Chapter

9

Summary and Anticipated Responses to Elwha River Dam Removal

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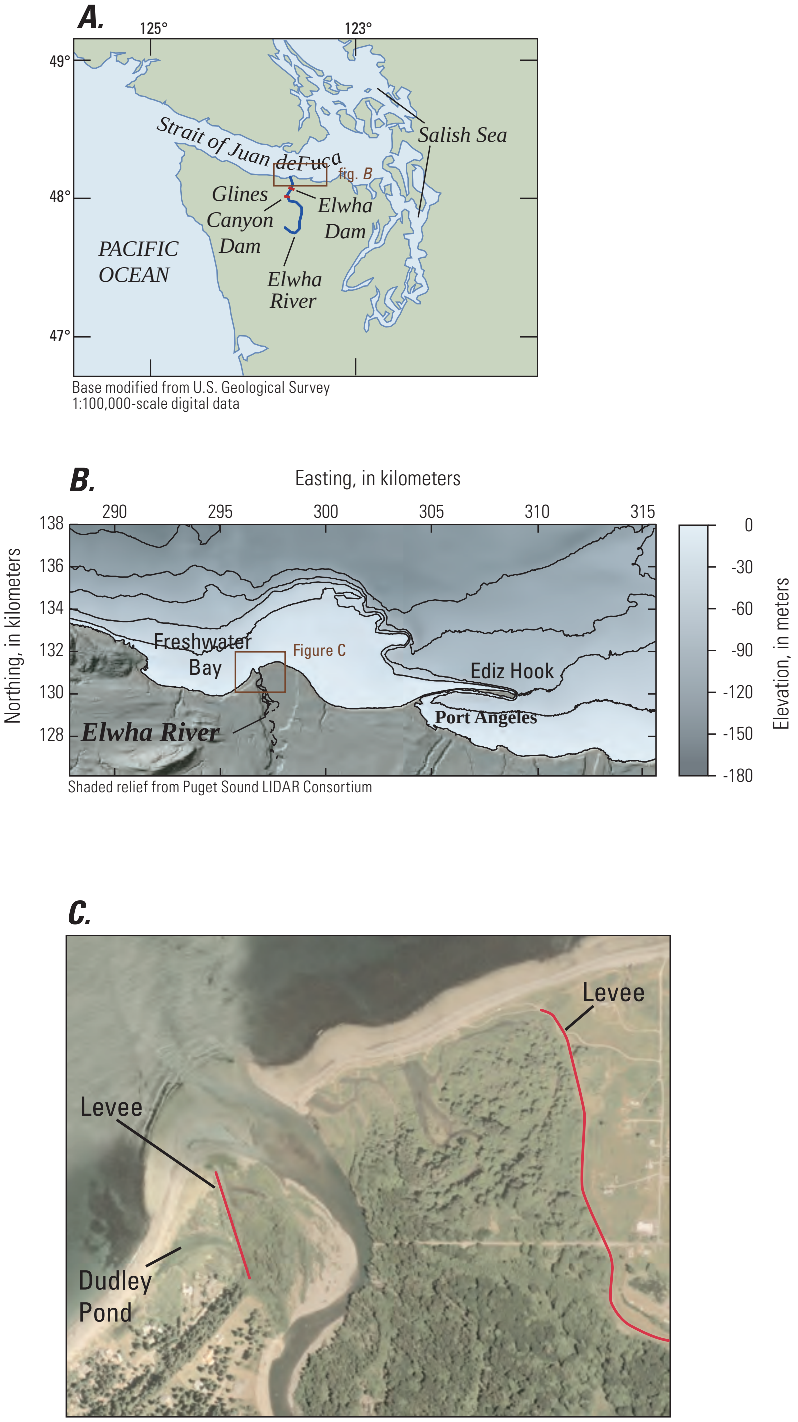
Abstract

Starting in September 2011, the removal of two large dams on the Elwha River will begin an unprecedented river restoration project because of the size of the dams, the volume of sediment released, the pristine watershed upstream of the dam sites, and the potential for renewing salmon populations. Ecosystem studies of the Elwha watershed indicate that the effects of almost 100 years of damming are measurable and of consequence. These effects include smaller spawning salmon populations, massive sediment retention behind the dams, coarsening of the riverbed downstream of the dams, low nutrient concentrations in the river waters, and coastal erosion that has accelerated markedly with time. During and after the removal of these dams, the Elwha River and its ecosystems will be altered by a renewal of sediment discharge downstream of the dams and a reintroduction of salmon spawning upstream of the dams. This chapter summarizes the pre-dam and current state of the river and its coastal ecosystems, and describes the likely outcomes of river restoration on the Elwha River ecosystems.

