7 m/yr is within error margin of analysis and so is not represented by arrows. Photographs taken in 1965, superimposed on airborne lidar image obtained in 2000 by the Puget Sound Lidar Consortium.

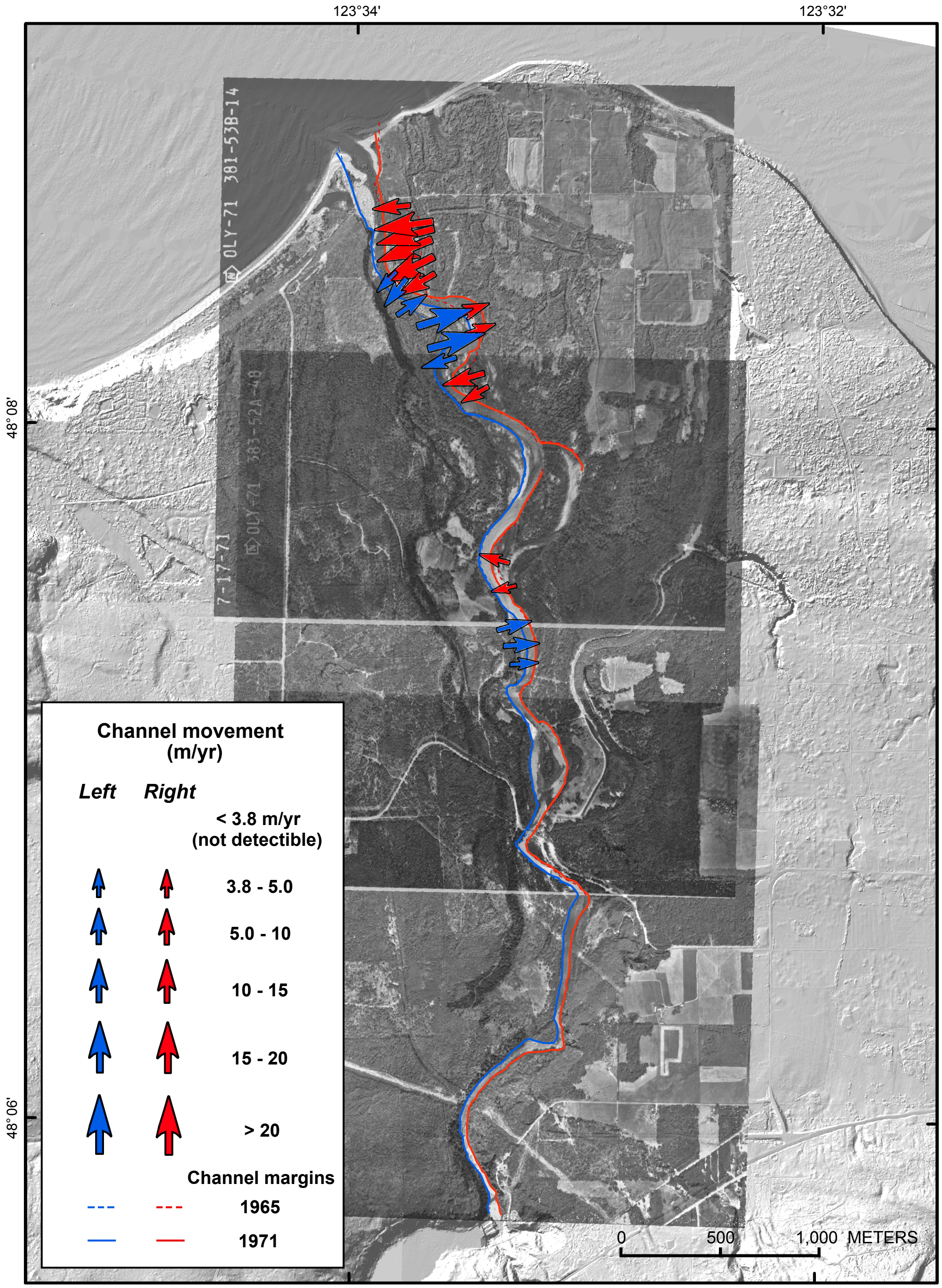

Figure 6. Channel change on the lower Elwha River, Wash. (fig. 1), between 1965 and 1971. Blue and red arrows indicate net movement in position of river-left (western) and river-right (eastern) active-floodplain margins, respectively, with size of arrows indicating magnitude and direction of channel movement. Channel movement of < 3.8 m/yr is within error margin of analysis and so is not represented by arrows. Photographs taken in 1971, superimposed on airborne lidar image obtained in 2000 by the Puget Sound Lidar Consortium.

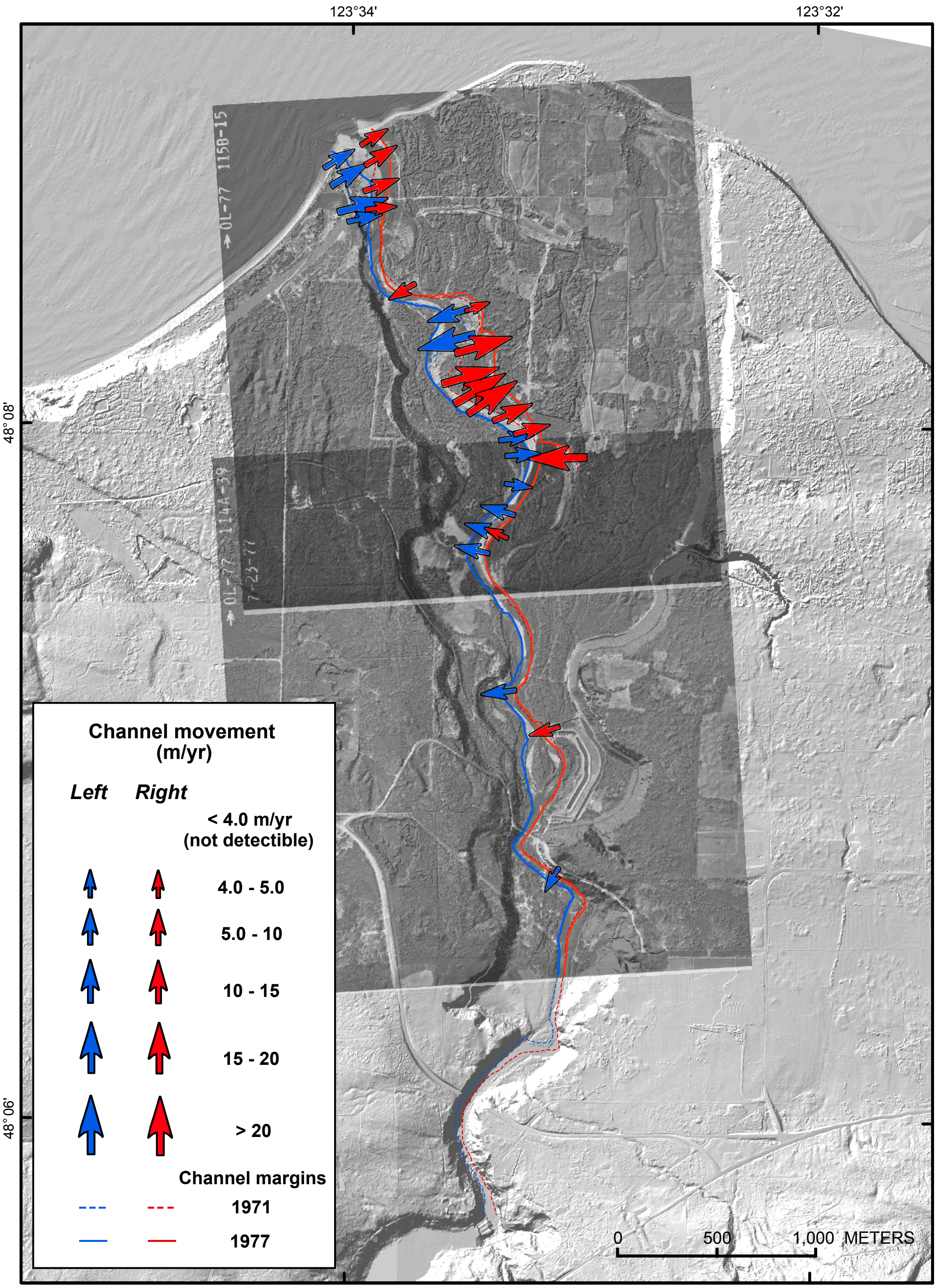

Figure 7. Channel change on the lower Elwha River, Wash. (fig. 1), between 1971 and 1977. Blue and red arrows indicate net movement in position of river-left (western) and river-right (eastern) active-floodplain margins, respectively, with size of arrows indicating magnitude and direction of channel movement. Channel movement of <4.0 m/yr is within error margin of analysis and so is not represented by arrows. Photographs taken in 1977, superimposed on airborne lidar image obtained in 2000 by the Puget Sound Lidar Consortium.

