Chapter 3

Geomorphology of the Elwha River and its Delta

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Abstract

The removal of two dams on the Elwha River will introduce massive volumes of sediment to the river, and this increase in sediment supply in the river will likely modify the shapes and forms of the river and coastal landscape downstream of the dams. This chapter provides the geologic and geomorphologic background of the Olympic Peninsula and the Elwha River with emphasis on the present river and shoreline. The Elwha River watershed was formed through the uplift of the Olympic Mountains, erosion and movement of sediment throughout the watershed from glaciers, and downslope movement of sediment from gravitational and hydrologic forces. Recent alterations to the river morphology and sediment movement through the river include the two large dams slated to be removed in 2011, but also include repeated bulldozing of channel boundaries, construction and maintenance of flood plain levees, a weir and diversion channel for water supply purposes, and engineered log jams to help enhance river habitat for salmon. The shoreline of the Elwha River delta has changed in location by several kilometers during the past 14,000 years, in response to variations in the local sea-level of approximately 150 meters. Erosion of the shoreline has accelerated during the past 80 years, resulting in landward movement of the beach by more than 200 meters near the river mouth, net reduction in the area of coastal wetlands, and the development of an armored low-tide terrace of the beach consisting primarily of cobble. Changes to the river and coastal morphology during and following dam removal may be substantial, and consistent, long-term monitoring of these systems will be needed to characterize the effects of the dam removal project.

Introduction

The removal of the Elwha and Glines Canyon Dams will introduce massive volumes of sediment into the Elwha River, some of which will be transported to the Strait of Juan de Fuca coastal waters. This sediment perturbation will likely modify the shapes and forms, that is, the "geomorphology," of the landscape downstream of the dams. One important step to characterizing these future changes is a thorough description of the present geomorphology of the Elwha River and its coast. If these changes are not measured and described, future changes to the river, flood plain, and coastal landforms cannot be tracked, and the effects of the dam removal will remain unknown.

The present geomorphology of the Elwha River results from an uplifting mountain range, large changes in sea level, former alterations to the landscape by glaciers, and continual modification and movement of materials by winds, waves, rain, snow, river discharge, and the force of gravity. The watershed has also been modified by human activity, most notably from the two large dams that prevent sediment movement down the river. Less obvious, but also important, are the numerous human alterations to the river channel.

This chapter introduces the geomorphic setting of the Elwha River and its coast, explores the recent history of the Elwha River and its delta, and describes the effects that human intervention has had on these systems. This geomorphic framework will help track future changes to this system after the dams are removed.

Geologic Setting

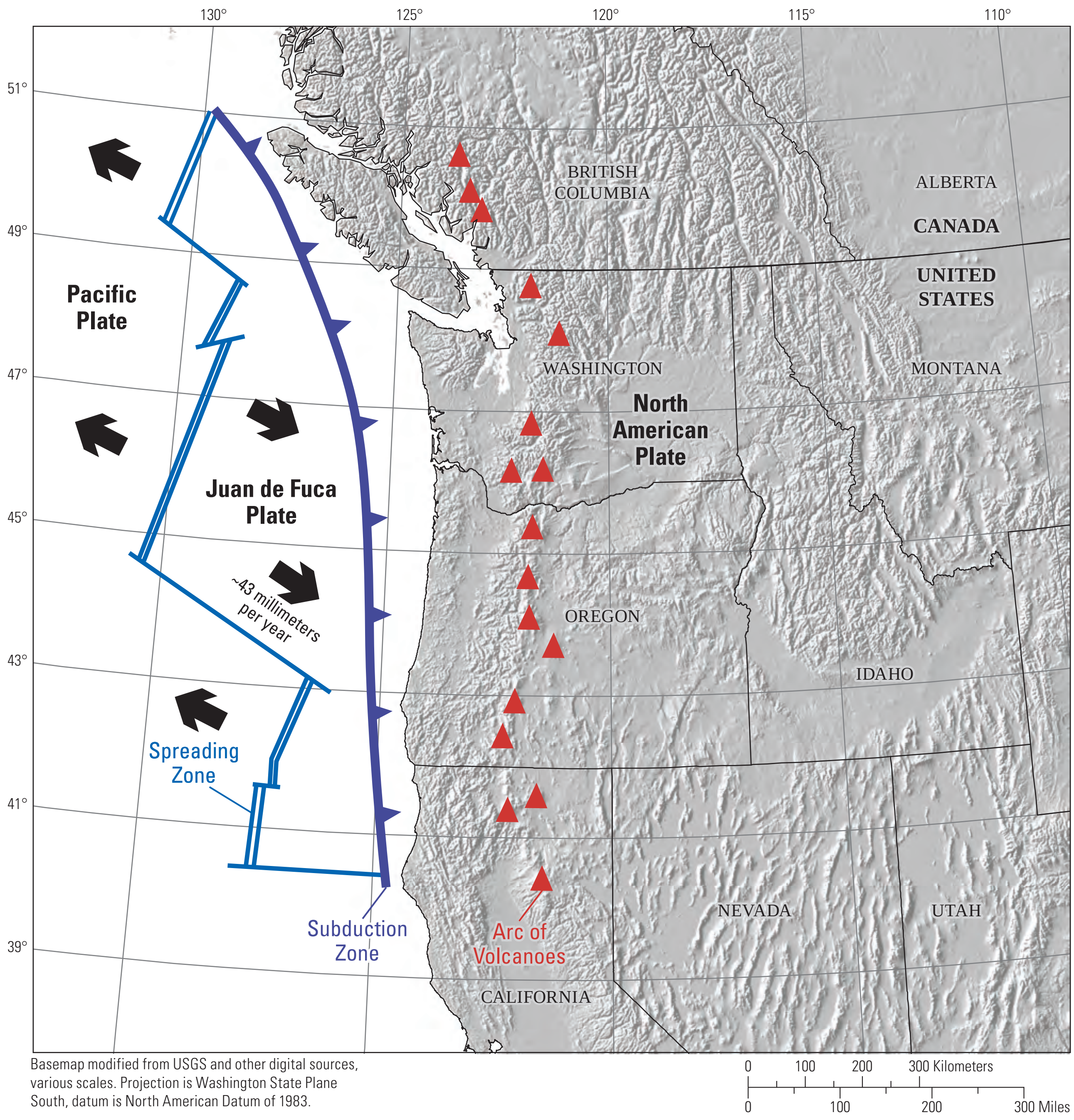
Tectonics

The steep and glaciated Olympic Mountains include some of the highest coastal peaks along Cascadia and form the headwaters of the Elwha River drainage basin. These mountains were formed by the convergence of the oceanic Juan de Fuca plate with the continental North American plate through the Cascadia subduction zone (fig. 3.1). As the Juan de Fuca plate converged with the North American plate at a rate of approximately 43 mm/yr, part of the oceanic rocks and sediments accreted onto the front of the North American plate rather than subducting under it. The Olympic Mountains are the highest part of this "accretionary wedge" of marine rocks that spans the majority of the Cascadia subduction zone (fig. 3.1).

Evidence for the accretion of marine rocks abounds throughout the mountainous terrain of the Olympic Peninsula, where the primary rock types are slightly altered sedimentary (that is, "metasedimentary") rocks that originated underneath the seafloor (fig. 3.2). These uplifted rocks are known as the Olympic subduction complex (OSC; Brandon and others, 1998), which is an exposed part of the accretionary wedge that underlies most of the offshore continental margin (Stewart and Brandon, 2004). The deformed phyllites and schists that make up the OSC were originally deposited on the seafloor in Eocene to Miocene time (55.8 to 5.3 million years before present [BP]) as a result of numerous sediment-laden turbidity currents plunging down the continental slope into deep water (Orange and others, 1993; Brandon and others, 1998; U.S. Geological Survey Geologic Names Committee, 2010).

A distinct boundary exists between the sedimentary rocks of the OSC and the Coast Range terrane (CRT; Brandon and others, 1998), which are sequences of volcanic and sedimentary rocks (fig. 3.2). The CRT also was formed in the ocean, as evidenced by its marine sedimentary rocks and pillow basalts, the latter being the result of underwater volcanism. The structural boundary between the older CRT and the OSC is the extensive Hurricane Ridge Fault and its equivalents (Tabor and Cady, 1978; Gertsel and Lingley, 2003; Polenz and others, 2004). Because the Hurricane Ridge Fault crosses the Elwha River basin near Lake Mills (fig. 3.2), bedrock lithology of the Elwha River basin upstream of Lake Mills differs substantially from the basin downstream of Lake Mills.

Over geologic time, the rocks of the central Olympic Mountains are uplifting at a rate of approximately 0.6 mm/yr (Brandon and others, 1998; Batt and others, 2001). This uplift of the Olympic Mountains maintains steep slopes in the Elwha River watershed and erosional processes such as rockfalls, shallow and deep landslides, and debris flows that generate substantial quantities of sediment for the river (Montgomery and Brandon, 2002; Acker and others, 2008). The rate of tectonic uplift in the Elwha River watershed decreases between the central Olympic Mountains and the coast to rates of less than 0.3 mm/yr (Tabor and Cady, 1978; Brandon and others, 1998; Polenz and others, 2004).



Basemap modified from USGS and other digital sources, various scales. Projection is Washington State Plane South, datum is North American Datum of 1983.

Figure 3.1 Generalized plate tectonics map of the Cascadia subduction zone of North America.

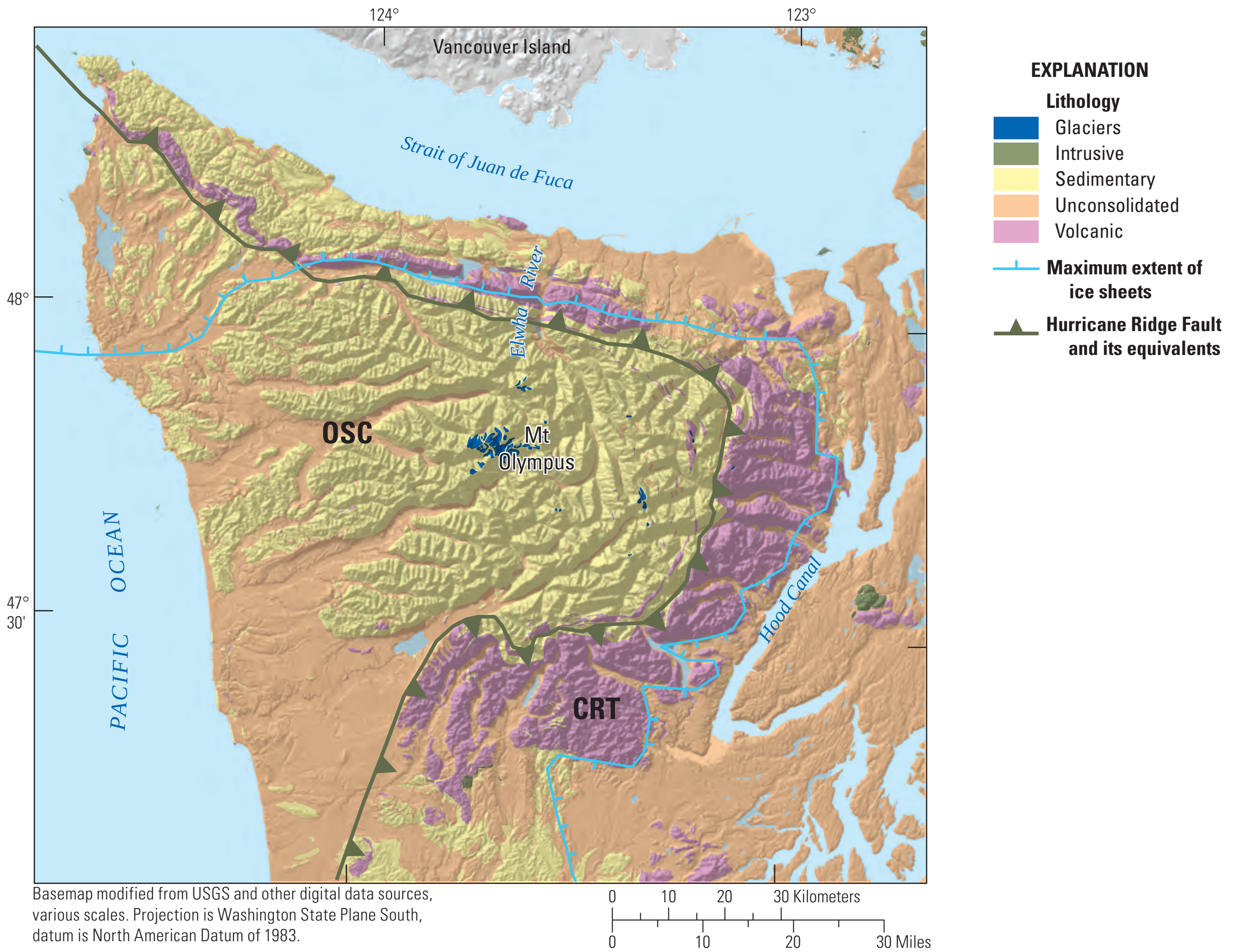


Figure 3.2 Generalized geological map of the Olympic Peninsula, Washington. The fault between the Olympic subduction complex (OSC) and the Coast Range terrane (CRT; Brandon and others, 1998) is shown with a green line. Maximum extent of the most recent Cordilleran ice sheet was to the north and east of the blue line. Map created after Tabor (1987), Brandon and others (1998), and Schuster (2005).