Introduction

The removal of two large dams on the Elwha River presents an opportunity to restore natural fluvial processes to a mostly pristine watershed and rebuild iconic salmon runs. After removal of the dams, salmon populations are expected to increase dramatically over their present numbers (U.S. Department of the Interior, 1995a; Ward and others, 2008), restoring several important runs to this Pacific Northwest river that once produced large numbers of fish (U.S. Department of the Interior and others, 1994; Wunderlich and others, 1994). The removal of the Elwha and Glines Canyon Dams also presents an opportunity to restore beaches along the Strait of Juan de Fuca with sediment that has been trapped for nearly a century by dam-impounding reservoirs (fig. 9.1). Coastal erosion of as much as 22 m over the past 16 years east of the river mouth is encroaching on the Lower Elwha Klallam Tribal reservation (Warrick and others, 2009), and on vital wetlands and estuaries that provide critical habitat for rearing juvenile salmon.

Although expectations are high for returning salmon populations to the river, restoring river function, and restoring beach sediment supply, a number of uncertainties are associated with the restoration of the Elwha River ecosystem. The rebuilding of salmon populations, for example, is of particular interest. The spatial and temporal patterns of reemerging life-history diversity and competition among natural- and hatchery-origin fish are complex and not fully understood. However, these processes ultimately will affect salmon recolonization, future population status (Brenkman and others, 2008; Pess and others, 2008), and will be a large determinant of ecosystem restoration success. Similarly, the supply of sediment to the lower river and beaches downstream of the dams is uncertain. It is not known how much of the sediment trapped behind the dams will be eroded and transported downstream. Of the sediment that is transported downstream, it is not known how much will be transported all the way to the Strait of Juan de Fuca, and if that amount will be enough to slow or stop the coastal erosion.



Base modified from U.S. Geological Survey
1:100,000-scale digital data

Shaded relief from Puget Sound LIDAR Consortium

Aerial photography from 2006 U.S. Department of Agriculture NAIP

Figure 9.1. The coastal setting of the Elwha River, Washington.

The return of fish populations and restoration of sediment supply will cause numerous changes to the Elwha River ecosystem. For example, large amounts of silt and sand, along with gravel and cobbles may be deposited in the bed of the lower river, which would alter the grain-size distribution in the riverbed, the structure of pools and riffles, and the suitability of spawning habitat. The return of large numbers of fish to the lower river and estuary may alter nutrient concentrations, thereby changing the chemistry, and ultimately the productivity, of these systems. The fining of bed sediments may alter the suitability of the ecosystem for kelp species if large amounts of fine sediment are delivered offshore. The response of ecosystem processes, structure, habitat, and the biological resources they support will be complex, and are largely unpredictable. The scientific knowledge of many of these ecosystem linkages is limited and the results of this large-scale restoration project are uncertain, which highlights the need for ongoing multidisciplinary scientific research.

The scale of the Elwha River Restoration Project is unprecedented. The Elwha and Glines Canyon Dams will be the largest dams removed in the United States, and to our knowledge, the world. Moreover, the removal of these dams will cause the largest controlled release of sediment into a river and adjacent marine waters. This project represents one of the best remaining opportunities in the conterminous United States to restore salmon in large portions of a watershed that are protected as wilderness. The Elwha River dam-removal and ecosystem-restoration project also is an opportunity for increasing scientific understanding (Gelfenbaum and others, 2006). Billions of dollars are spent on ecosystem restoration around the nation, sometimes with highly uncertain outcomes. With the large numbers of dams around the nation reaching the end of their constructed lifespan or economic productivity, the impetus for dam removal is accelerating and becoming much less controversial than in the past (Hart and others, 2002; Heinz Center, 2002). Moreover, relicensing efforts for existing dams have a critical need for the best available sediment- and river-response data to assess the costs and benefits of dam removal compared with continued operation. Meaningful monitoring efforts are needed to document ecosystem recovery and to assess the benefits of restoration expenditures (Duda and others, 2008).