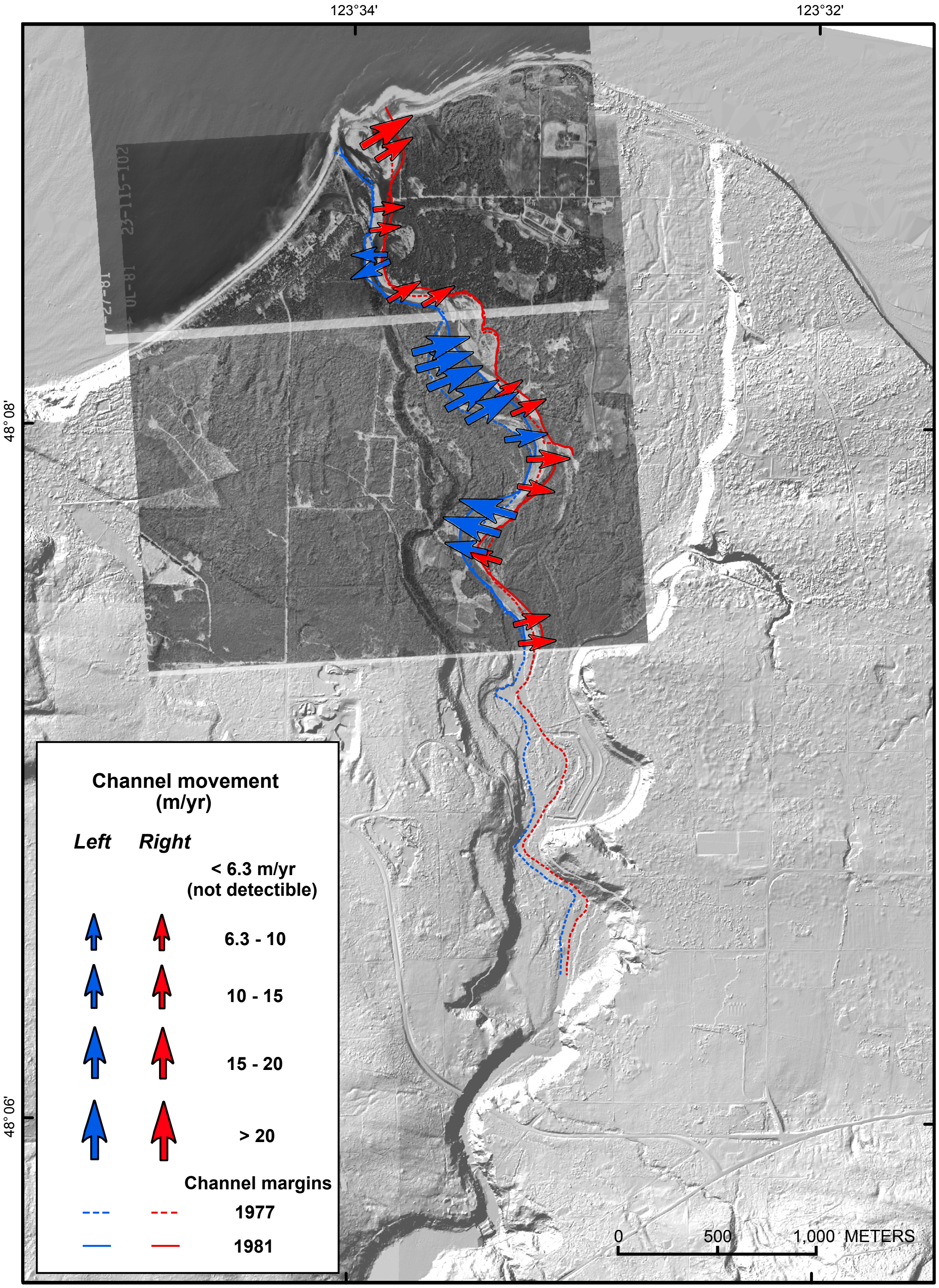

Figure 8. Channel change on the lower Elwha River, Wash. (fig. 1), between 1977 and 1981. Blue and red arrows indicate net movement in position of river-left (western) and river-right (eastern) active-floodplain margins, respectively, with size of arrows indicating magnitude and direction of channel movement. Channel movement of <6.3 m/yr is within error margin of analysis and so is not represented by arrows. Photographs taken in 1981, superimposed on airborne lidar image obtained in 2000 by the Puget Sound Lidar Consortium.

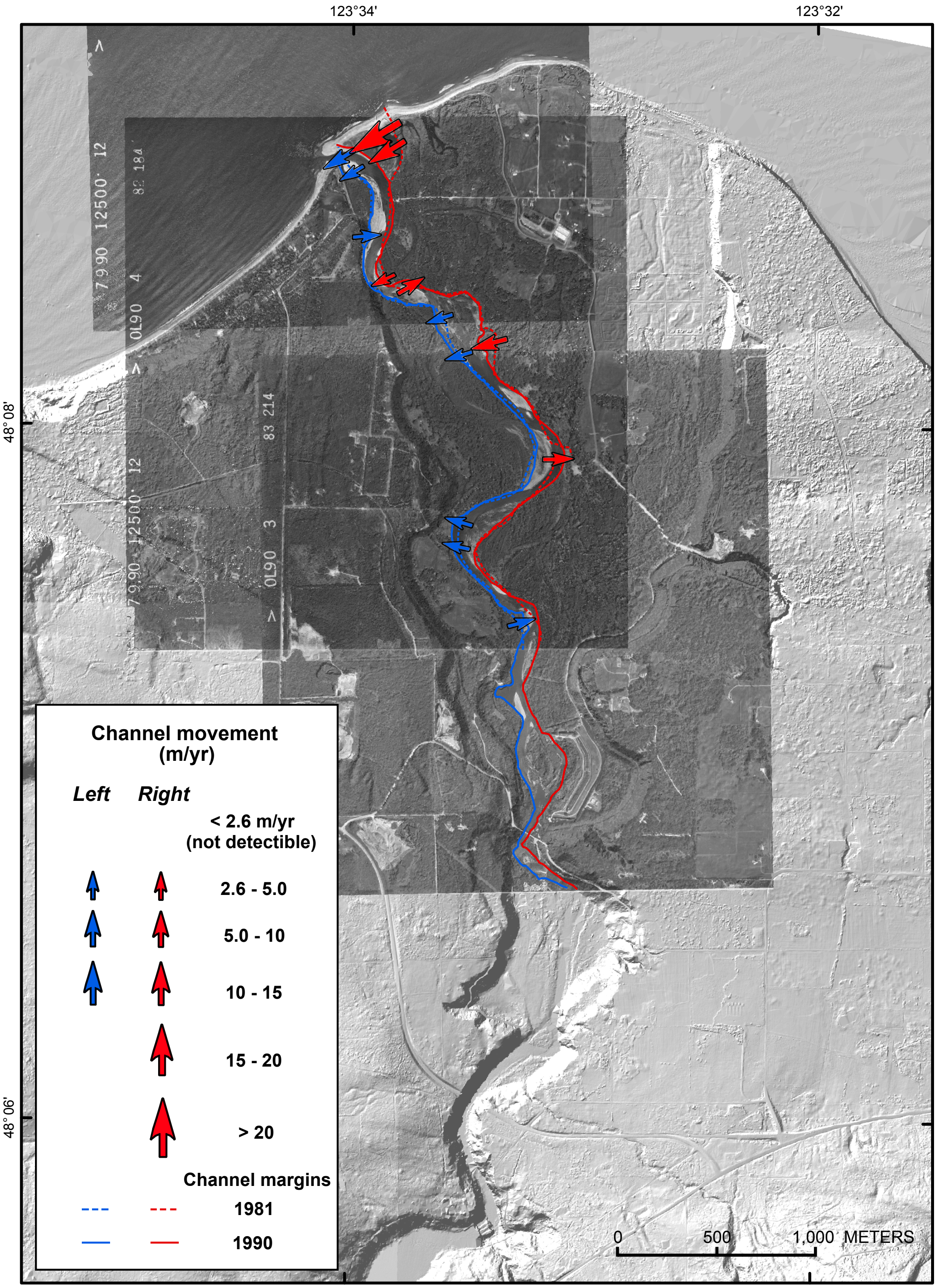

Figure 9. Channel change on the lower Elwha River, Wash. (fig. 1), between 1981 and 1990. Blue and red arrows indicate net movement in position of river-left (western) and river-right (eastern) active-floodplain margins, respectively, with size of arrows indicating magnitude and direction of channel movement. Channel movement of <2.6 m/yr is within error margin of analysis and so is not represented by arrows. Photographs taken in 1990, superimposed on airborne lidar image obtained in 2000 by the Puget Sound Lidar Consortium.