Glacial Processes During the Quaternary Period

Profound new forces at the close of the Pliocene (approximately 2.6 million years ago) shaped the uplifted rocks of the Olympic Mountains. Sweeping down from their northern source in the highlands of British Columbia, massive continental ice sheets buried the Puget Sound and its margins. At the same time, valley glaciers sourced in the hinterlands of the Olympic Mountains carved out deep U-shaped troughs in the valleys (Easterbrook, 1986; Batt and others, 2001; Mosher and Hewitt, 2004). In the most recent glacial episode, these valley glaciers reached their maximum extent at about 19,000 years BP (Easterbrook, 1986), before being overridden at their margins by the ice sheets advancing from the north. At about 14,000 years BP, the continental ice sheet reached its maximum extent, approximately 11 km inland of the present coastline in the region of the lower Elwha River watershed (fig. 3.2). The maximum thickness of the ice sheet has been estimated to be 1,900 m in the central Strait of Juan de Fuca (McNulty, 1996; Porter and Swanson, 1998; Mosher and Hewitt, 2004; Polenz and others, 2004). The weight of the ice sheet depressed the land surface, sinking the ground surface almost 150 m in the region of the Strait (Mathews and others 1970; Waitt and Thorson, 1983; Dethier and others, 1995; Huntley and others, 2001). The land surface rose quickly as the ice retreated northward toward Canada, recovering much of its former elevation after about 2,000 years.

Remnants of the ice age persist today as small alpine glaciers around Mount Olympus (fig. 3.2). Additional evidence of the ice age is scattered widely across the Olympic Mountains, particularly where the Juan de Fuca continental ice lobe repeatedly dammed the waters of the Elwha River watershed, creating a lake in the lower Elwha River watershed. Sediment deposits from this pro-glacial lake, with poorly sorted, poorly stratified glacial outwash alluvium and stratified sediment dominated by silt and clay, are visible today in bluff exposures along the lower Elwha River and may represent the most substantial modern sources of sediment downstream of Elwha Dam (Tabor, 1975, 1987; McNulty, 1996; Polenz and others, 2004).

Profile of the Elwha River

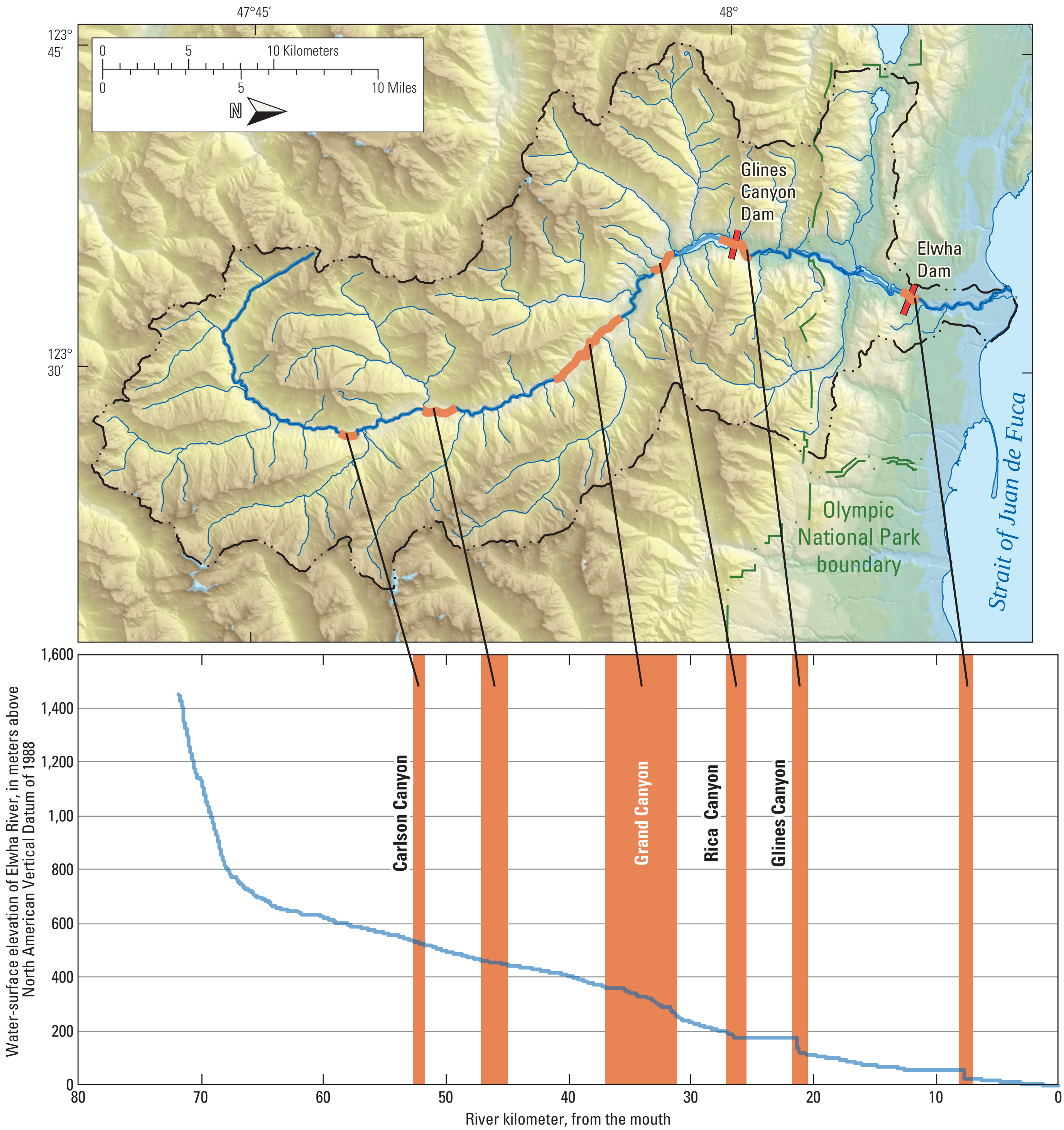
Wherever the waters of the Elwha River cross over the hard, folded rocks of the ancient accretionary wedge, the river is confined within bedrock canyons. Between these canyon segments, wide valleys of alluvium create conditions for active bank erosion and frequent channel migration (Kloehn and others, 2008; Draut and others, 2011). The longitudinal profile of the Elwha River is steepest in the headwaters and flattest near sea level (fig. 3.3). Below approximately 600 m elevation, the slope of the Elwha River is roughly constant at about 0.009 until the Lake Mills delta. There are short, steeper reaches within the Grand Canyon of the Elwha River and Rica Canyon, where the river slope increases to about 0.006. Between Glines Canyon Dam and the coast, the river slope decreases to an average of approximately 0.0013, and the flattest part of the river is immediately upstream of the river mouth (fig. 3.3). The two reservoirs formed by Glines Canyon Dam and Elwha Dam create prominent steps in the longitudinal water surface profile, which will be removed through the lowering of the reservoirs and the erosion of sediment that should follow dam removal.

Lower Elwha River Morphology

The final 7.8 kilometers of the river between the Elwha Dam and the Strait of Juan de Fuca is the flattest reach and is termed the “lower river” (fig. 3.4). This final reach is the most heavily altered reach of the river and will experience the largest effects of renewed sediment supply following dam removal (Draut and others, 2008; Konrad, 2009).

The upper 1.3 km of the lower river lies within a bedrock gorge, and the lowermost 6.5 km is within a broad alluvial flood plain (fig. 3.4). The river channel splits into two to three narrower channels for much of the alluvial section, a planform morphology called “anabranching” (compare to Smith and Smith, 1980; Harwood and Brown, 1993; Knighton and Nanson, 1993). Gravel bars and vegetated islands separate these narrow channels (Pohl, 1999, 2004; Draut and others, 2008; Kloehn and others, 2008). Unconsolidated sediment of these bars and islands contains large proportions of reworked glacial materials that are poorly sorted and have grain sizes ranging from silt and clay to cobbles (Draut and others, 2011).

An anabranching river such as the lower Elwha is understood to be distinctive from single-channel meandering rivers and braided rivers but has elements of both (fig. 3.5). Islands in anabranching rivers can be large relative to the width of the channel and commonly are stable over decades and even centuries. Individual channels meander or may exhibit smaller-scale braiding but eventually rejoin together (Knighton, 1998). Processes that cause anabranching are not fully understood.



Base map modified from USGS and other digital sources, various scales. Projection is Washington State Plane South. Datum is North American Datum of 1983.

Figure 3.3. Longitudinal profile of the water-surface elevation of the main-stem Elwha River calculated from a 10-meter digital elevation model of the Olympic Peninsula, Washington.

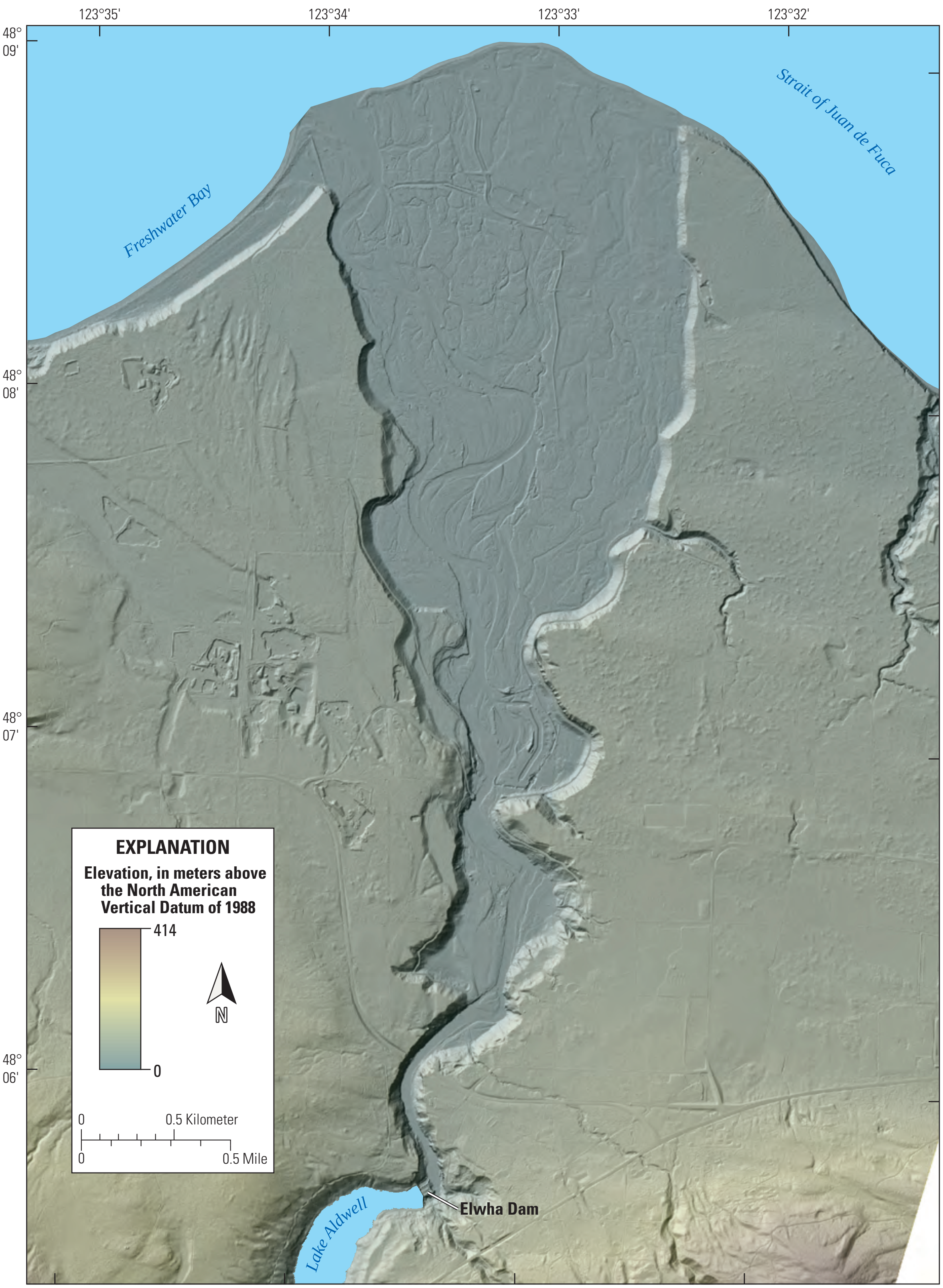


Figure 3.4. Topography of the flood plain and delta of lower Elwha River, Washington. Lidar survey dated between April 4 and 6, 2009, by Terra Remote Sensing, Inc. Horizontal resolution is 1.8 meters.