As noted in the previous chapters of this report, as well as numerous other reports documenting scientific investigations of the Elwha River basin, the Elwha River ecosystem has been affected by the Elwha and Glines Canyon Dams, and removal of those dams will affect it further. However, it is also likely that dam removal and ecosystem restoration may not simply restore the ecosystem to its pre-dam state, but may instead result in something new. The concept of “alternative stable states” proposes that there are suites of abiotic and biotic conditions in an ecosystem that lead to particular assemblages of uniquely adapted species. As the system is perturbed with small changes, the density or species composition of the system may temporarily change, but will drift back into the equilibrium state when the perturbation ceases. Larger perturbations that exceed a given threshold, on the other hand, can lead to a phase shift in the system that gives rise to a new stable state (Holling, 1973; Bender and others, 1984; Beisner and others, 2003). Due in part to the steepness of the basin, and the proximity between the upper reaches of the river and the coast, the dam removal project will create short duration, high intensity changes and long term, low intensity ecosystem changes. It may be that the high sediment load during and following dam removal will be large enough to change the existing aquatic and terrestrial flood plain ecosystems into a new stable state. This is certainly the case for the former reservoir sections that will change from lentic (lake-like) to lotic (river-like) water bodies. In the years following dam removal, as more coarse-grained sediments arrive from the former reservoirs, this lower intensity stressor may or may not change the ecosystem. It is not known if multiple phase shifts will arise in the Elwha River after dam removal, or if the ecosystem will settle into a new equilibrium following the high intensity changes shortly after dam removal.

Additionally, the large numbers of salmon anticipated to return to the river and the large volume of sediment expected to be mobilized after dam removal, will create a system response with large “signals” relative to the “noise” of natural background changes. For these reasons, a comprehensive research and monitoring program such as that described in this report will have a high likelihood of successfully documenting ecological changes caused by dam removal.

A comprehensive description of the ecosystem response to dam removal will require the monitoring of multiple interrelated variables across a varied geographic domain that will depend on the sediment grain size mobilized (Woodward and others, 2008). For example, ecosystem responses will vary across the different sections of the river (upstream of, between, and downstream of the dams), the reservoirs, beaches, and the adjacent nearshore zone of the Strait of Juan de Fuca. The response in each of these domains will depend on the grain size of the sediment that accumulates there, which may include very fine-grained (silt and clay) to very coarse-grained (cobble and gravel) sediments. Sediment accumulations may ultimately affect each of the relevant ecosystem components, including:

(1) processes such as sediment transport, nutrient dynamics, and spawning; (2) habitat structure defined by substrate type, channel morphology, flow velocity, and water depth; and (3) biological function such as species assemblages into communities of, for example, invertebrates or riparian vegetation. Ultimately, the effects on these ecosystem processes, habitats, and biological functions will influence the economic, cultural, and societal benefits that these ecosystem services provide. Not all components of the ecosystem will respond on the same time scale. The response will vary with time, from pre-dam removal, during removal (1–3 years), post-removal (3–7 years), and long-term (7–20 years). Some responses will occur quickly, and others will take much longer.

One of the primary purposes of this report is to document the physical and biological conditions of the lower Elwha River and coastal ecosystems in anticipation of the large-scale changes that may be caused by dam removal. This summary chapter (1) provides a summary of the important findings or characteristics of the lower Elwha River and nearshore zone as described in the previous chapters of this report, (2) describes linkages among the components to form a system perspective, and (3) describes predictions of the lower river and coastal physical and biological responses to dam removal. Although scientists and managers may strive for quantitative predictions of the responses to dam removal, at this stage, many predictions will be qualitative and conceptual. The remainder of this summary chapter is organized by geographic domain, starting with the lower river and estuary, then moving to the beaches and nearshore. Within each geographic domain, the important physical and biological characteristics of the ecosystem, as they exist prior to dam removal, and how they might change during and after dam removal will be described.