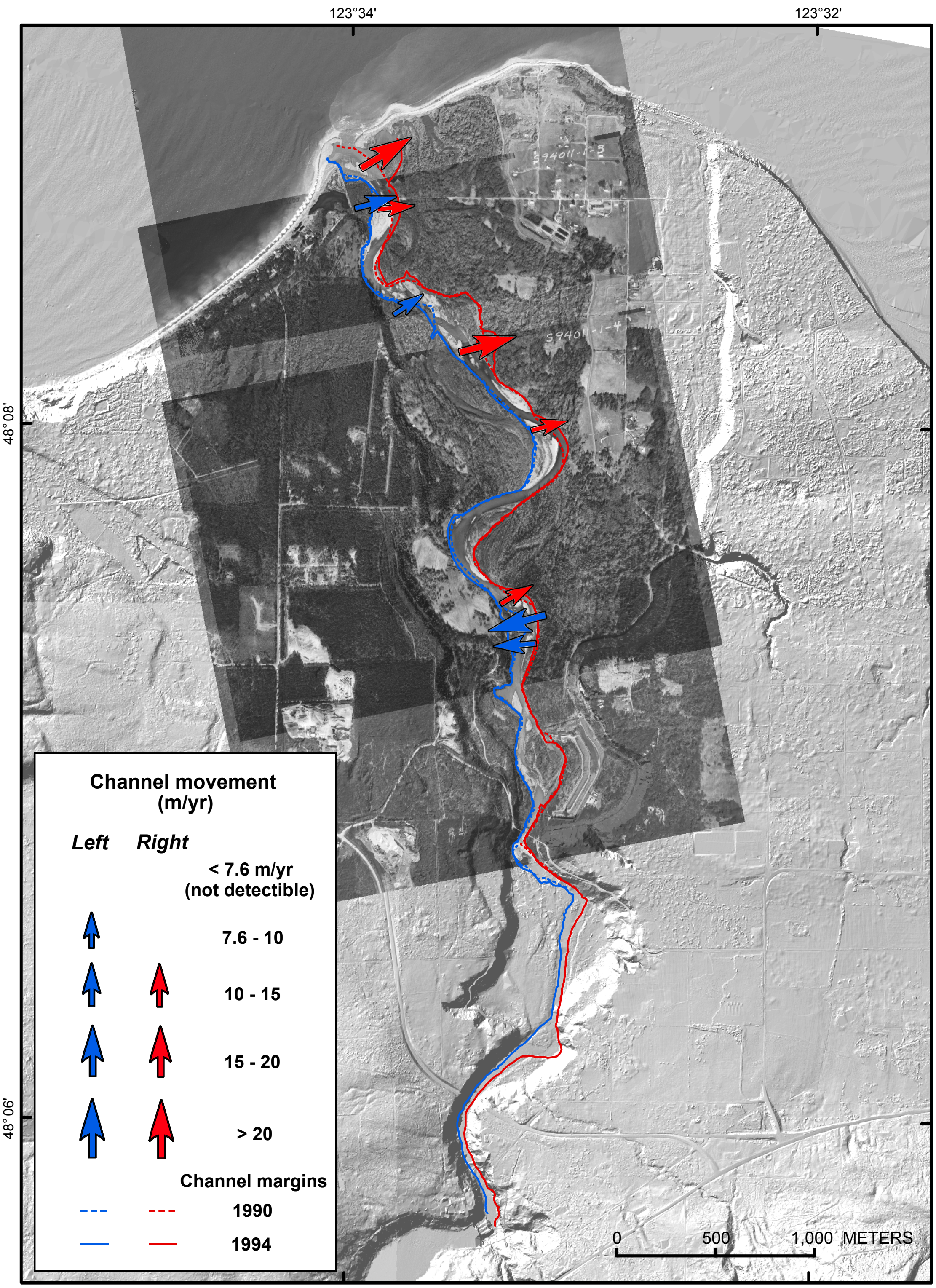

Figure 10. Channel change on the lower Elwha River, Wash. (fig. 1), between 1990 and 1994. Blue and red arrows indicate net movement in position of river-left (western) and river-right (eastern) active-floodplain margins, respectively, with size of arrows indicating magnitude and direction of channel movement. Channel movement of <7.6 m/yr is within error margin of analysis and so is not represented by arrows. Photographs taken in 1994, superimposed on airborne lidar image obtained in 2000 by the Puget Sound Lidar Consortium.

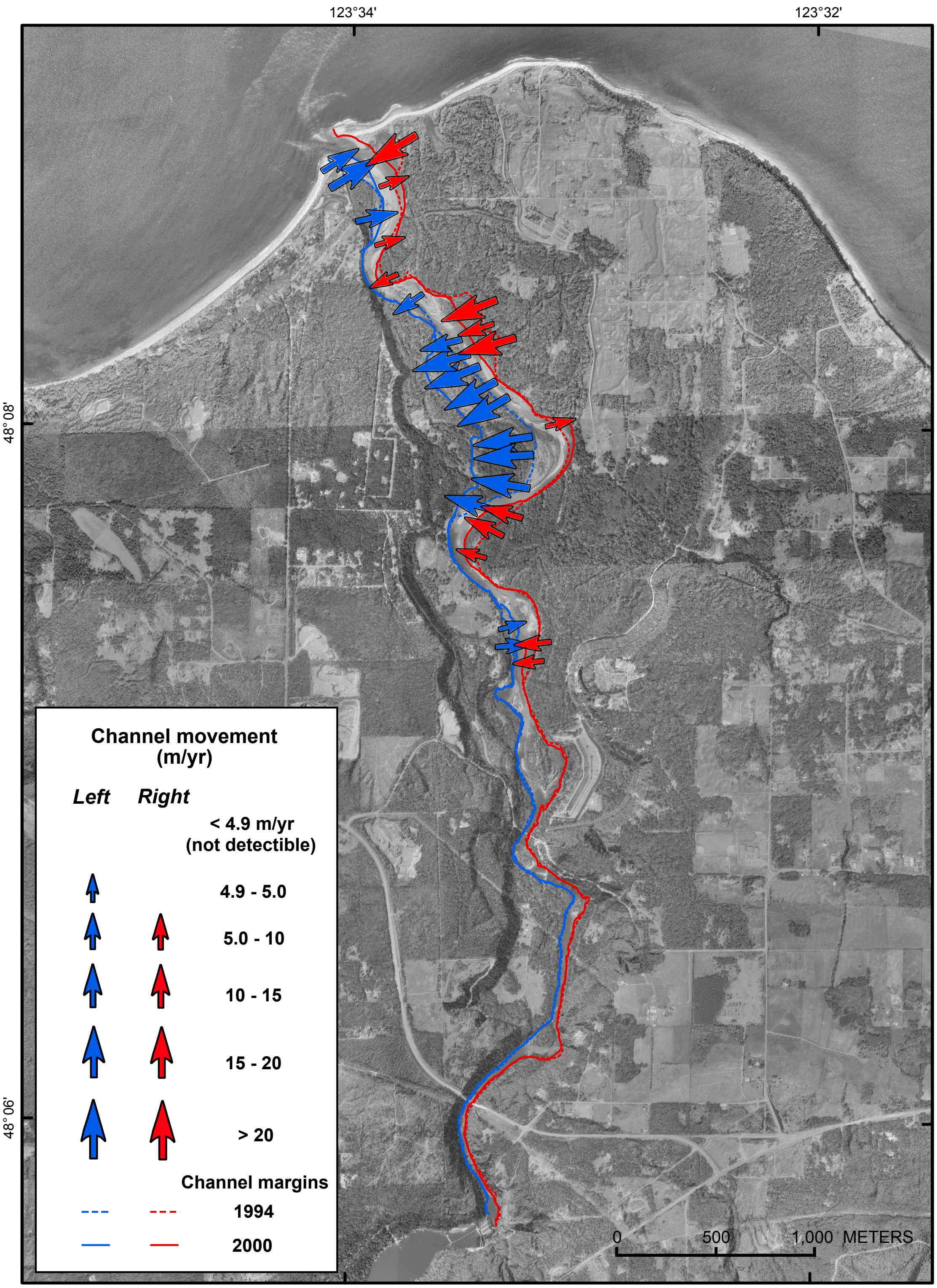

Figure 11. Channel change on the lower Elwha River, Wash. (fig. 1), between 1994 and 2000. Blue and red arrows indicate net movement in position of river-left (western) and river-right (eastern) active-floodplain margins, respectively, with size of arrows indicating magnitude and direction of channel movement. Channel movement of <4.9 m/yr is within error margin of analysis and so is not represented by arrows. Photographs taken in 2000, superimposed on airborne lidar image obtained in 2000 by the Puget Sound Lidar Consortium.