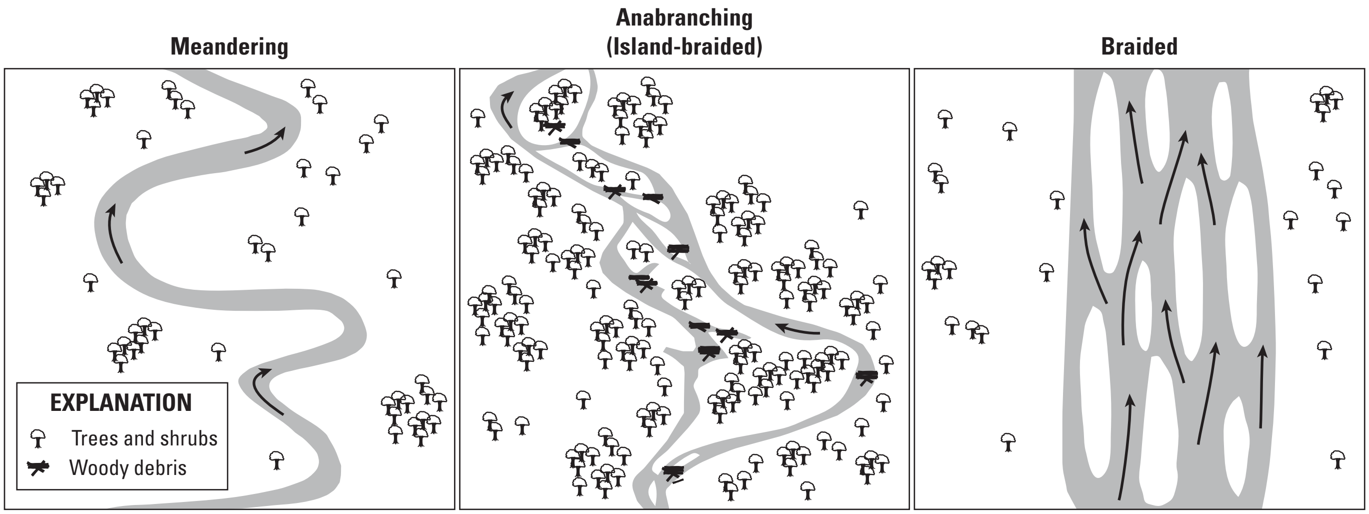


Figure 3.5. Schematic diagrams showing channel planforms for meandering to braided geomorphic types. The lower Elwha River is characterized as anabranching, which has characteristics of meandering and braided systems.

The total number of channels along a cross-section of the lower Elwha River varies between one and three. Large islands between the channels can be many times wider than the individual channels themselves and can persist for decades (Draut and others, 2008, 2011). The lower Elwha River is similar in size, shape, slope, and discharge rates to other anabranching rivers of the western Washington region described by Beechie and others (2006) (fig. 3.6), which suggests that this morphology is not unique for the region. The flood plain and islands of the lower Elwha River are heavily wooded. Initially these landforms are vegetated by alder and cottonwood trees, and older surfaces abound with secondary successional trees including spruce, hemlock, and cedar (for example, Beechie and others, 2006; Kloehn and others, 2008).

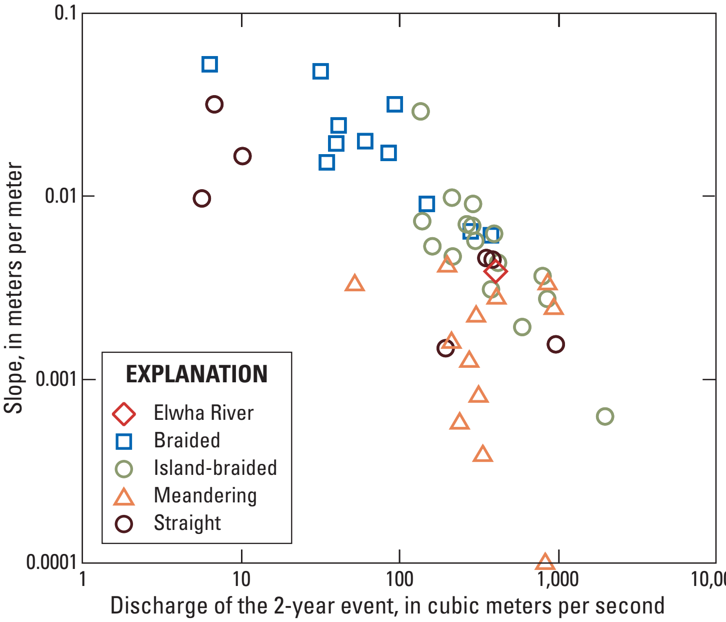


Figure 3.6. Comparison of the channel form of the lower Elwha River to 42 river reaches from other rivers in western Washington. Slope in the average slope of the river section and discharge is calculated as the 2-year peak discharge which represents an approximation of bankfull flow. Adapted from Beechie and others (2006).

Historical Channel Changes in the Lower River

Draut and others (2008, 2011) used 14 sets of sequential aerial photographs obtained between 1939 and 2009 to document historical changes to channel position and morphology in the lower Elwha River. The photographs provided evidence of effects from large floods and human modifications of the flood plain. Changes were greatest along the lowermost 3 km of the river, where absolute changes in the channel position between 1939 and 2009 averaged approximately 160 m and in some places measured as much as 660 m (Draut and others, 2011).

The centerline of the main channel has moved laterally in time due to the erosion of channel banks and the avulsion of new channels (fig. 3.7; Draut and others, 2011). Although new channels can form rapidly in response to high flow events or human modifications, the older "abandoned" channels often appear to be active (unvegetated) for several years after the avulsion, even though they receive little flow.

A few of the channel changes between 1939 and 2009 in the lowest part of the Elwha River are highlighted in figure 3.8. Most notably the two major active channels observed in the 1939 photograph were reduced to only one by 1965 (fig. 3.8). Dike construction in 1950 (Pohl, 1999) led to the abandonment of river flow into the formerly dominant eastern channel, although this eastern channel remained open to coastal waters for many years, as seen in the 1956 photograph (fig. 3.8*B*, see also fig. 3.7*A*). By 1965, the mouth of the abandoned eastern channel was closed (fig. 3.8*C*); this former channel became coastal lakes and wetlands that have served as salmonid rearing habitats or high-flow refugia when hydraulically connected to the river. The 1965 photograph also shows the effects of levee construction on the western side of the river mouth and straightening of the channel sponsored by Clallam County in 1964 (fig. 3.8*C*). This western levee redirected the river toward the north and cut off Dudley Pond from river and tidal flow.

Following construction of the 1964 west levee, the channel began to meander in the lowest 3 km ("C" in fig. 3.7). The rate of lateral channel migration in the final river meander has been measured at several meters per year from topographic surveys and aerial photographs (fig. 3.9). Most channel movement occurs during high flows of winter, and negligible channel change is observed during the summer.

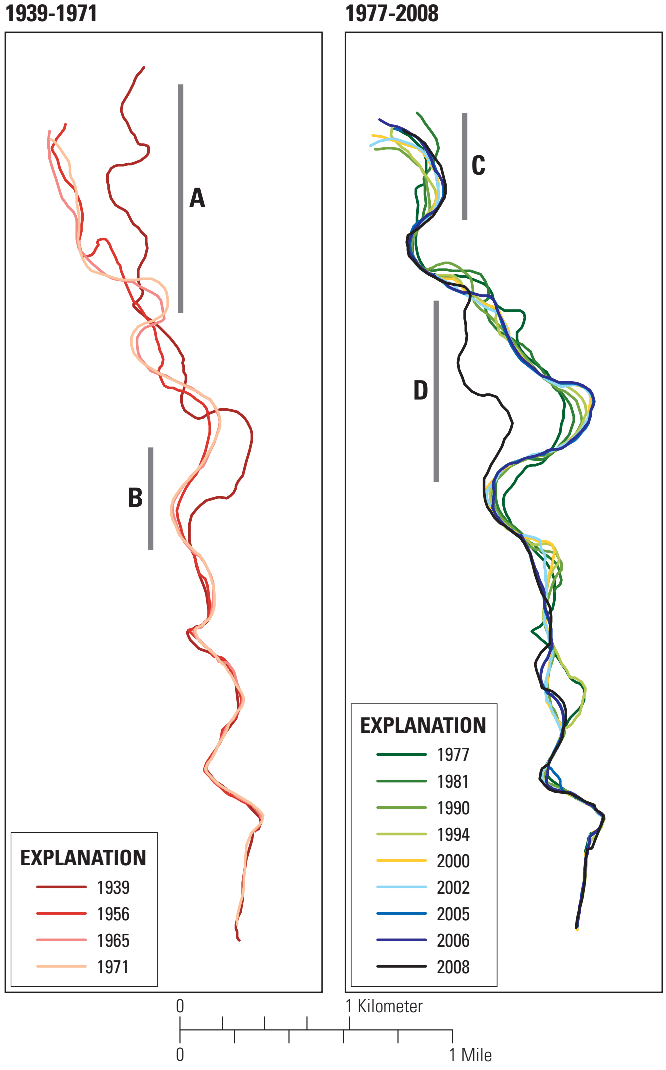


Figure 3.7. Historical changes in the location of the channel midline, Elwha River, Washington, during 1939–1971 and 1977–2008. The dominant channel was mapped in reaches where multiple channels were present (after Draut and others, 2011). Four historical changes to the lower river thalweg are described the text and labeled with *A*–*D*.

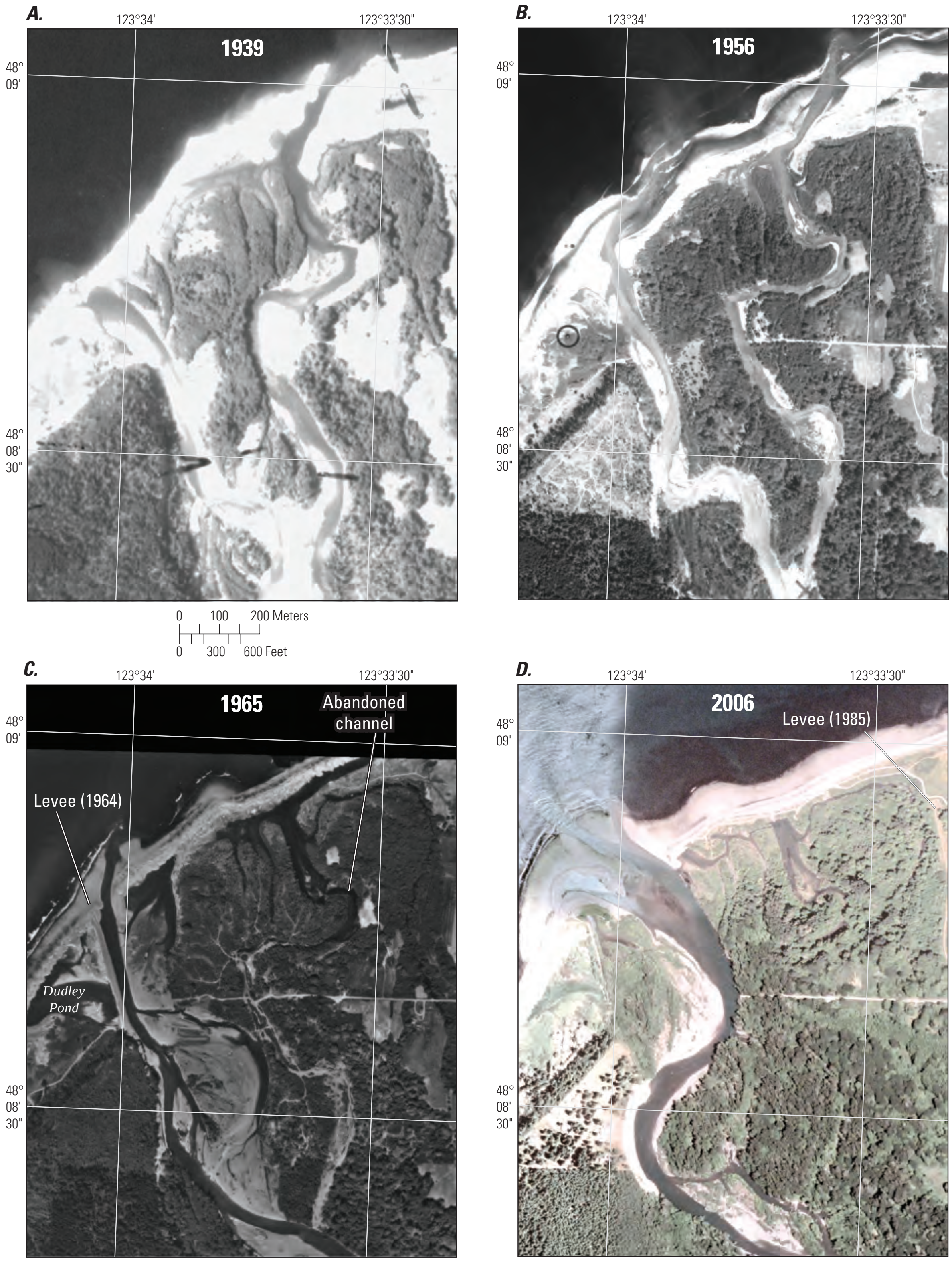


Figure 3.8. Aerial photographs showing effects of human modifications and channel meander and avulsion changes in the mouth of the Elwha River, Washington, between 1939 and 2006. (After Draut and others, 2008.)