Lower Elwha River and Estuary

The 7.8-km-long lower Elwha River, between Elwha Dam and the Elwha River estuary, is characterized by various morphologies, including a narrow bedrock gorge, reaches with multiple channels and large vegetated islands, and reaches with a single meandering channel. In the upper 1.3 km of the reach, the channel is confined to a narrow bedrock gorge, limiting channel migration and sediment storage. The last 6.5 km before the river meets the sea is characterized by an ‘anabranching’ morphology that is the result of a unique combination of river gradient, flow conditions, large woody debris, and sediment supply, which are functional attributes associated with extensive channel switching, or avulsions. Detailed analysis of channel position over the last century from historical aerial photographs documented that the lower river channel has moved tens to hundreds of meters by gradual channel migration and by more abrupt avulsions (Draut and others, 2008, 2011). Avulsions are thought to occur when obstacles, such as piles of woody debris, temporarily block flow, as may have happened in winter floods of 1979 and 1980, forcing the river to cut a new path downstream. Repeated avulsions result in the formation of numerous interconnected channels, backwaters, and side channels, which provide important biological functions, a dynamic lotic ecosystem, and shifting riparian and estuarine habitats for many plant and animal species (Beechie and others, 2006; Tooth and others, 2008).

The hydrology of the lower river is typical for moderately sized watersheds in the Pacific Northwest, with the largest peak flows in winter due to heavy rainfall and smaller peak flows caused by spring snowmelt. The lowest flows of the year occur from August through October. Because the dams were built primarily for power generation and were typically operated as run-of-river, the dams have had little effect on the duration and magnitude of peak flows (Duda and others, 2011a, chapter 1, this report). Dam operations have had moderate effect on some aspects of the hydrograph, such as low flows and the rates at which flows increased and decreased, and they have had considerable effects on the supply of sediment and of large woody debris.

Sediment supply to the lower Elwha River from upstream has been reduced by the two dams, except for small quantities of fine-grained suspended sediment that bypasses the dams during floods. However, the lower river has compensated somewhat for the loss of upstream sediment supply by recruiting sediment from within its flood plain. Over the last century about 19 million cubic meters of sediment has been trapped behind Elwha and Glines Canyon Dams (U.S. Department of the Interior, 1995b; Bountry and others, 2010; Czuba and others, 2011, chapter 2, this report). Deltas formed at the inlets of Lake Mills and Lake Aldwell (combined) consist of about 50 percent coarse sand and gravel, and about 50 percent fine-grained silt and clay. This is the largest known reservoir sediment volume known to be associated with any dam removal project.

Reductions in the upstream sediment supply have resulted in bed coarsening and armoring downstream of the dams (Pohl, 2004; Kloehn and others, 2008, Morley and others, 2008; Draut and others, 2011). Additionally, Kloehn and others (2008) determined that the proportion of the flood plain older than 75 years, as determined by vegetation mapping and historical aerial photographs, increased with time downstream of the dams over the last half century, whereas the proportion of younger surfaces decreased with time. The conclusion drawn by Kloehn and others (2008) is that the reduced sediment supply has increased the stability of the river flood plains downstream of the dams. Kloehn and others (2008), however, did not collect channel stability data directly and an alternative explanation for the aging vegetation population could be changes in logging practices. Draut and others (2011) refined the characterization of the lower river, having determined that the upper reaches of the lower river were more stable because of bed armoring caused by lack of sediment supply. However, mobility in the lower reaches of the river was similar to the unregulated river upstream of the dams. Despite the lack of sediment supply from upstream of the dams, the lowermost river recruits enough sediment from bank erosion to maintain near-natural mobility of the channel in the lower reaches before the estuary (Draut and others, 2011). The response of the Elwha riverbed generally is consistent with other rivers with reduced sediment supply downstream of dams (Williams and Wolman, 1984; Collier and others, 1996; Pizzuto, 2002; Grant and others, 2003).