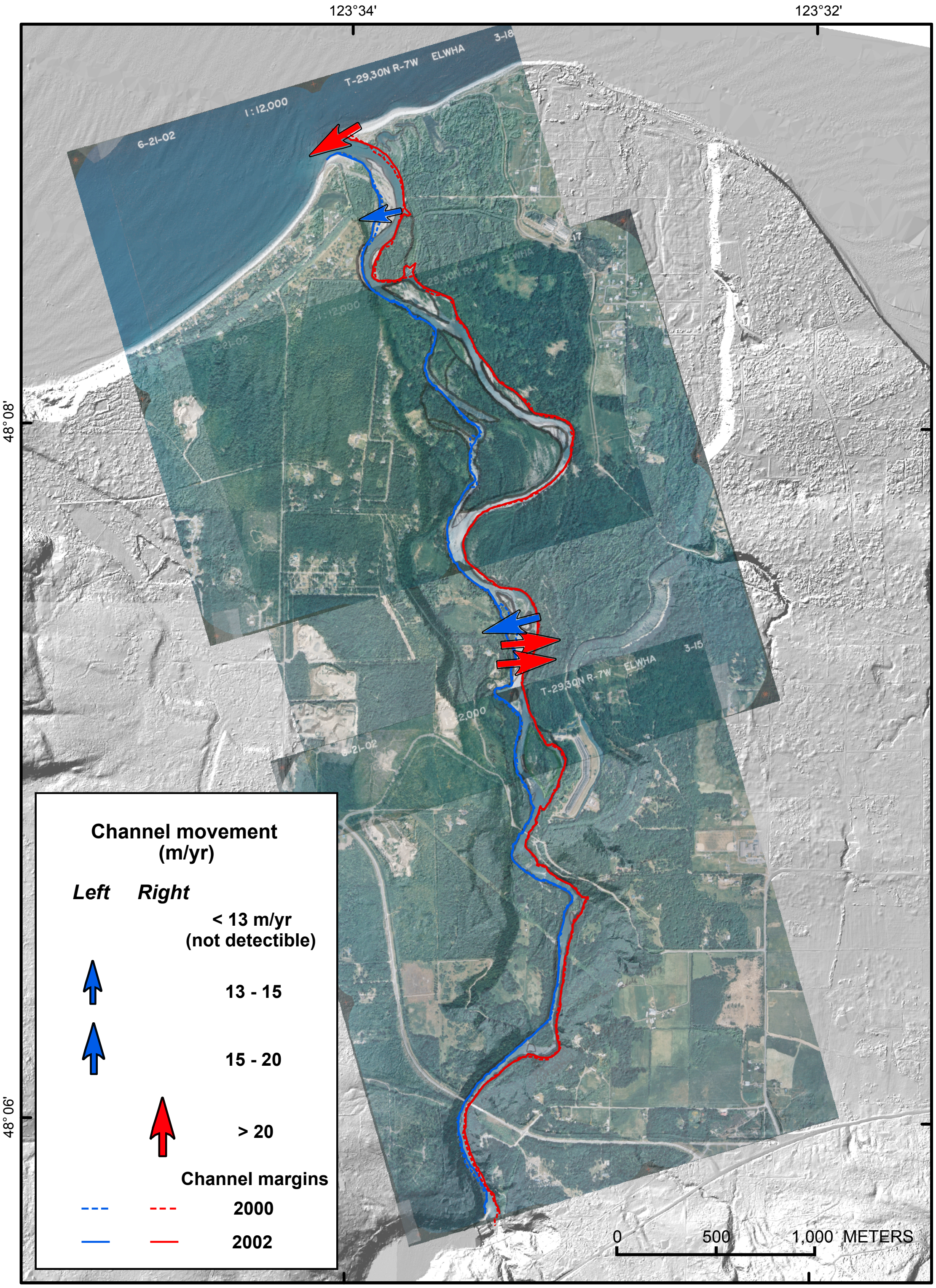

Figure 12. Channel change on the lower Elwha River, Wash. (fig. 1), between 2000 and 2002. Blue and red arrows indicate net movement in position of river-left (western) and river-right (eastern) active-floodplain margins, respectively, with size of arrows indicating magnitude and direction of channel movement. Channel movement of <13 m/yr is within error margin of analysis and so is not represented by arrows. Photographs taken in 2002, superimposed on airborne lidar image obtained in 2000 by the Puget Sound Lidar Consortium.

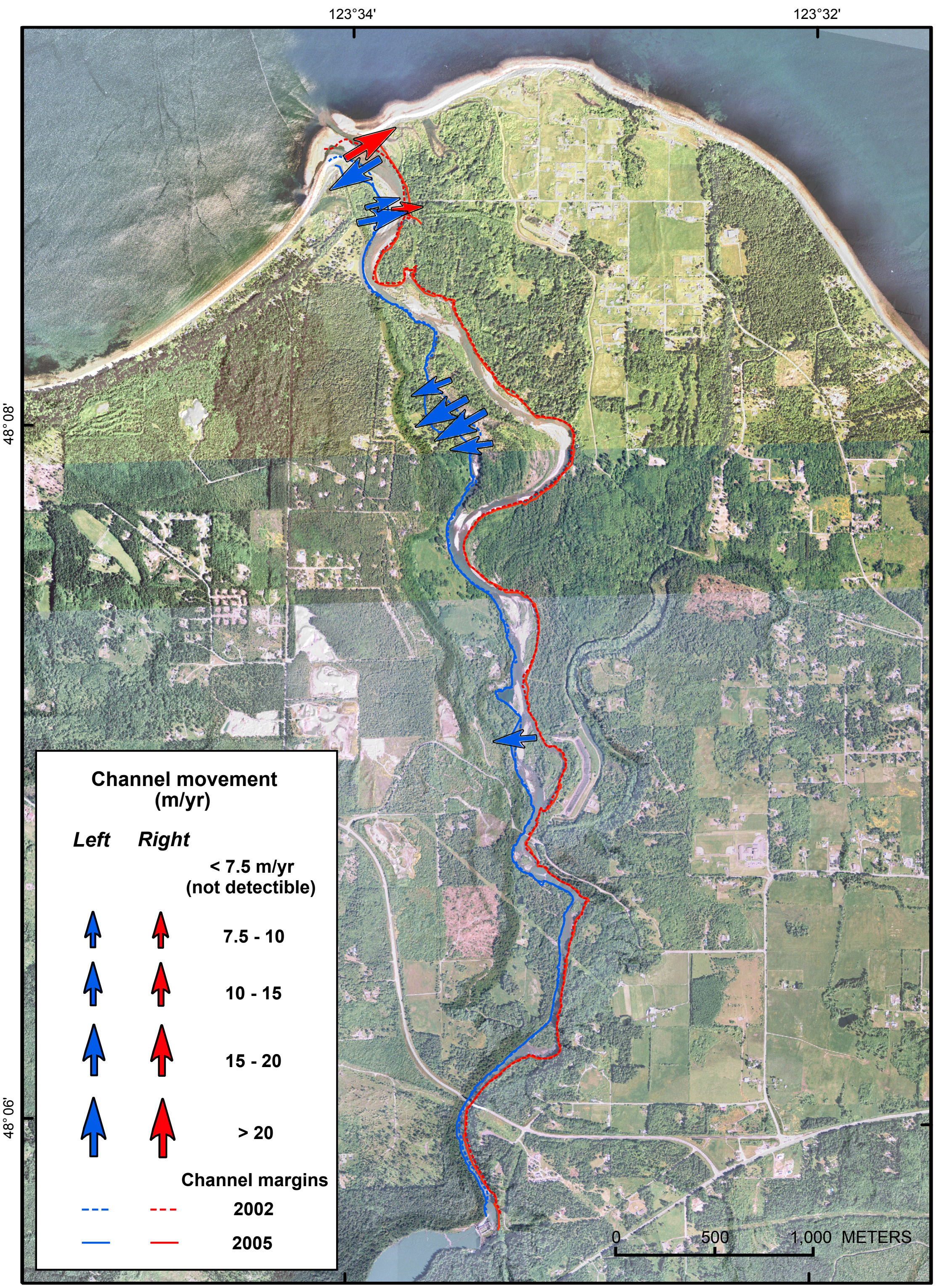

Figure 13. Channel change on the lower Elwha River, Wash. (fig. 1), between 2002 and 2005. Blue and red arrows indicate net movement in position of river-left (western) and river-right (eastern) active-floodplain margins, respectively, with size of arrows indicating magnitude and direction of channel movement. Channel movement of <7.5 m/yr is within error margin of analysis and so is not represented by arrows. Photographs taken in 2005, superimposed on airborne lidar image obtained in 2000 by the Puget Sound Lidar Consortium.