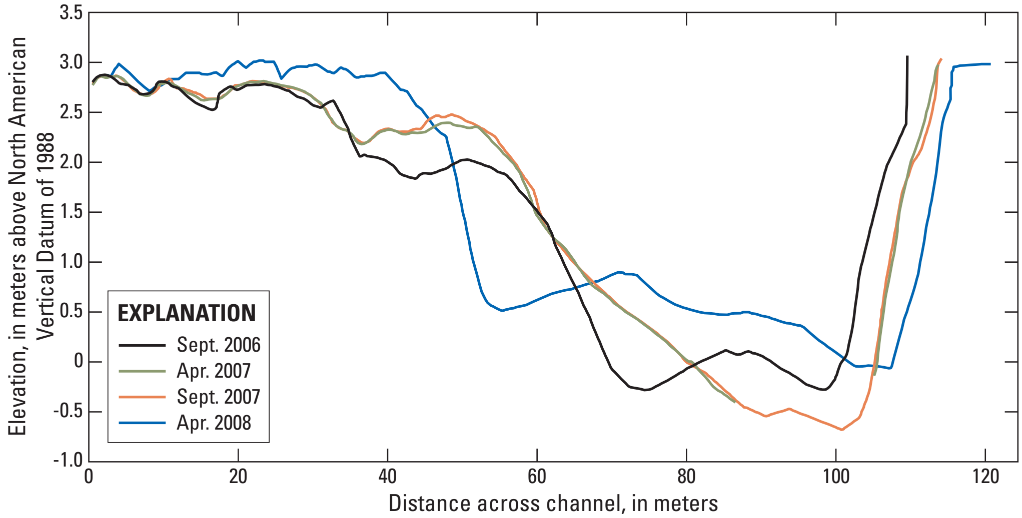


Figure 3.9. Measured channel change on the final meander showing several meters of lateral migration per year of the lower Elwha River, Washington. (After Draut and others, 2010.)

During the winter high flows between 1994 and 2000, an avulsion formed a new westernmost channel in the Elwha River; this new channel has been referred to as the Hunt Road Channel ("*D*" in fig. 3.7). A large flood in December 2007 broadened this new channel, after which most of river discharge flowed down the Hunt Road Channel (fig. 3.10). This 2007 flood also downed hundreds trees that accumulated in woody debris piles throughout this reach (fig. 3.11).

Several other human modifications have been made to the lower Elwha River during the 20th century. Additional modifications include the following:

1. Repeated bulldozing of channel boundaries by private-party landowners between the 1950s and 1980s;
2. Excavation of a north-trending artificial meander cutoff by Clallam County in 1947 to reduce the flood risk east of the natural (eastward migrating) meander ("*B*" in fig. 3.7);
3. Construction of a levee that is set back from the river on its east side by the U.S. Army Corps of Engineers in 1985 (fig. 3.8*D*);
4. Construction of an outfall channel leading from the tribal fish hatchery to the main river channel;
5. Construction of a weir and diversion channels for near the State-run fish hatchery about 4.5 km upstream of the river mouth (Johnson, 1994; Pohl, 1999; Draut and others, 2008); and
6. Restoration of in-stream habitat by the Lower Elwha Klallam Tribe primarily through the placement of large woody debris in channels (see sidebar 3.1).

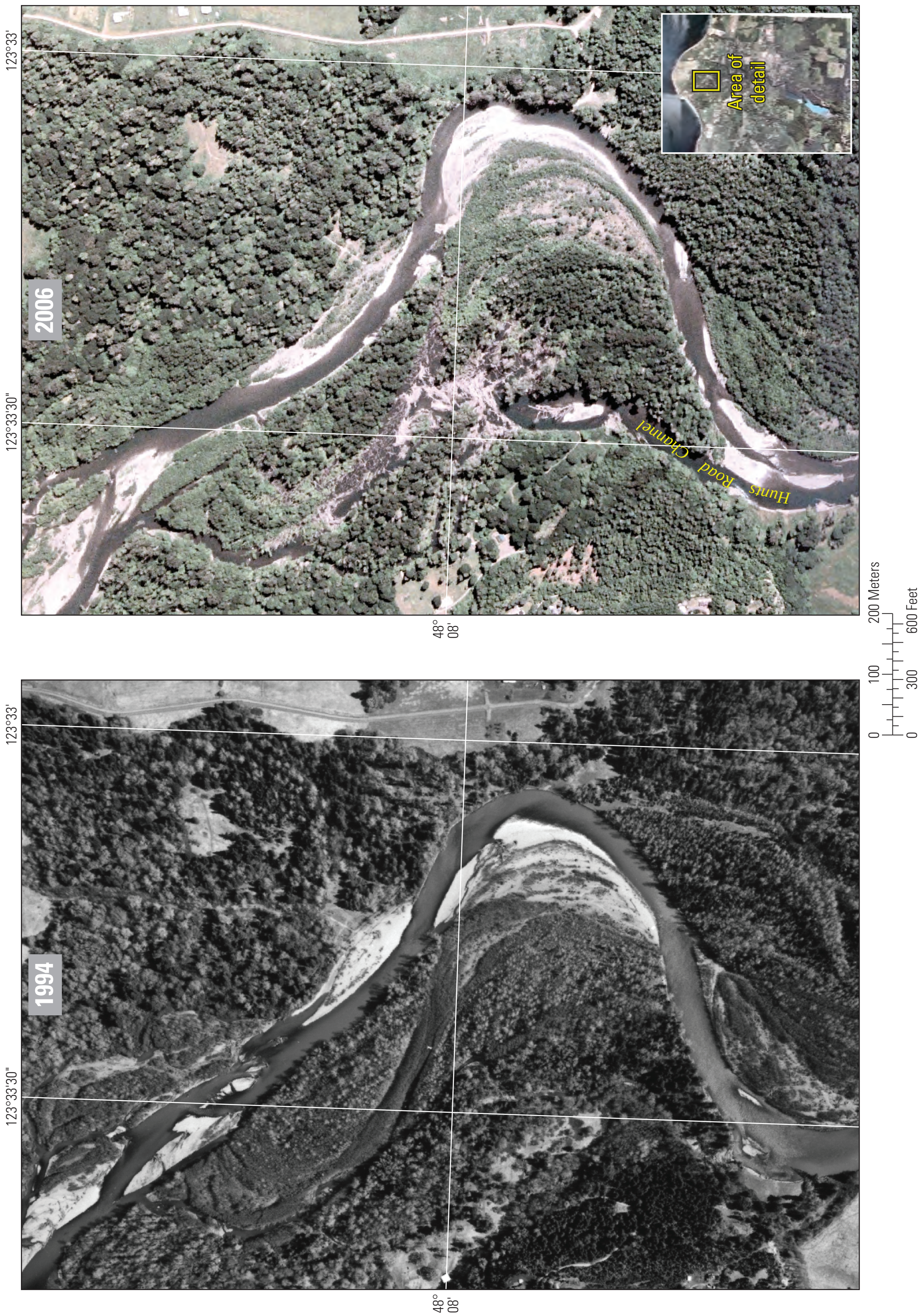


Figure 3.10. Historical aerial photographs showing a major channel avulsion in the lower Elwha River, Washington, 1994 and 2006.

Figure 3.11. Woody debris resulting from channel avulsion in the lower Elwha River, Washington. Flow direction is from the top to the bottom of the photograph. The avulsion point is shown at the top of the photograph. (Photograph taken by Tom Roorda, Northwestern Territories, Inc., April 4, 2007.)

Current Sediment Supply to the Lower River

For almost 100 years, the Elwha River dams have captured all upper-watershed sand and gravel before it could reach the lower river, leading to bed armoring and coarsening in the lower river (Pohl, 2004; Kloehn and others, 2008; Curran and others, 2009; Draut and others, 2011). In the absence of this supply, bank erosion of older fluvial or glacial deposits constitutes the primary supply of coarse sediment to the lower river. We know of no estimate of the amount of this sediment recruited by bank erosion and channel migration, although research on other rivers demonstrates this process can be important for sediment supply (Collins and Dunne, 1989; Martin and Church, 1995; Wallick and others, 2009).

Lateral erosion of the river into a 38-m-high bluff of glacial till immediately upstream of the river mouth may contribute an important input of bed material (fig. 3.12). Using repeat aerial photography (fig. 3.8), Draut and others (2008) showed that this bluff retreated about 70 m between 1965 and 2006. Extrapolated to the full 310 m bluff length, this retreat would have contributed about 820,000 m^3 during these 41 years, which is equivalent to an annual rate of about 21,000 m^3/yr.

The final potential sources of sediment to the lower watershed are the drainage area and the small tributaries that drain directly into the lower river. Most of this lower catchment area is privately owned and used for wood production, small farms, and open space, and little information is available about the rates and patterns of sediment contributions from this lower landscape.

Figure 3.12. Large bluff immediately upstream of the mouth of the Elwha River, Washington. This bluff has eroded substantially during the past several decades, and it may be a primary source of sediment to the lower river and littoral cell. (Photograph taken by Amy E. Draut, U.S. Geological Survey, September 8, 2008.)

Sidebar 3.1 Flood Plain Restoration in the Lower Elwha River

Michael L. McHenry, Habitat Manager, Lower Elwha Klallam Tribe

The construction of the Elwha and Glines Canyon Dams in the Elwha River in the early 20th century prevented fish migration and captured sediment and wood that previously helped form and maintain the ecosystem of the river flood plain. Downstream of the dams, these effects were magnified by flood plain logging, removal of logjams, and channelization, activities that were common practice in western Washington rivers. As a result of the cumulative effects of dam construction and historical flood plain management practices, habitat conditions for anadromous salmon in the lower river are degraded. For instance, the lower river has incised into its river bed, lost suitable-sized spawning gravels, increased in temperature, lost connectivity with parts of its flood plain, and lost habitat complexity.

Although dam removal will assist with correcting many of the ecological problems besetting the Elwha River and its imperiled salmon populations, it will not immediately correct the degraded flood plain habitats of the lower river. In an effort to improve flood plain habitats in the Elwha River prior to dam removals, the Lower Elwha Klallam Tribe has been conducting numerous flood plain restoration actions, which include removing unneeded dikes, installing dozens of engineered log jams throughout the channel and flood plain, correcting fish migration barriers, planting thousands of native trees and shrubs, and controlling the spread of exotic vegetation (figs. S3.1.1 and S3.1.2). The restoration efforts are designed to maximize potential habitat areas that can accommodate all the sediment that will be released by dam removal. For example, dike removals increase flood plain capacity and allow the river to occupy areas currently inaccessible to habitat forming processes.

Engineered log jams (ELJs) are designed to mimic the natural architecture of large, stable logjams that are critical to anastomosing of forested island channel morphology commonly found in large western Washington rivers. ELJs at the river reach level may be used to promote island formation, to activate side channels (in conjunction with dike removals), and reduce flow velocities. ELJs also promote habitats that are used heavily by adult and juvenile salmonids of all species. ELJs typically develop large, complex scour pools that interact with groundwater to provide the cool temperature refugia preferred by salmon. Monitoring has shown that these habitats contain 2–6 times as many juvenile salmon as similar habitats without complex wood structures.

Efforts to revegetate the flood plain have focused on previously disturbed areas in the flood plain that were either open or lightly vegetated. Elevation models and existing tree height data obtained by lidar were used to identify areas for planting a mixture of native coniferous and deciduous trees. More than 20,000 trees and shrubs have been planted in this effort. Concurrently, the tribe has been aggressively controlling non-native exotic vegetation that has invaded the flood plain.