The lower Elwha River merges into a geomorphically diverse estuarine complex. The estuary includes the river mouth, several coastal ponds on either side of the river mouth, and several small side channels that connect these water bodies (fig. 9.1*C*). Within the estuary, river water, seawater, and groundwater mix to provide brackish conditions and habitat for young salmonids and other fish and wildlife species (Magirl and others, 2011, chapter 4, this report; Duda and others, 2011b, chapter 7, this report). The zone of saltwater-freshwater mixing varies as a function of tidal stage, river discharge, and storm surges, as well as channel morphology.

The estuary has a broad suite of vegetation types, including (1) mixed riparian forest, (2) young willow/alder forests, (3) riparian shrub, (4) shrub–emergent marsh transition, (5) emergent marsh, and (6) dunegrass. It contains a diverse assemblage of plant species, as Shafroth and others (2011, chapter 8, this report) found more than 120 plant species during surveys of each of the vegetation types. The riparian shrub and shrub–emergent marsh transition vegetation types had the highest total richness (52 species), although the emergent marsh vegetation type had the lowest total richness (31 species). About one-third of plant species currently around the estuary are non-native.

The estuary is tidally influenced and brackish, although water level and salinity patterns across this system vary in space and time. Numerous channels, which play an important role in estuarine circulation, regulate the exchange of water between the river mouth and the coastal ponds. This is determined by the differences in the water levels, salinity, and temperature between the eastern and western areas of the estuary across all seasons. Dudley Pond is contained behind a flood-control levee on the west side of the river mouth. Lacking a direct surface-water connection to the river, the pond is less saline, warms to higher temperatures, and has smaller variability in water levels compared to the lentic waters of the eastern estuary that contain numerous surface water connections (Magirl and others, 2011, chapter 4, this report; fig. 4.3). The morphology of the interestuarine channels does change with time as sediment is moved in the river mouth by river discharge events and coastal waves. High flows in the river also alter the water conditions in the estuary by raising water levels and flushing out saline water for as long as several days (see example in Magirl and others, 2011, this report, fig. 4.7).

The removal of Elwha and Glines Canyon Dams will not instantaneously result in resupply of sediment to the lower river and coast. Instead, the dam removal process itself will take several years, with complete removal anticipated in about 2.5 years after deconstruction commences (Duda and others, 2011a, chapter 1, this report). While the dams are being removed, it is anticipated that some fine-grained sediment will be remobilized from reservoir deposits, especially during winter and spring floods. Most of the fine sediment will be transported through the lower river and enter the nearshore region (Randle and others, 2006), to be dispersed by tidal currents and waves (fig. 9.2). A much smaller amount of the fine sediment will be deposited in the flood plain of the lower river, although fine-sediment deposition, where it occurs, likely will influence the hydrology, vegetation, and habitats of the river flood plain.

The rate of transport and timing of arrival of coarse-grained bedload to the lower Elwha River will depend on the number, magnitude, and duration of floods in the years during and after dam removal (Randle and others, 2006; Konrad, 2009). Coarse-sediment release may begin during the second winter season after the start of deconstruction, although large quantities of bedload probably will not pass the Glines Canyon Dam site until the winter of the final year of the project (2013–14). This enhanced bedload transport will continue down the middle reach of the river (between the two dams) for another 2–5 years after complete removal of Glines Canyon Dam (Randle and others, 2006; Czuba and others, 2011, chapter 2, this report).

As sediment is transported downstream of the reservoir sites, alluvial sections of the Elwha River will accumulate sediment and aggrade (fig. 9.3). Sand and gravel is expected to fill pools, and may cause more active channel migration and channel avulsions. Because of aggradation and fining of material in the lower river, the channel could see increased braiding, at least temporarily (Draut and others, 2011). This likely would result in a straighter channel alignment (steeper slope), which is consistent with a braided channel planform (Randle and Bountry, 2008). In the decades after dam removal, Kloehn and others (2008) suggest the rate of channel migration may increase in the river sections below the dams. Draut and others (2011) determination of local fine sediment supply along the flood plain of the lower river indicates that the rate of channel migration may remain stable over the long term.