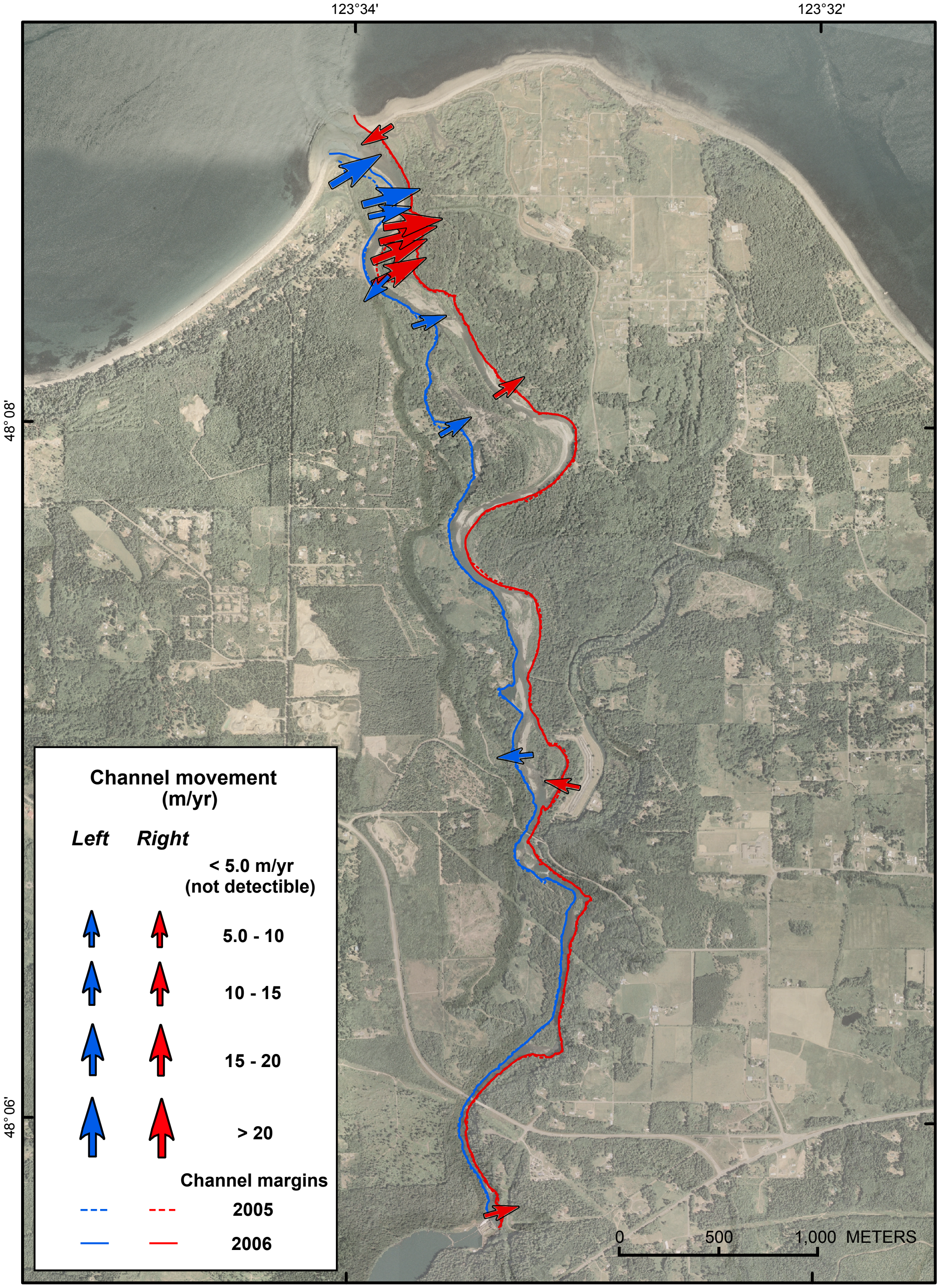

Figure 14. Channel change on the lower Elwha River, Wash. (fig. 1), between 2005 and 2006. Blue and red arrows indicate net movement in position of river-left (western) and river-right (eastern) active-floodplain margins, respectively, with size of arrows indicating magnitude and direction of channel movement. Channel movement of <5.0 m/yr is within error margin of analysis and so is not represented by arrows. Photographs taken in 2006, superimposed on airborne lidar image obtained in 2000 by the Puget Sound Lidar Consortium.

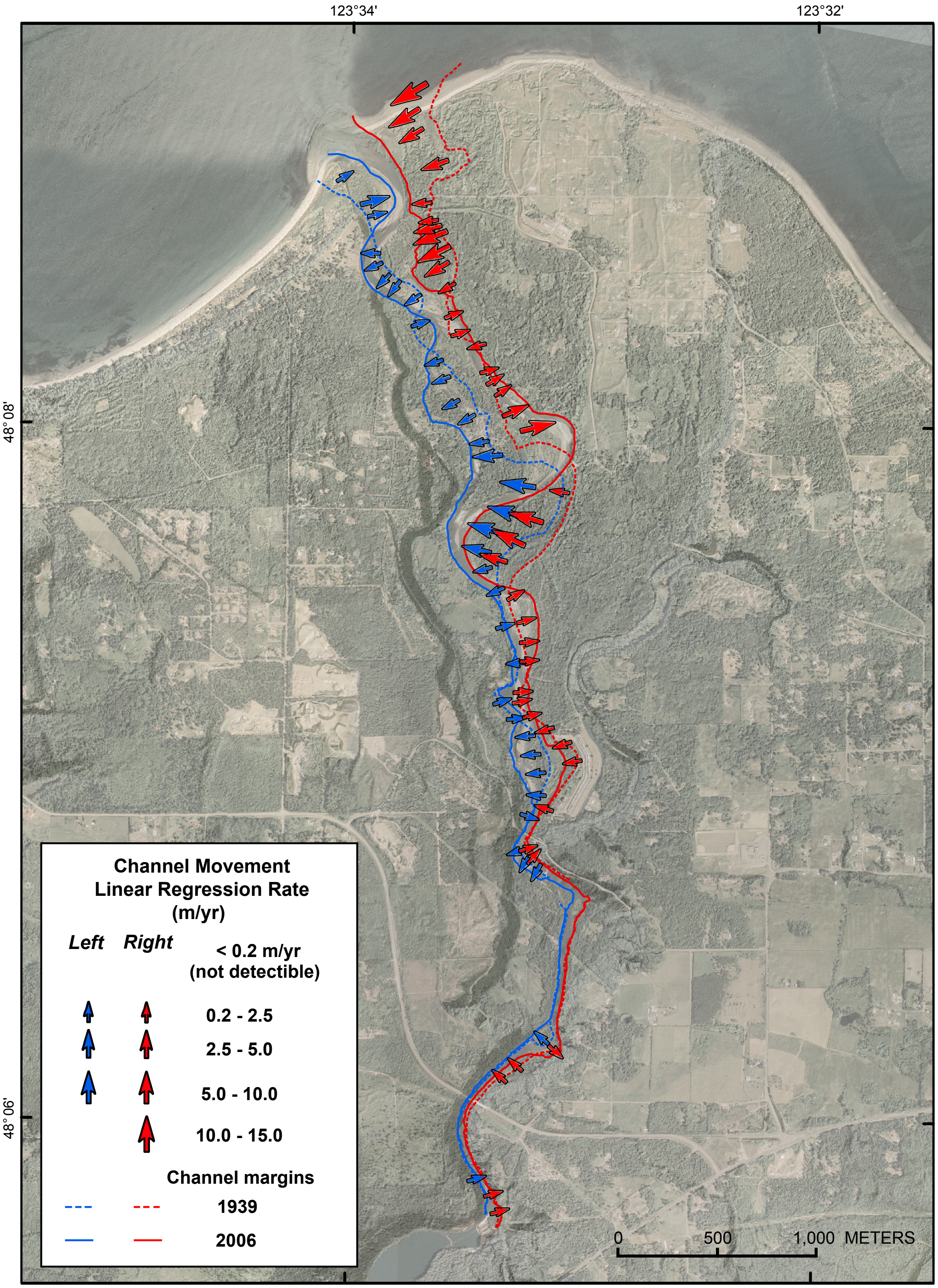

Figure 15. Channel change on the lower Elwha River, Wash. (fig. 1), between 1939 and 2006. Blue and red arrows indicate net movement in position of river-left (western) and river-right (eastern) active-floodplain margins, respectively, with size of arrows indicating magnitude and direction of channel movement. Channel movement of <0.2 m/yr is within error margin of analysis and so is not represented by arrows. Photographs taken in 2006, superimposed on airborne lidar image obtained in 2000 by the Puget Sound Lidar Consortium.