Figure S3.1.1. Newly constructed engineered log jam on the Elwha River, Washington during winter flooding 2009. This structure is one of 50 that the Lower Elwha Klallam Tribe has installed in the lower Elwha River prior to dam removal.

Figure S3.1.2. Newly activated flood plain overflow channel during the first winter following removal of a 1,500 foot flood plain dike on the Elwha River, Washington, 2009.

Coastal Morphology

The Elwha River delta (fig. 3.13) is a wave-dominated deltas within the broader Puget Sound region (Shipman, 2008; Warrick and others, 2009a). The morphology of wave-dominated deltas are controlled largely by littoral redistribution of river sediment. Waves at the Elwha River delta arrive from the west, and these waves induce littoral currents and sediment transport toward the east (toward Ediz Hook), as described in Warrick and others (2011, chapter 5, this report).

Glacial processes have carved irregular shoreline shapes into the entire coastline of Puget Sound and deposited the coarse sediments that compose the beaches (Finlayson, 2006; Shipman, 2008). The Elwha River delta is different from inner Puget Sound beaches and deltas, however, because it is subject to waves from the Pacific Ocean. As shown below, these Pacific-derived waves—in addition to sea level and fluvial histories—are important characteristics that define the Elwha River coastal morphology. The Elwha River delta is lobate in shape and its beaches are composed largely of gravel, with some sand. These beaches have been eroding quickly during the past 80 years, a phenomenon which appears to be related to the loss of sediment supply caused by the Elwha River dams. The rapid erosion of the beaches is causing a distinct erosional morphology on the shoreline of the Elwha River delta.

Figure 3.13. The mouth and delta shoreline of the Elwha River, Washington. (Photograph taken by Ian M. Miller, University of California, Santa Cruz, February 12, 2005, at 11:24 Pacific standard time)

Sea-Level History

The shoreline of the Elwha River delta has moved more than 100 m in elevation over glacial time as a result of the rises and falls in the global (or “eustatic”) sea level that have resulted from varying quantities of ice storage, fluctuations in ocean water temperature, and the rising and falling of the Earth’s crust as it shifts under the weight of glacial ice sheets. With the retreat of the Juan de Fuca Lobe of the continental ice sheet approximately 14,000 years BP, the Strait of Juan de Fuca filled with seawater. Mosher and Hewitt (2004) detailed the subsequent sea-level history for the Strait of Juan de Fuca, and this record is compared graphically to the global eustatic sea level shown in figure 3.14. At the time of the ice sheet retreat, the eustatic sea level was approximately 70 m below current (2011) levels because of the tremendous amount of water trapped in the world’s ice sheets (fig. 3.14). In contrast, the relative sea level in the Strait of Juan de Fuca at this same time was approximately 50–75 m higher than the current levels, as evidenced by high altitude carbon-14 (^{14}C) dated marine sediments (Matthews and others, 1970; Waitt and Thorson, 1983; Dethier and others, 1995; Huntley and others, 2001). The approximately 150 m difference between the

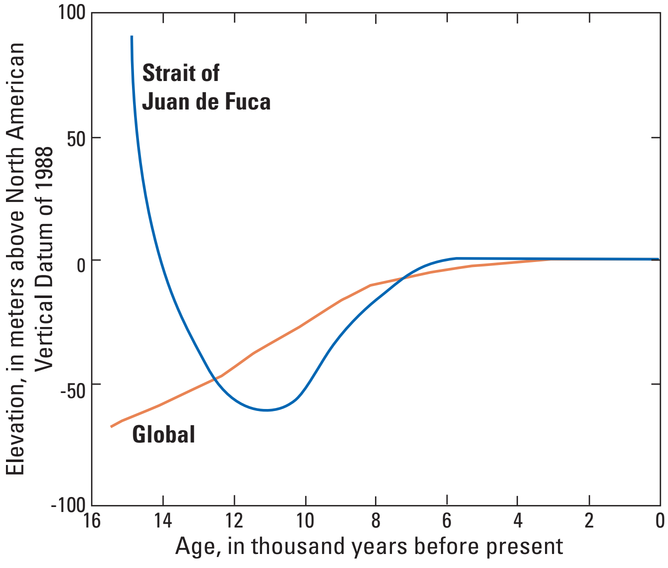


Figure 3.14. History of relative sea level for the Strait of Juan de Fuca off the coast of Washington (after Mosher and Hewitt, 2004). The global eustatic sea level curve (Global) is based on Peltier (2002).

global eustatic and the regional Strait of Juan de Fuca sea levels resulted from the depression of the Earth's crust under the thick ice sheet that covered the region.

The high-stand of relative sea level within the Strait of Juan de Fuca was short-lived, however, because the crust rebounded upward at rates much faster than the eustatic changes in sea level. This rebound induced rapid falling of relative sea level in the Strait, which reached an absolute minimum of approximately -55 m at about 10,500 years BP (Mosher and Hewitt, 2004; fig. 3.14). Following this minimum in sea level, changes in relative sea level have resulted from the combined effects of eustatic and glacial-isostatic changes. The eustatic changes brought relative sea level approximately to its present height at ca. 6,000 years BP, after which relative sea level has been relatively constant compared to the fluctuations between 6,000 and 14,000 years BP (fig. 3.14). Although the eustatic sea level has increased about 1.7 mm/yr over the past century (Intergovernmental Panel on Climate Change, 2007), the relative sea level changes in the region of the Elwha River have been negligible because of the continued uplifting of the landscape. This differs from the inner Puget Sound where relative sea level has been rising at about 2.0 mm/yr, and the outer coast where relative sea level has been falling at about 1.6 mm/yr during the past century (National Oceanic and Atmospheric Administration stations 9447130, Seattle and 9443090, Neah Bay).

Coastal Evolution Since the Pleistocene Time

The dynamic sea level following the most recent ice sheet retreat left clear imprints on the landscape of the Strait of Juan de Fuca. The transgression (or rising) of sea level in the Elwha River delta region started about 10,500 years BP and was followed by relative sea level stability since about 6,000 years BP. This transgression left the most defining physical features on the shoreline and submarine (or underwater) landscape. Coastal bathymetric surveys have identified a broad terrace extending several kilometers offshore of the present day Elwha River delta (fig. 3.15). This feature is an ancient delta that was built during the lowest sea levels, and three drowned littoral spits appear along its eastern edge (I–III in fig. 3.15). Such spits are built out at the termination of littoral sediment cells, and the presence and location of these drowned spits suggest that the shoreline position of the Elwha River delta was 3–5 km offshore of the present shoreline during lower sea levels (Galster and Schwartz, 1990; Mosher and Hewitt, 2004). Furthermore, these drowned spits step up in elevation from -25 m for the farthest offshore spit (I), to -8 and -6 m for spits II and III, respectively (Mosher and Hewitt, 2004). The consistent orientation of the drowned spits and Ediz Hook (spit labeled IV in fig. 3.15) indicates that transport of sediment along this shoreline has consistently been toward the east, which is in the same direction of littoral currents from the waves of the Pacific Ocean (see Warrick and others, 2011, chapter 5, this report). One hypothesis is that as relative sea level rose between approximately 10,500 and 6,000 years BP, the delta shoreline was eroded inland at an average rate of about 0.7 m/yr (Galster and Schwartz, 1990). During at least three episodes of this transgression, the terminal spit was abandoned and a new spit was formed farther upslope.

The present-day Elwha River delta has a lobate planform centered on the river flood plain (fig. 3.15). This geomorphic shape suggests that either the presence of the flood plain, or discharge of sediment from the river, has defined this sinuous morphology of the delta. One leading hypothesis holds that this sinuous form did not result solely from river depositional patterns but rather from a combination of sediment supply from the river that kept the position of the delta's shoreline relatively steady during the past 6,000 years, coupled with more than 1 km of erosion of the adjacent coastal bluffs on both sides of the delta during the past 6,000 years (equivalent to an average erosion rate of 0.2 m/yr; Galster and Schwartz, 1990). The sediment supplied by the combination of erosion of these coastal bluffs and sediment discharge from the river built the 5 km spit, Ediz Hook, in this strongly unidirectional eastward littoral cell (Galster and Schwartz, 1990). The beaches of the Elwha littoral cell are composed of mixed sediment grain sizes (sand to boulder), which is generally consistent with many of the Strait of Juan de Fuca beaches, owing to the abundance of coarse sediment in the glacial landforms of the region (Shipman, 2008).

Historical Shoreline Changes

The 20th century oral histories from Lower Klallam Elwha Tribal members describe hundreds of meters of land lost from coastal erosion of the beach east of the river mouth ("east beach") and a fundamental shift of the low-tide area of the beach from being favorable shellfish habitat to a cobble substrate poorly suited for shellfish habitat (Reavey, 2007; Warrick and others, 2009a). The changes described by the Lower Elwha Klallam Tribe are consistent with aerial-photograph-derived erosion rates (fig. 3.16), which have accelerated significantly from 0.8 to 1.4 m/yr during 1939–90 and 1990–2006, respectively (Warrick and others, 2009a). Further, this oral history is consistent with the current differences between the west beach, which has not changed significantly in position and is mostly sand and gravel, and the east beach, which is eroding and has a cobble low-tide terrace (fig. 3.17).

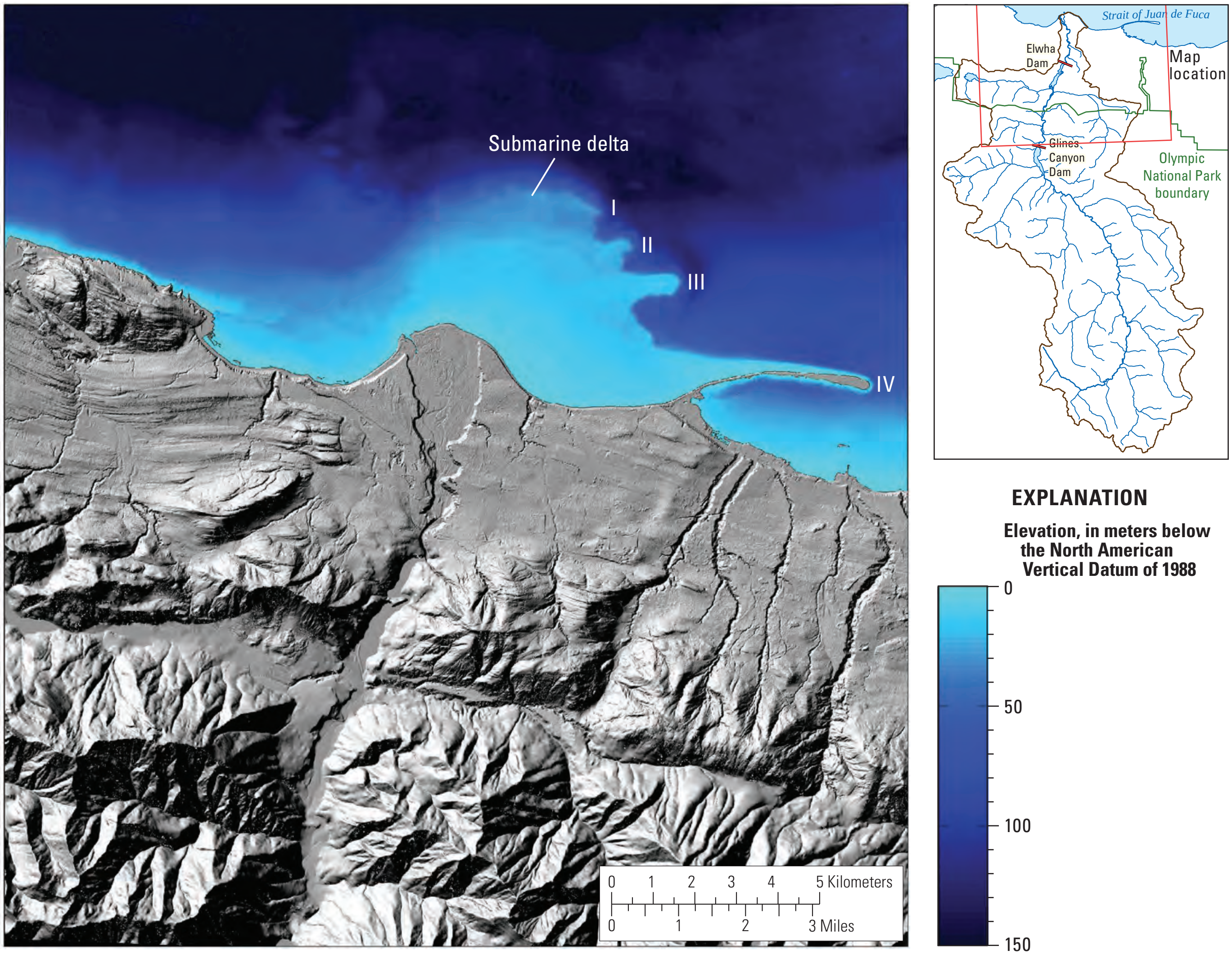


Figure 3.15. Coastal bathymetry of the broad submarine delta plain, three drowned spits (I–III), and the Ediz Hook (IV), which represents the terminus of the current littoral cell of the Elwha River delta, Washington. Source data are a merger of Finlayson (2005), Cochrane and others (2008), and Warrick and others (2010).