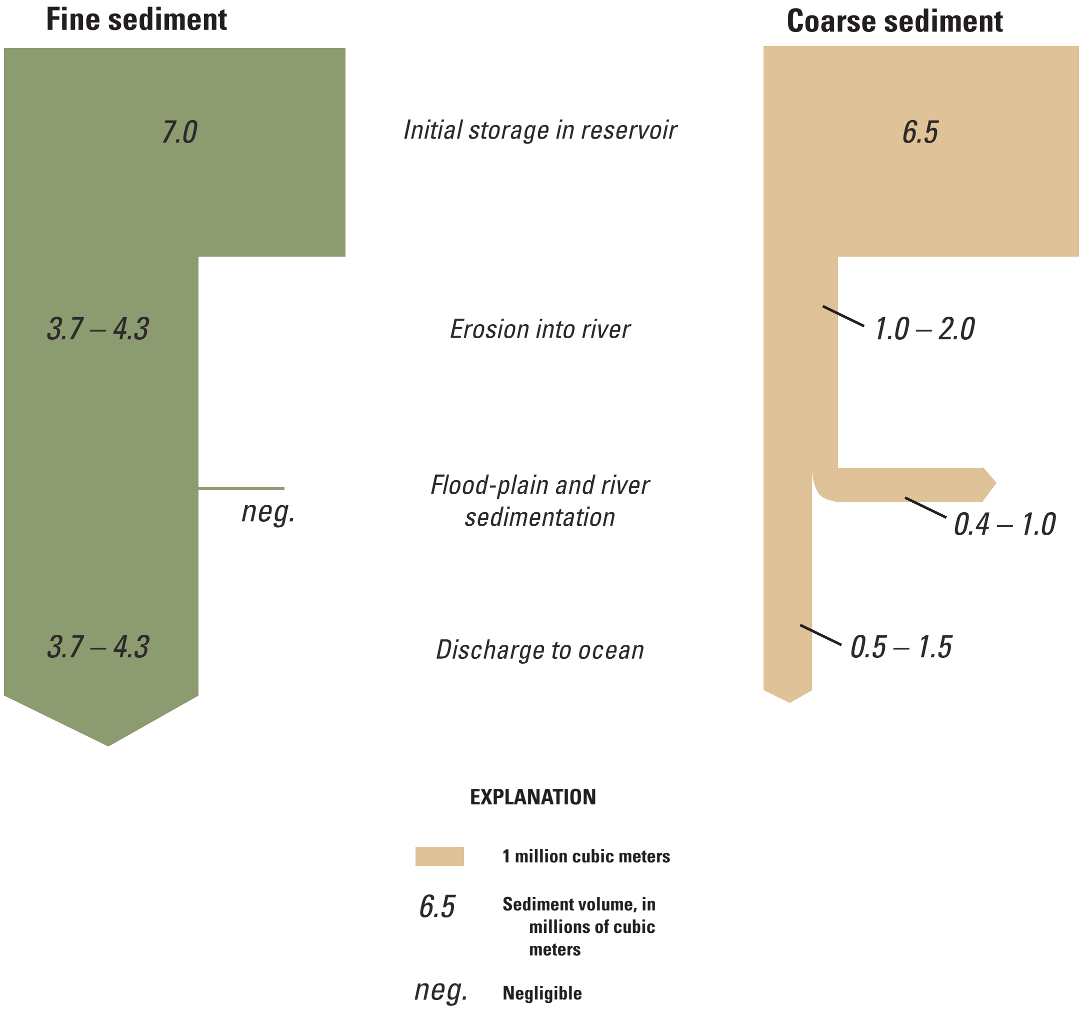


Figure 9.2. Conceptual sediment budget for fine and coarse sediment stored in the two Elwha River reservoirs during the first 3 years after dam removal, Elwha River, Washington. (After numerical modeling simulations by Randle and others, 1996). The range of values presented in this figure show the variation in simulated output of four contrasting hydrologic scenarios. Fine and coarse sediment separated by the grain-size threshold of 0.063 millimeters.