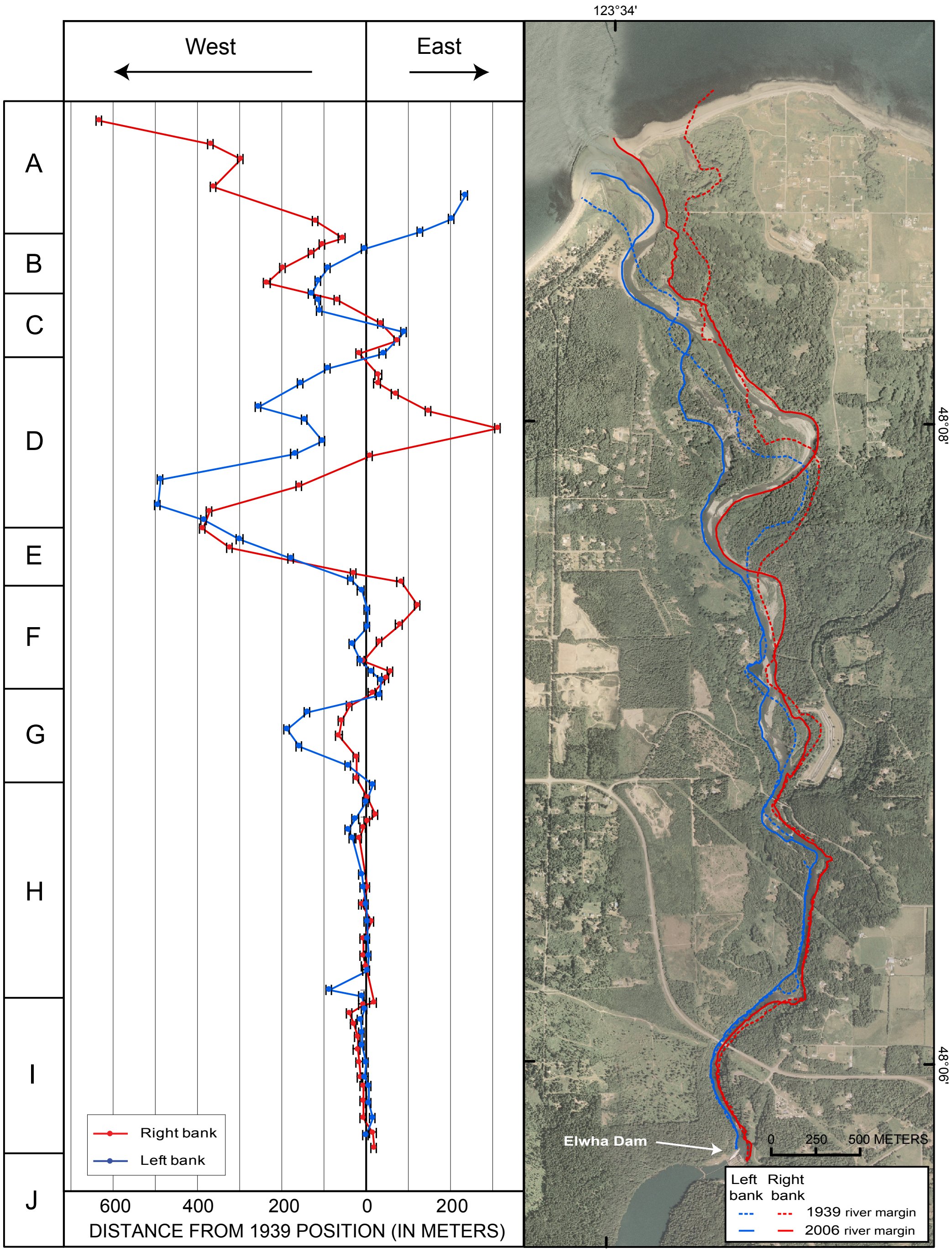

Figure 16. Net changes in channel position on the lower Elwha River, Wash. (fig. 1), between 1939 and 2006, showing position of left (western) and right (eastern) active-floodplain margins in 2006 relative to their 1939 position. Aerial photograph shows 1939 and 2006 active-floodplain margins superimposed on 2006 orthophotograph. Regions A–J labeled at extreme left indicate zones of channel evolution, as follows: A, narrowing of river mouth, largely caused by abandonment of an eastern distributary channel during the 1950s and early 1960s as a result of artificial channelization in 1950 (see fig. 17); B, westward shift of channel and meander migration into a large bluff at western channel margin (fig. 2*A*); C, meander migration with little widening or narrowing; D, substantial widening of active floodplain, meander migration, and major avulsion, which in this reach has occurred through both natural (late 1990s) and artificial (late 1940s) means (see fig. 18); E, predominantly westward shift of the active channel without substantial changes in width; F, moderate widening and eastward shift of the active floodplain; G, westward shift and widening of active floodplain, affected by water diversion to State-run fish hatchery, immediately east of river, and affected by artificial channel straightening in 1950 (Pohl, 1999); H, little change in floodplain morphology; I, bedrock canyon; little change in floodplain morphology; J, Lake Aldwell, reservoir upstream of Elwha Dam.

Table 2. 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 averaged for cross-channel transects spanning as much of the river length as was visible in each set of aerial photographs (a maximum of 64 transects, spaced at ~100-m intervals); asterisks indicate values that are less than the error calculated for that time step. Last row lists annualized rates of channel change for the entire study interval (1939–2006), calculated from a linear-regression analysis of transect positions in each of the time steps studied; rates of change for other time steps (other rows) were calculated as end-point rates of change]

Time step	Average absolute movement of left (western) bank (m)	Average absolute movement of right (eastern) bank (m)	Average annualized movement of left (western) bank (m/yr)	Average annualized movement of right (eastern) bank (m/yr)
1939–56	53	27	3.1	1.6
1956–65	33	92	3.7	10
1965–71	17*	34	2.8*	5.6
1971–77	23*	36	3.9*	6.0
1977–81	54	28	13	7.2
1981–90	17*	31	2.0*	3.5
1990–94	12*	16*	3.1*	4.2*
1994–2000	40	22*	6.4	3.5*
2000–2	5.8*	8.4*	2.9*	4.3*
2002–5	13*	7.6*	4.4*	2.5*
2005–6	6.6*	15	4.9*	11
1939–2006	**85**	**89**	**1.1**	**1.5**

Table 3. 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 aerial photographs (26 cross-channel transects, spaced at ~100-m intervals, in regions A–E, fig. 16). Asterisks indicate values that are less than the error calculated for that time step. Last row lists annualized rates of channel change for the entire study interval (1939–2006), calculated from a linear-regression analysis of transect positions in each of the time steps studied; rates of change for other time steps (other rows) were calculated as end-point rates of change]

Time step	Average absolute movement of left (western) bank (m)	Average absolute movement of right (eastern) bank (m)	Average annualized movement of left (western) bank (m/yr)	Average annualized movement of right (eastern) bank (m/yr)
1939–56	65	31	3.8	1.8
1956–65	46	140	5.1	15
1965–71	24	56	3.9	8.9
1971–77	32	58	5.4	9.6
1977–81	56	26	14	6.5
1981–90	16*	24	1.8*	2.6*
1990–94	15*	21*	4.1*	5.7*
1994–2000	87	42	14	6.7
2000–2	7.6*	7.4*	3.8*	3.8*
2002–5	24	8.1*	7.8	2.7*
2005–6	11	30	8.2	22
1939–2006	160	150	2.0	2.6

lateral movement by tens to hundreds of meters occurred between 1939 and 2006, exceeding 400 m at some sites on the floodplain (fig. 16), with the greatest change evident 2 to 3 km upstream of the river mouth (region D, fig. 16) due to meander migration, avulsion of new channels, and at least one incident of artificial meander cutoff, in 1947 (Johnson, 1994, fig. 4).

Absolute and annualized rates of change in channel position over each time step, averaged among transects that spanned as much of the river length as was visible in each set of aerial photographs (a maximum of 64 possible transects; the upstream extent of each set of photographs is shown in figs. 4–15) are listed in table 2. Because not all sets of aerial photographs covered the same parts of the floodplain, these analyses were repeated using only those parts of the floodplain common to all sets of aerial photographs, as listed in table 3 (26 of the 64 transects, spanning regions A–E, fig. 16). Absolute channel change and annualized rates of change in channel position are greater in table 3 than in table 2 because the floodplain area common to all sets of aerial photographs includes the lowermost part of the alluvial floodplain, where the greatest channel change occurred, and excludes the bedrock canyon (fig. 1*B*), where the least change occurred.