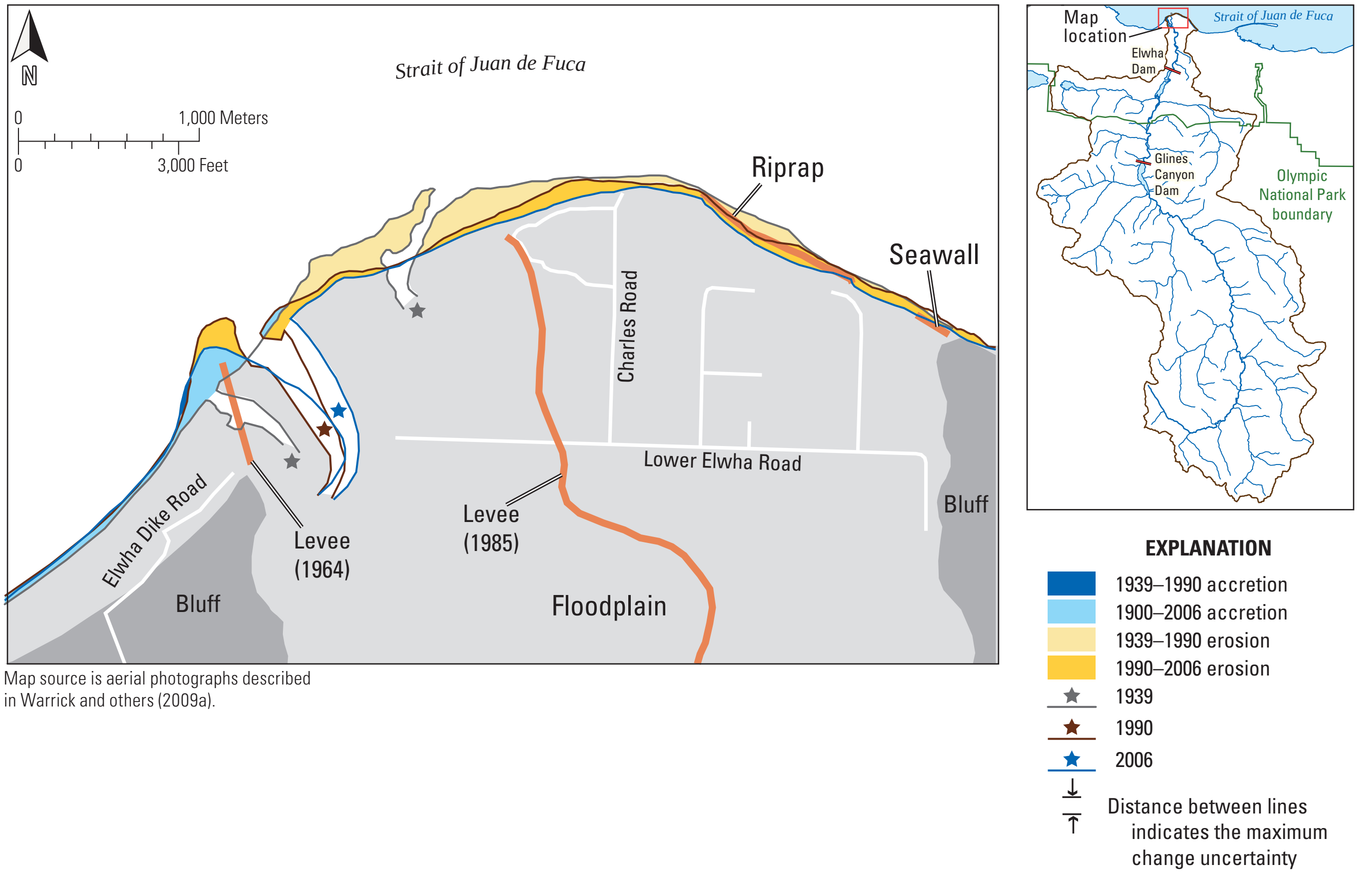


Figure 3.16. Shoreline change of the Elwha River delta, Washington, between 1939 and 2006. (After Warrick and others, 2009a.)

Figure 3.17. Differences between the beach on the west and east sides of the current river mouth of the Elwha River delta, Washington.

Historical changes to the position of the river and the shoreline also are largely responsible for the formation and destruction of the coastal wetlands near the river mouth. The series of aerial photographs, shown in figure 3.8, shows how abandoned river channels become coastal lakes and estuarine channels once the river changes course. Erosion of the shoreline commonly pushes some sand and gravel inland over the beach berm, into sediment lobes termed "overwash deposits" (fig. 3.18). These overwash deposits decrease the size of coastal lakes and estuarine channels by filling the water body with sediment (fig. 3.18). Thus, coastal erosion, which has been considerable since the dams have been in place, has resulted in wetland loss around the Elwha River delta.

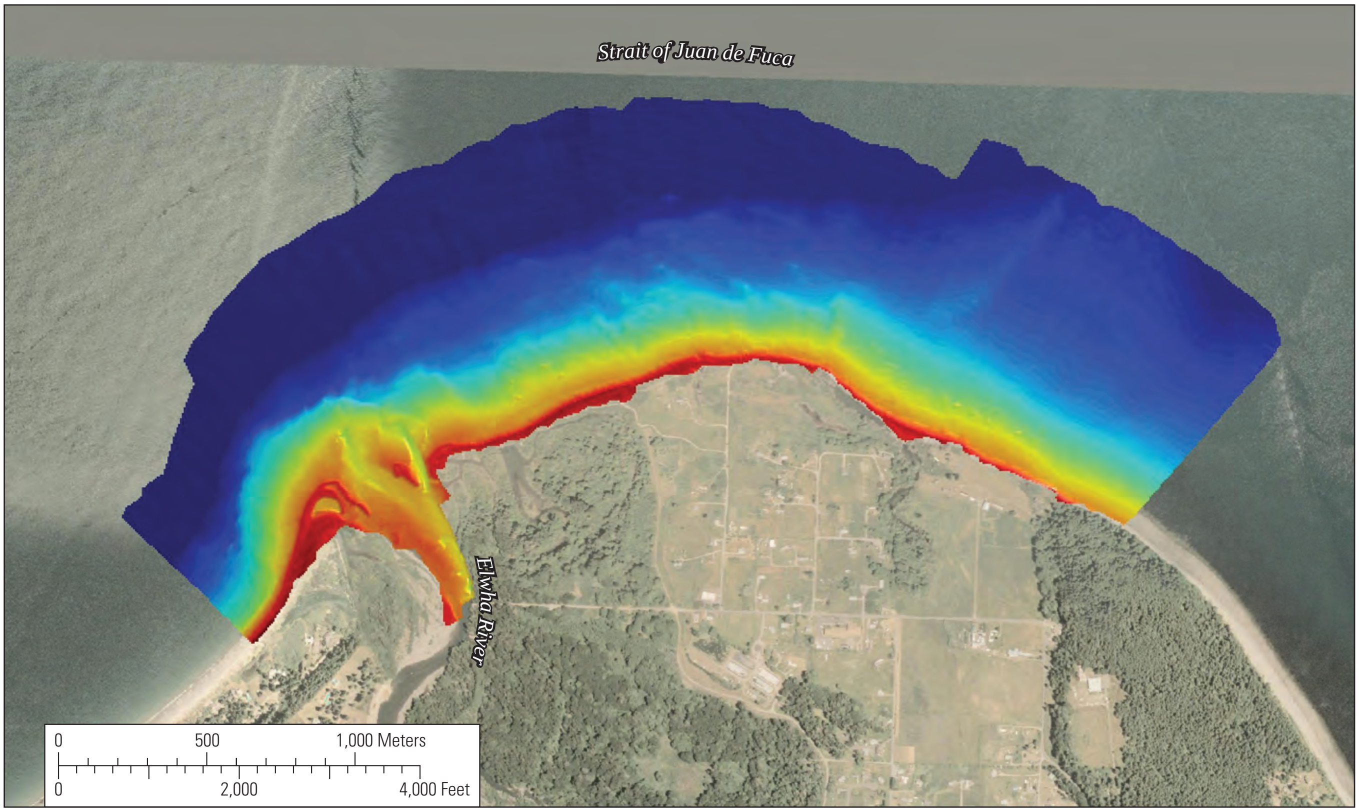
Figure 3.18. Aerial photographs of historical changes from shoreline erosion and overwash deposition resulting in coastal wetland loss in the eastern Elwha River delta, Washington. (After Warrick and others, 2009a).

Recent Coastal Monitoring

In response to the ongoing retreat of the Elwha River delta shoreline and because of the potential for restoration of this shoreline following dam removal, the Lower Elwha Klallam Tribe, the U.S. Geological Survey (USGS), and the Washington State Department of Ecology have collaborated on a coastal monitoring program since 2004. One of the primary tools used in this monitoring is high-resolution topographic surveying with real time kinematic global positioning systems (RTK-GPS). These RTK-GPS surveys require several scientific technicians to hike GPS receivers across the beach to measure topography and to drive small vessels with receivers and echo sounders through the coastal waters to measure seafloor bathymetry (fig. 3.19). The use of these surveying techniques results in high-resolution topographic maps of the study area (fig. 3.20) that can be used to detect change (Warrick and others, 2010).

These surveys show that the beaches of the Elwha River delta can be divided into three sections: (1) the steep, cuspate beach west of the river mouth ("west beach"); (2) the dynamic river mouth; and (3) the erosional beach east of the river mouth that has a distinct cobble low-tide terrace ("east beach"). The cuspate, west beach has changed little in position over the recent monitoring period (figs. 3.21 and 3.22), which is consistent with the historical analysis of this beach from aerial photographs discussed above. The east beach has eroded rapidly with a shoreward movement of the beach profile (figs. 3.21 and 3.22). The low-tide terrace portion (below approximately 1 m elevation NAVD 88) of the east beach is much more stable (fig. 3.21). The net effect of shoreline erosion of the east beach is landward movement of the beach face and broadening of the low-tide terrace. The cobble-faced low-tide terrace of the east beach is an armored portion of the beach resulting from beach erosion (Warrick and others, 2009a).

Figure 3.19. Topographic and bathymetric surveys using real time kinematic global positioning system (RTK-GPS) from (*A*) hiked backpack systems and (*B*) personal watercraft with integrated echo sounders along the of the Elwha delta coast, Washington.



Aerial photography from USDA - NAIP, 2006. Bathymetric data from Warrick and others (2010).

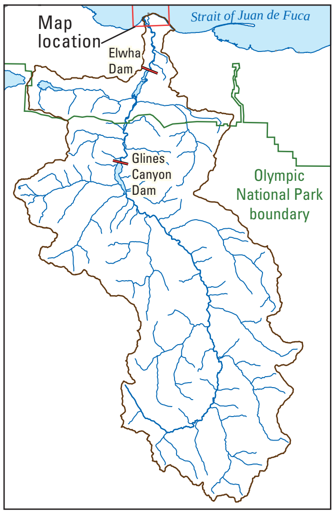


Figure 3.20. Topography and bathymetry from real time kinematic global positioning system (RTK-GPS) surveys of the Elwha River delta, Washington, during summer 2008. (Aerial photography from the U.S. Department of Agriculture National Agriculture Imagery Program (NAIP) survey of 2006.)

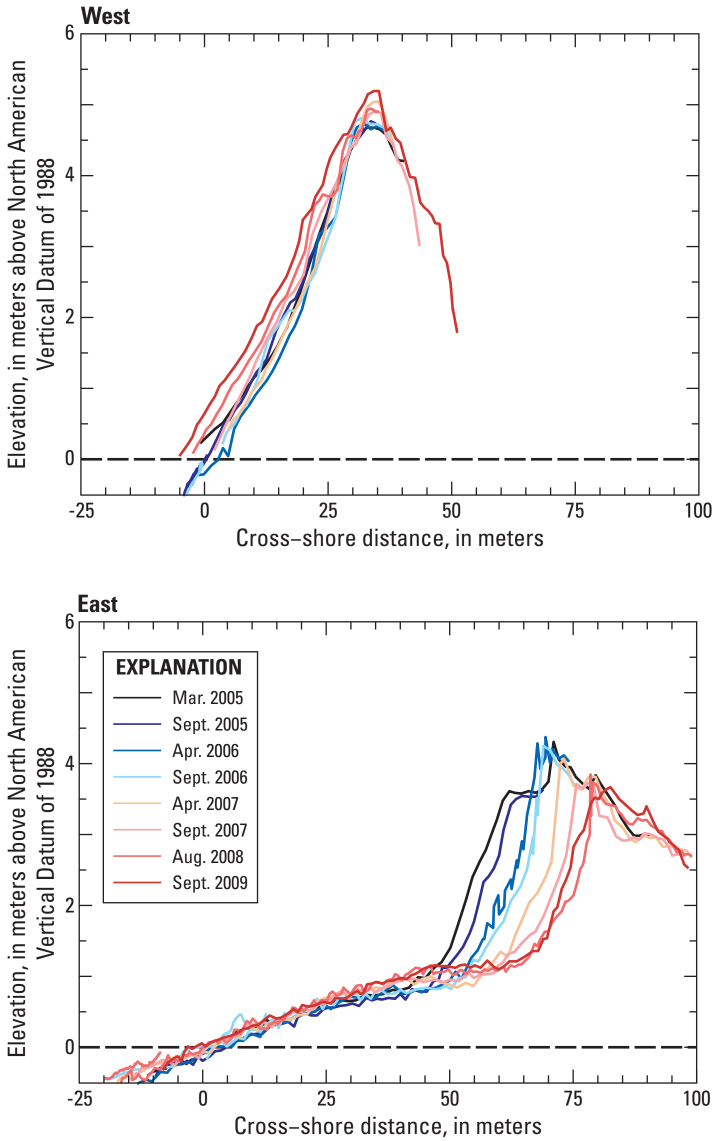


Figure 3.21. Example beach topographic profiles for the west and east beaches of the Elwha River delta, Washington, from surveys by the U.S. Geological Survey. The west beach has been relatively stable over time, whereas the east beach has eroded substantially.

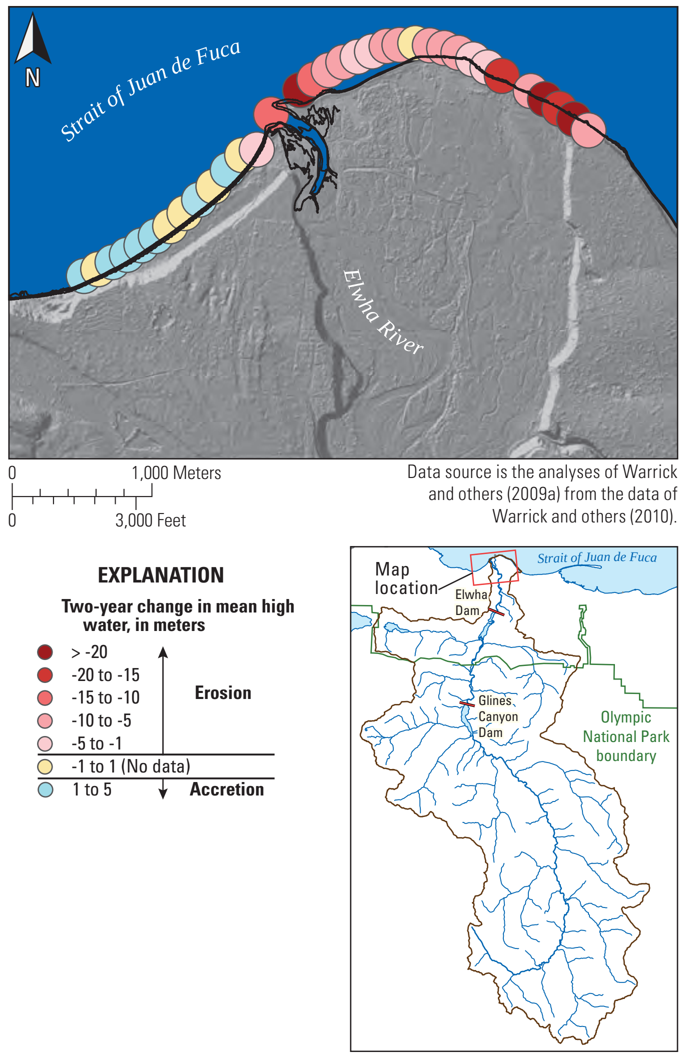


Figure 3.22. Shoreline change along the beaches of the Elwha River delta, Washington, during 2004–06 from real time kinematic global positioning system (RTK-GPS) surveys. (After Warrick and others, 2009a.)

The most dynamic part of the Elwha River delta shoreline is the river mouth, which is influenced by tidal flow, river discharge, and waves that move and reorganize sediment around the river mouth. Evidence of these changes comes from 3 years (2007–09) of topographic surveys in and around the river mouth (fig. 3.23). It is important to note that these surveys suggest that the river mouth region gained significant volumes of sediment in the time between the surveys (approximately 34,000 m^3 in 2007–08 and approximately 21,000 m^3 in 2008–09), even though the east beach underwent net erosion during the same time. These results suggest that the river is still contributing significant amounts of sediment to the coastal system (a conclusion which is consistent with the observations of Draut and others, 2011) and that much of the fluvial sediment in the delta is emplaced in the bar of the river mouth.

Sidebar 3.2 Mapping Grain Size with Digital Photos

Jonathan A. Warrick

Removal of the Elwha River dams will release large volumes of sediment into the lower Elwha River and the Strait of Juan de Fuca. We expect this flood of sediment to modify coastal landforms by accretion and to change fluvial and coastal habitat substrate from coarse to fine sediment. Simultaneous tracking of topographic change and sediment size may allow for the development of models for these changes that could be used for future restoration projects. Traditional methods for grain size analysis – including pebble counts and physical sampling – are labor intensive and costly. The use of digital photography alleviates many of these problems by providing a rapid sampling of the land or seafloor surface (Adams, 1979). The USGS has been developing and using digital photographic methods for the Elwha River study area since 2004 to assist in tracking the changes induced by dam removal.

To sample grain size on the beach or a river bar, photographs were taken at regular intervals across these landforms. Photographs must be taken orthogonally to the ground surface to limit distortion of surface features. Traditionally, the calculation of grain size parameters for each photograph was obtained from manual sizing and counts from each photograph, which required 1–2 hours of analysis time for each photograph. New methods suggested by Rubin (2004) have significantly shortened analysis time owing to an automated calculation of grain size based on spatial patterns in each photograph. These "cobble cam" techniques were applied to the Elwha River flood plain and coastal landforms by Warrick and others (2009b) with excellent results. Photographic sampling from Elwha River landforms show a broad diversity in grain size and sorting (fig. S3.2.1). Comparisons of the automated analyses with physical samples of the substrate show that errors in the analyses are only 14 percent, which are more than adequate to characterize the differences prevalent in these landforms. There are significant differences in the grain sizes across river bars, beach cusps, and the low-tide terrace to foreshore transition (see fig. S3.2.2). The successful development and implementation of these methods should allow for the quantification of changes throughout the Elwha River landforms as they occur in the future.

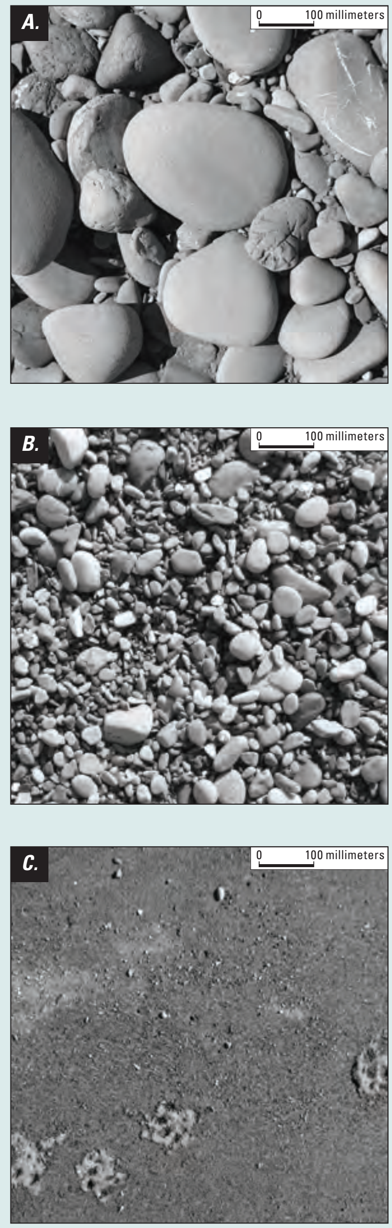


Figure S3.2.1 Examples of a range in grain size from (*A*) cobble (*C*) sand of the Elwha River delta beach, Washington. (After Warrick and others, 2009b).

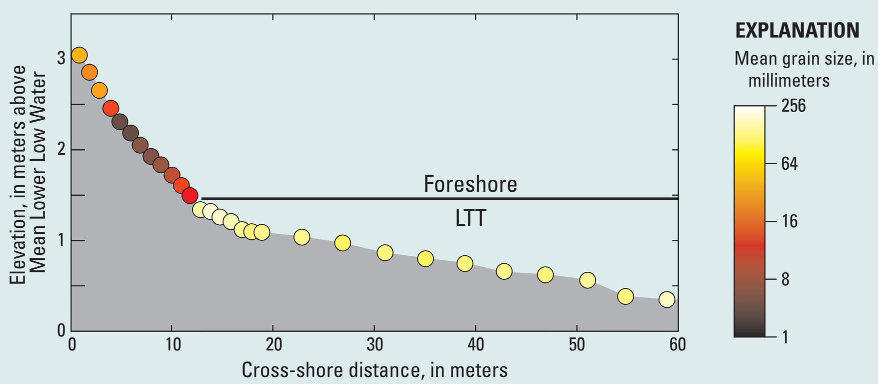


Figure S3.2.2 Example results of the mean sediment grain size from Cobble Cam photographic analyses across the east beach of the Elwha River delta (after Warrick and others, 2009b). A distinct grain size change is apparent between the foreshore and the low-tide terrace (LTT).

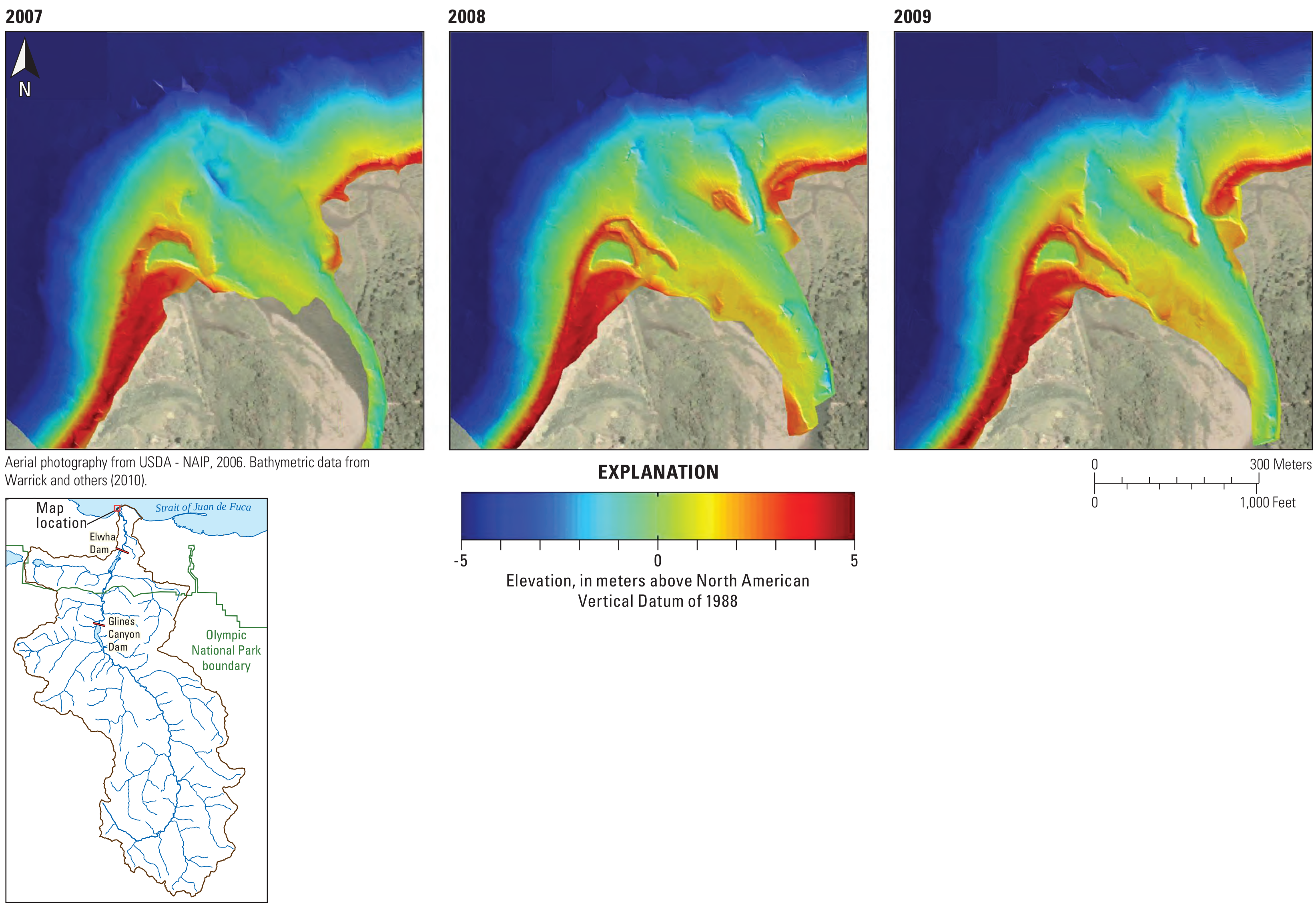


Figure 3.23. Topographic and bathymetric survey maps showing the evolution and growth of the river mouth bar of the Elwha River during 2007–09. All three surveys were conducted in the late summer (August–September) each year.