Discussion

Channel Evolution on the Lower Elwha River

Changes in the morphology of the active Elwha River floodplain are a function of channel response to seasonally varying discharge, as well as to manmade floodplain modification. Along the lowermost ~3 km of the alluvial floodplain, absolute changes in the positions of channel margins averaged ~160 m between 1939 and 2006 (table 3). During this analysis, some subjectivity was inherent in identifying active-floodplain margins when a particular channel was being abandoned. Although new channels can be occupied suddenly in response to a single flood event, older channels are generally not abandoned instantaneously and may still appear to be active (unvegetated) in subsequent photographs even though newer avulsions have captured most of the flow. Numerous changes in channel position have occurred by migration of meander bends (progressive erosion of cutbanks toward the outer bend in a downstream direction), as well as by avulsion of new channels, a process that commonly occurs in anabranching rivers as the flow forms a new path around such obstacles as large woody debris and associated sedimentary deposits (figs. 17–19).

Beginning in the 1940s, channel migration on the lower river was affected not only by hydrology but also by manmade modification of the floodplain. In one of the largest projects, a north-trending artificial meander cutoff ~1 km long was excavated in 1947 by Clallam County to reduce the flood risk east of the natural (eastward migrating) meander there (Johnson, 1994, fig. 4). Over the next 5 decades, the artificially straightened channel evolved into a new meander pair as the channel adopted an increasingly northeastward trend (figs. 5–10) until a new, natural avulsion occurred to the west between 1994 and 2000 (figs. 11, 18). Another major channel shift occurred between 1939 and 1965 1 to 1.5 km upstream of the river mouth, as the distributary system on the Elwha delta switched gradually from having two major active channels to occupying only the western channel (figs. 5, 17). Abandonment of the eastern channel may have been partly a natural occurrence, but was largely due to artificial channel diversion (dike construction in 1950; Pohl, 1999). The former eastern distributary channel now comprises tidal ponds and wetlands (fig. 17*D*).

In 1964, Clallam County sponsored the construction of a levee west of the river mouth (fig. 17); the western margin of the lowermost river channel was bounded directly by this levee in aerial photographs from 1990 and 2005 (figs. 9, 13). A similar dike, set back from the river on its east side, was built by the U.S. Army Corps of Engineers in 1985 (fig. 17). Other engineering works on the lower river have included construction of an outfall channel from the tribal fish hatchery, perpendicular to the river on its east side (region A, fig. 16), and construction of a weir and diversion channels for a State-run fish hatchery ~4.5 km above the river mouth (region G, fig. 16). Private-party landowners also used bulldozers to modify channel boundaries repeatedly between the 1950s and 1980s (regions C–F, fig. 16; Johnson, 1994; Pohl, 1999).

The time step between 1977 and 1981 encompassed greater-than-usual annualized rates of change in channel position on both the eastern and western margins of the lower Elwha River (table 3). This 4-year interval included two winter floods that were the largest such events between 1955 and 1990, with daily averaged discharges of 535 m^3/s on December 17, 1979, and 558 m^3/s on December 26, 1980. Channel change between 1977 and 1981, attributed largely to those two major floods, included westward and eastward migration of two successive meanders centered ~2.5 km upstream of the river mouth, and an eastward shift (avulsion) of the left channel margin by >160 m along nearly 1 km of river length (mean shift as measured at 6 transects; see fig. 8).

We note that, particularly when analyzing flood response, a nonrandom sampling interval (temporal spacing of aerial photographs) affects the calculated annualized rates of change in channel position. Most of the apparent rapid channel change measured on aerial photographs taken on July 1, 2005, and November 7, 2006 (table 3), for example, is attributable to a flood with a daily averaged discharge of 374 m^3/s on November 6, 2006. Resources have been available in recent years for event-response photographic missions such as in November 2006. More frequent aerial photography in response to floods effectively increases the ability to detect rapid and episodic channel change. If the interval between aerial photographs had been longer and encompassed other, relatively dry years, the geomorphic effects of the November 2006 flood would have been less apparent in this analysis, and the annualized rate of change in channel position, would have been lower. Therefore, calculating truly representative annual rates of change in channel position, and resolving the geomorphic effects of individual floods, are complicated by variation in sampling (aerial photographic) intervals that are sometimes, but not always, dictated by the timing of floods.

Geomorphic evolution of the lower Elwha River since 2000 may have been affected by the placement of engineered logjams that were constructed to reduce bank erosion and to improve habitat for salmonid fish (McHenry and others, 2007). The 21 engineered logjams, with a total wood volume of more than 2,000 m^3, resulted in an increase in fine-sediment storage in the lee of the logjams, primarily in scour pools that developed after the logjams were emplaced. The presence of new pools and woody debris promoted significantly greater primary productivity in the vicinity of these engineered logjams, which are used as spawning habitat by salmonid fish (Chinook, chum, and coho salmon and steelhead; McHenry and others, 2007).

The rates and patterns of channel movement on the lower Elwha River (tables 2 and 3) are comparable to those reported on the undammed Quinault and Queets Rivers on the west side of Washington's Olympic Peninsula (O'Connor and others, 2003), both of which are wider than the Elwha River—mean floodplain width is ~1250 m on the Queets and lower Quinault Rivers and ~2470 m on the upper Quinault River, in comparison to 50–720 m on the lower Elwha River in 2006—and both of which receive more runoff than the Elwha River, owing to higher rainfall on the west side of the Olympic Mountains. Annualized rates of change in channel position on the lower Quinault River, based on cross-channel transect measurements, were 5.0±3.9 m/yr between 1902 and 1997 (O'Connor and others, 2003). The Queets River yielded similar rates, 5.6±4.5 m/yr between 1900 and 1994, and underwent the most substantial migration because of meander and cutoff of five large meander loops (O'Connor and others, 2003). Transects across the upper Quinault River indicated annual channel-migration rates of 8.8±4.1 m/yr between 1902 and 1994 (O'Connor and others, 2003).

Potential Effects of Dam Removal on the Lower Elwha River

This study is intended to provide a dataset against which post-dam-removal channel evolution can be compared. According to the environmental-impact statement, increased sediment influx from the two reservoirs (Lakes Aldwell and Mills) after dam removal will induce aggradation and fining of the bed below the dams, and the lower river could respond to the new sediment supply by changing from an anabranching

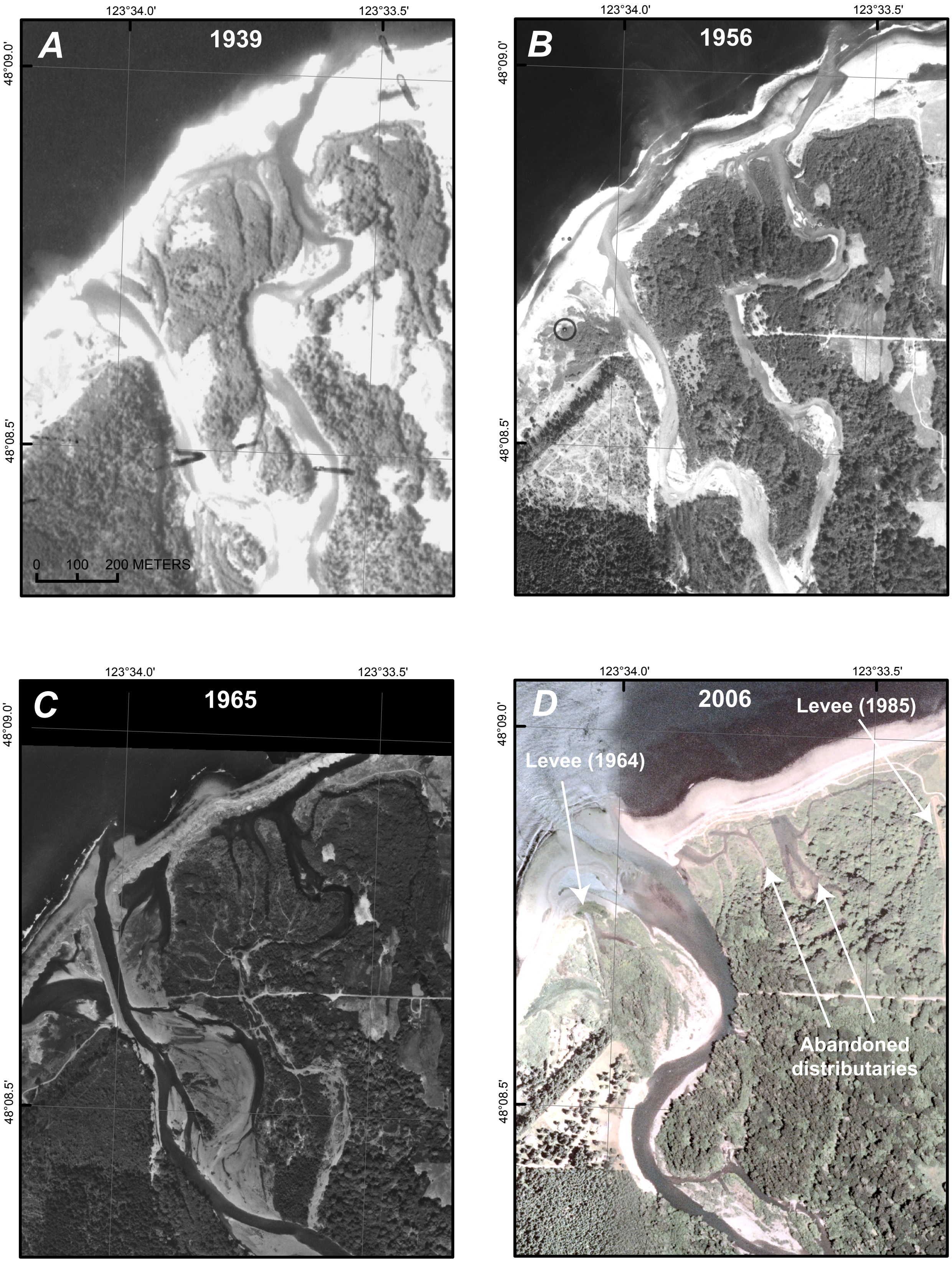

Figure 17. Aerial photographs of the Elwha River mouth, Wash. (fig. 1), in 1939 (*A*), 1956 (*B*), 1965 (*C*), and 2006 (*D*). Flood-control levees in figure 17*D* were emplaced by Clallam County in 1964 (west of river mouth) and by the U.S. Army Corps of Engineers in 1985 (set-back dike east of river). Tidal ponds and wetlands occupy sites of former distributary channels. Artificial channel diversion in 1950 promoted abandonment of eastern distributary channel (Pohl, 1999).

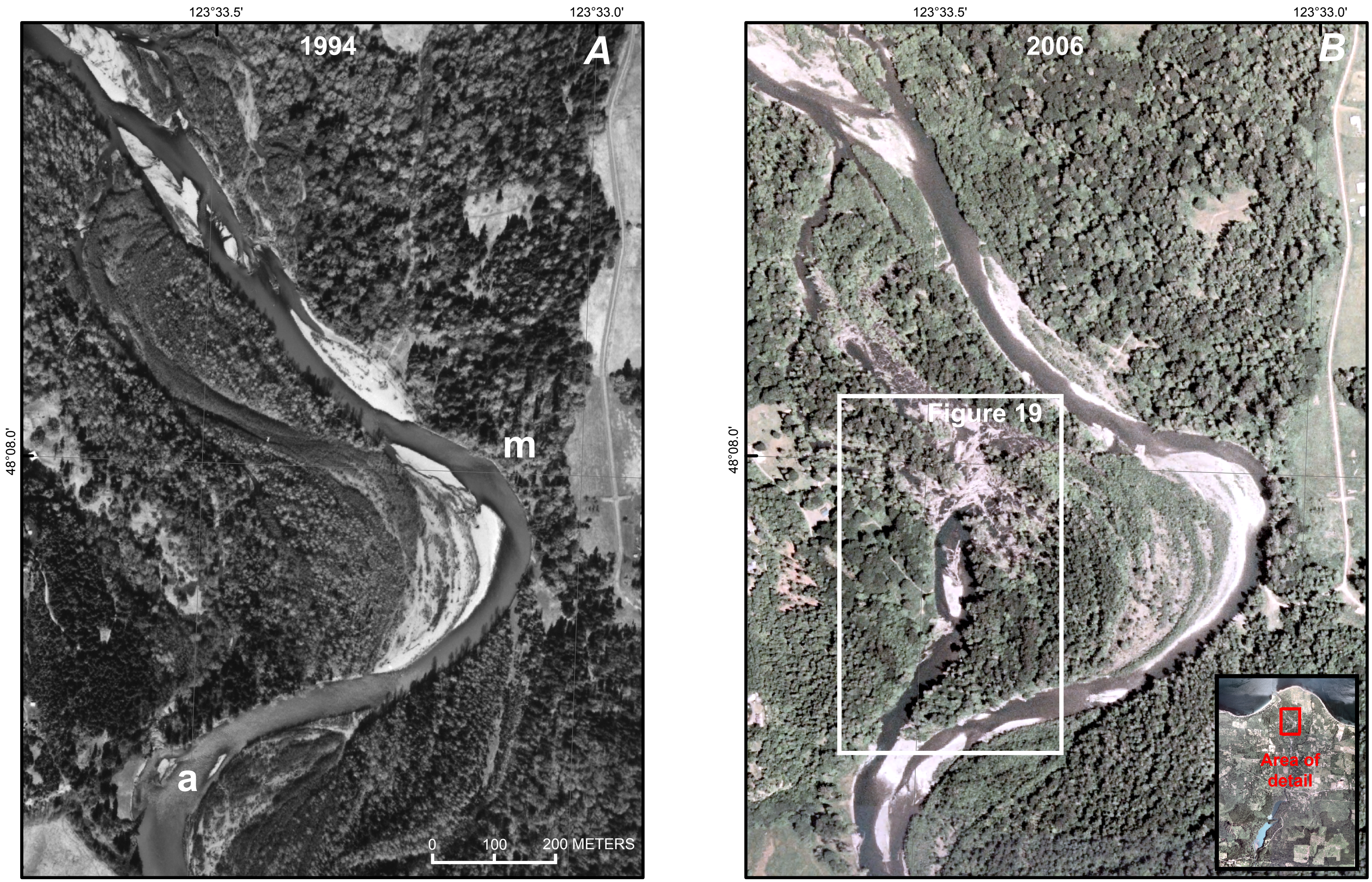

Figure 18. Aerial photographs of meanders on the Elwha River, Wash. (fig 1), in 1994 (*A*) and 2006 (*B*), showing examples of meander migration and channel avulsion. Meander m has migrated consistently eastward and downstream throughout study interval (figs. 15, 16), though temporarily slowed by interaction with an earlier, artificial cutoff (fig. 5). Major avulsion of a new, western channel from site a occurred between 1994 and 2000. By 2002, western channel had widened substantially and encompassed a large logjam (white box), part of which is shown in figure 19.

channel to a more braided system, at least temporarily, as the pulse of sediment is accommodated and a new equilibrium is reached (Randle and others, 1996). Such predictions are based on documented responses of other fluvial systems to increased sediment load (Smith and Smith, 1984; Wohl and Cenderelli, 2000; Bushaw-Newton and others, 2002; Doyle and others, 2002; Grant and others, 2003; Randle, 2003; Rathburn and Wohl, 2003). The local magnitude, spatial distribution, and longevity of channel-bed aggradation that might occur are unknown, and the accuracy of any attempts to predict specific local responses is uncertain (Doyle and others, 2002; Pizzuto, 2002) because these parameters depend not only on channel geometry but also on the flows that will follow sediment input (Wohl and Cenderelli, 2000). Present and future studies on the Elwha River provide an important opportunity to study watershed response to a large, regulated influx of sediment, and should generate a body of research relevant to the anticipated increase in the number of dam-removal projects over the coming decades. Analysis of new aerial photographs will continue until, and after, dam removal and will be supplemented by field surveys of channel transects several times per year to generate a comprehensive picture of geomorphic evolution.

Conclusions

Analyses of historical aerial photographs reveal episodic and spatially substantial changes in channel position and form on the Elwha River below Elwha Dam between 1939 and 2006. Absolute positional changes of active-floodplain margins commonly exceeded 50 m over that time interval, and have exceeded 400 m locally. Annualized rates of change in channel position on the alluvial floodplain were typically ~2 to 10 m/yr; higher annualized rates are, over some time intervals, attributable to unusually high winter floods that can cause episodic channel avulsion and pronounced lateral migra-

Figure 19. Large logjam 1.8 km upstream of the Elwha River mouth, Wash. (fig. 1), in western of two main channels. Photograph by T. Roorda of Northwestern Territories, Inc., taken April 4, 2007.

tion of meander bends. Manmade modification of the floodplain between the 1940s and 1980s also substantially changed channel form and position. Rates of channel movement on the lower Elwha River are comparable to those measured on the Queets and Quinault Rivers on the west side of the Olympic Peninsula. Quantifying the rates and patterns of channel change on the dammed Elwha River provides an important basis against which to compare channel evolution after dam removal, part of a major river-restoration project planned to occur within the decade.

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