Summary

The Elwha River lies at the intersection of uplifting land and an eroding coast. In the past, movement of sand and gravel from the steep, eroding glaciated mountains provided the flood plain with sediment that formed spawning habitats for fish and provided a material to buffer the shoreline from energetic waves. Humans have altered this balance by trapping sediment behind dams and by modifying the river channel and shoreline, actions which have altered the position and form of the river channel, reduced sediment and woody debris fluxes through the lower river, and caused significant increases in coastal erosion of the beach east of the river mouth. Consequently, coastal wetlands also are shrinking around the Elwha River delta.

Restoration activities, including the placement of engineered log jams in the river channel, removal of dikes and other flood plain alterations, and the removal of two large dams, should further modify the geomorphology of this river and its coast, with the expectation of restoring some of the lost ecosystem functions. Consistent, long-term monitoring of these systems is needed to quantify the effectiveness of these restoration efforts.

References Cited

Adams, J., 1979, Gravel size analysis from photographs: ASCE Journal of the Hydraulics Division, v. 105, no. 10, p. 1247-1255.

Acker, S.A., Beechie, T.J., and Shafroth, P.B., 2008, Effects of a natural dam-break flood on geomorphology and vegetation on the Elwha River, Washington, U.S.A.: Northwest Science, v. 82 (special issue), p. 210-223.

Batt, G.E., Brandon, M.T., Farley, K.A., and Roden-Tice, M., 2001, Tectonic synthesis of the Olympic Mountains segment of the Cascadia wedge, using two-dimensional thermal and kinematic modeling of thermochronological ages: Journal of Geophysical Research, v. 106, B11, p. 26,731-26,746.

Beechie, T.J., Liermann, M., Pollock, M.M., Baker, S., and Davies, J., 2006, Channel pattern and river-floodplain dynamics in forested mountain river systems: Geomorphology, v. 78, p. 124-141.

Brandon, M.T., Roden-Tice, M.K., and Garver, J.I., 1998, Late Cenozoic exhumation of the Cascadia accretionary wedge in the Olympic Mountains, northwest Washington State: Geological Society of America Bulletin, v. 110, p. 985-1009.

Cochrane, G.R., Warrick, J.A., Saby, Y., Finlayson, D., and Harney, J., 2008, Sea-floor mapping and benthic habitat GIS for the Elwha River delta nearshore, Washington: U.S. Geological Survey Data Series 320. (Also available at http://pubs.usgs.gov/ds/320/.)

Collins, B., and Dunne, T., 1989, Gravel transport, gravel harvesting, and channel-bed degradation in rivers draining the southern Olympic mountains, Washington, U.S.A.: Environmental Geology, v. 13, no. 3, p. 213-224.

Curran, C.A., Konrad, C.P., Higgins, J.L., and Bryant, M.K., 2009, Estimates of sediment load prior to dam removal in the Elwha River, Clallam County, Washington: U.S. Geological Survey Scientific Investigations Report 2009-5221, 19 p. (Also available at http://pubs.usgs.gov/sir/2009/5221/.)

Dethier, D.P., Pessl, F., Keuler, R.F., Balzarini, M.A., and Pevear, D.R., 1995, Late Wisconsinan glaciomarine deposition and isostatic rebound, northern Puget Lowland, Washington: Geological Society of America, Bulletin, v. 107, no. 11, p. 1288-1303.

Draut, A.E., Logan, J.B., McCoy, R.E., McHenry, M., and Warrick, J.A., 2008, Channel evolution on the lower Elwha River, Washington, 1939–2006: U.S. Geological Survey Scientific Investigations Report 2008-5127, 32 p. (Also available at http://pubs.usgs.gov/sir/2008/5127/.)

Draut, A.E., Logan, J.B., and Mastin, M.C., 2011, Channel evolution on the dammed Elwha River, Washington, USA: Geomorphology, v. 127, p. 71-87.

Easterbrook, J., 1986, Stratigraphy and chronology of Quaternary deposits of the Puget lowland and Olympic Mountains of Washington and the Cascade Mountains of Washington and Oregon: Quaternary Science Reviews, v. 5, p. 145-159.

Finlayson, D.P., 2005, Combined bathymetry and topography of the Puget Lowland, Washington State: University of Washington

Finlayson, D.P., 2006, The geomorphology of Puget Sound beaches: Seattle, Wash., University of Washington, Ph.D. thesis, 216 p.

Galster, R.W., and Schwartz, M.L., 1990, Ediz Hook—A case history of coastal erosion and rehabilitation: Journal of Coastal Research, v. SI-6, p. 103-113.

Gertsel, W.J., and Lingley, W.S., Jr., 2003, Geologic map of the Mount Olympus 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources, Open-File Report 2003-4, scale 1:100,000.

Harwood, K., and Brown, A.G., 1993, Fluvial processes in a forested anastomosing river—Flood partitioning and changing flow patterns: Earth Surface Processes and Landforms, v. 18, p. 741-748.

Huntley, D.H., Bobrowsky, P.T., and Clague, J.J., 2001, Ocean drilling program leg 169S—Surficial geology, stratigraphy and geomorphology of the Saanich Inlet area, southeastern Vancouver Island, British Columbia: Marine Geology, v. 174, no. 1-4, p. 27-41.

Intergovernmental Panel on Climate Change (IPCC), 2007, Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change: Cambridge University Press, 996 p.

Johnson, P., 1994, Historical assessment of Elwha River fisheries: National Park Service, draft report, 355 p.

Kloehn, K.K., Beechie, T.J., Morley, S.A., Coe, H.J., and Duda, J.J., 2008, Influence of dams on river-floodplain dynamics in the Elwha River, Washington: Northwest Science, v. 82 (special issue), p. 224-235.

Knighton, D., 1998, Fluvial forms and processes—A new perspective: London, Arnold Publishers, 383 p.

Knighton, A.D., and Nanson, G.C., 1993, Anastomosis and the continuum of channel pattern: Earth Surface Processes and Landforms, v. 18, p. 613-625.

Konrad, C.P., 2009, Simulating the recovery of suspended sediment transport and river-bed stability in response to dam removal on the Elwha River, Washington: Ecological Engineering, v. 35, no. 7, p. 1104-1115.

Martin, Y., and Church, M., 1995, Bed-material transport estimated from channel surveys—Vedder River, British Columbia: Earth Surface Processes and Landforms, v. 20, p. 347-361.

Mathews, W.H., Fyles, J.G., and Nasmith, H.W., 1970, Postglacial crustal movements in southwestern British Columbia and adjacent Washington state: Canadian Journal of Earth Sciences, v. 7, p. 690-702.

McNulty, T., 1996, Olympic National Park—A natural history: Houghton Mifflin Company, 272 p.

Montgomery, D.R., and Brandon, M.T., 2002, Topographic controls on erosion rates in tectonically active mountain ranges: Earth and Planetary Science Letters, v. 201, no. 3-4, p. 481-489.

Mosher, D.C., and Hewitt, A.T., 2004, Late Quaternary deglaciation and sea-level history of eastern Juan de Fuca Strait, Cascadia: Quaternary International, v. 121, p. 23-39.

Orange, D.L., Geddes, D.S., and Moore, J.C., 1993, Structural and fluid evolution of a young accretionary complex—The Hoh rock assemblage of the western Olympic Peninsula, Washington: Geological Society of America Bulletin, v. 105, p. 1053-1075.

Peltier, W.R., 2002, On eustatic sea level history—Last glacial maximum to Holocene: Quaternary Science Reviews, v. 21, p. 377–396.

Pohl, M.M., 1999, The dams of the Elwha River, Washington—Downstream impacts and policy implications: Tempe, Arizona State University, Ph.D. thesis, 296 p.

Pohl, M., 2004, Channel bed mobility downstream from the Elwha dams, Washington: The Professional Geographer, v. 56, p. 422-431.

Polenz, M., Wegmann, K.W., and Schasse, H.W., 2004, Geologic map of the Elwha and Angeles Point 7.5-minute quadrangles, Clallam County, Washington: Washington Division of Geology and Earth Resources Open-File Report 2004-14, scale 1:24,000.

Porter, S.C., and Swanson, T.W., 1998, Advance and retreat rate of the cordilleran ice sheet in southeastern Puget Sound Region: Quaternary Research, v. 50, p. 205-213.

Reavey, K., 2007, The Elwha—A river and its people: Olympic Park Institute, 8 p., accessed June 23, 2008, at http://elwhascienceed.org/ copy_of_elwha-historypapers/.

Rubin, D.M., 2004, A simple autocorrelation algorithm for determining grain size from digital images of sediment: Journal of Sedimentary Research, v. 74, p. 160-165.

Schuster, J.E., 2005, Geologic map of Washington State: Washington Division of Geology and Earth Resources Geologic Map GM-53, 1 sheet, 44 p., scale 1:500,000.

Shipman, H., 2008, A geomorphic classification of Puget Sound nearshore landforms: U.S. Army Corps of Engineers, Puget Sound Nearshore Partnership Report No. 2008-01, 42 p.

Smith, D.G., and Smith, N.D., 1980, Sedimentation in anastomosed river systems: examples from alluvial valleys near Banff, Alberta: Journal of Sedimentary Petrology, v. 50, p. 157-164.

Stewart, R.J., and Brandon, M.T., 2004, Detrital-zircon fission-track ages for the “Hoh Formation”: implications for late Cenozoic evolution of the Cascadia subduction wedge: Geological Society of America Bulletin, v. 116, p. 60-75.

Tabor, R.W., 1975, Guide to the geology of Olympic National Park: University of Washington Press, 144 p., 2 pls.

Tabor, R.W., 1987, Geology of Olympic National Park: Seattle, Wash., Northwest Interpretive Association, 144 p.

Tabor, R.W., and Cady, W.M., 1978, Geologic map of the Olympic Peninsula, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-944, 2 sheets, scale 1:125,000.

U.S. Geological Survey Geologic Names Committee, 2010, Divisions of geologic time—Major chronostratigraphic and geochronologic units: U.S. Geological Survey Fact Sheet 2010–3059, 2 p.

Waitt, R.B., and Thorson, R.M., 1983, The Cordilleran Ice Sheet in Washington, Idaho, and Montana, *in* Wright, H.E., Jr., ed., 1983, Late-Quaternary environments of the United States, volume 1—The Late Pleistocene (Stephen C. Porter [ed.]): University of Minnesota Press, p. 53-70.

Wallick, J.R., Anderson, S.W., Cannon, C., and O'Connor, J.E., 2009, Channel change and bed-material transport in the lower Chetco River, Oregon: U.S. Geological Survey Open-File Report 2009-1163, 83 p.

Warrick, J.A., George, D.A., Gelfenbaum, G., Kaminsky, G., and Beirne, M., 2009a, Beach morphology and change along the mixed grain-size delta of the Elwha River, Washington: Geomorphology, v. 111, p. 136-148.

Warrick, J.A., George, D.A., Stevens, A.W., Eshleman, J., Gelfenbaum, G., Kaminsky, G.M., Schwartz, A.K., and Beirne, M., 2010, Beach morphology monitoring in the Elwha River littoral cell: 2004–2009: U.S. Geological Survey Data Series Report 288, 64 p. (Also available at http://pubs.usgs.gov/ds/288/.)

Warrick, J.A., Rubin, D.M., Ruggiero, P., Harney, J., Draut, A.E., and Buscombe, D., 2009b, Cobble cam—Grain-size measurements of sand to boulder from digital photographs and autocorrelation analyses: Earth Surface Processes and Landforms, v. 34, no. 13, p. 1811-1821.

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