In the lower river, the initial increases in sediment load likely will disrupt aquatic and riparian ecology. Vegetation changes related to dam removal will depend largely on how much an influx of large woody debris and sediment alters the distribution and character of geomorphic surfaces, in particular estuarine shorelines (fig. 9.4). Another factor relates to the spatial and temporal nature of tidal connections and whether or not the connections change as the river mouth reconfigures after dam removal. These connections affect water level fluctuations and salinity levels, which likely would influence the "emergent marsh" and "shrub-emergent marsh transition" vegetation types. Additionally, any changes that appreciably alter the hydrologic connections between the river and estuary or the sedimentation and turbidity in estuarine habitats could affect the timing and habitat use patterns of migrating juvenile salmonids, as well as the resident fish assemblage of the estuary (Shaffer and others, 2009; Duda and others, 2011b, chapter 7, this report).

As sediment deposition and incorporation of large-woody debris and organic matter occur, the quantity and quality of fish habitat is expected to increase downstream of the dams (Woodward and others, 2008). The major ecological change in the lower river and estuary likely will result from the return of large numbers of fish. If recolonization of upper areas of the watershed causes salmon to return to the river in numbers larger than current populations, as projections suggest, then the nutrient concentrations in the river and estuary may change at least during some parts of the year.

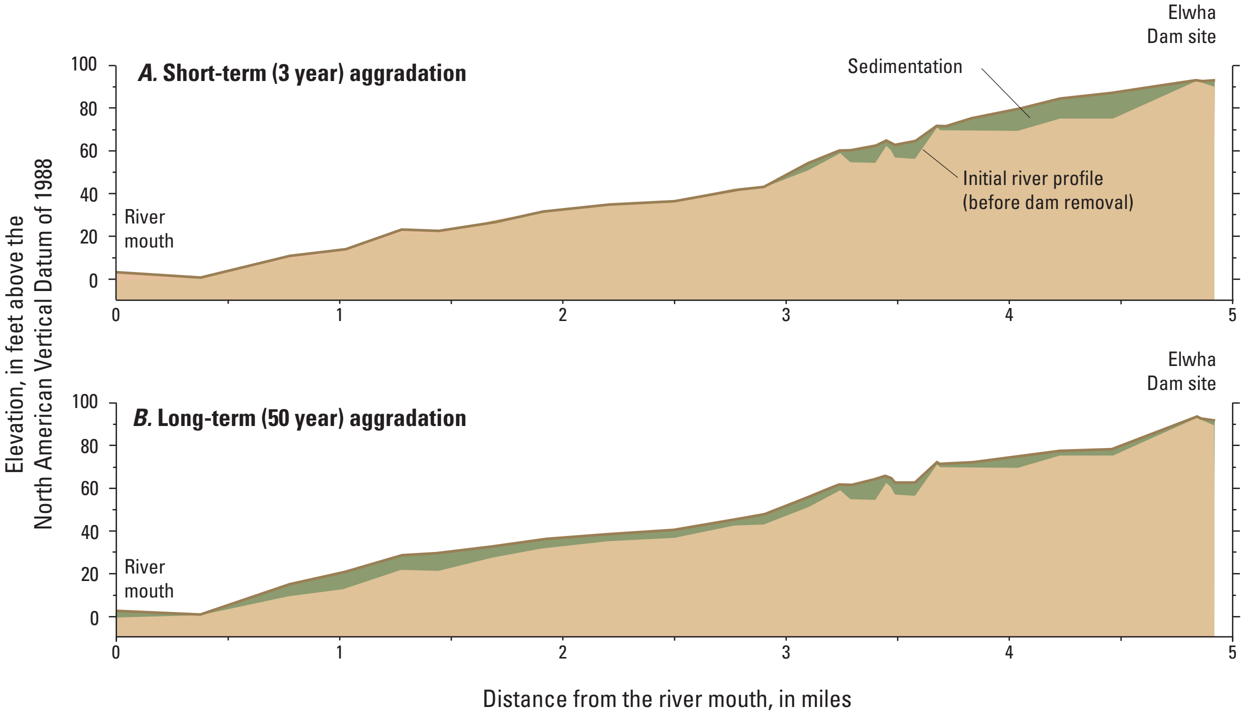


Figure 9.3. Schematic cross sections showing simulated response of the elevation to increased sediment loads after dam removal, Elwha River channel, Washington. (After Randle and others, 1996). Results shown for (*A*) short-term response following 3 years of renewed sediment supply and (*B*) long-term response after 50 years.

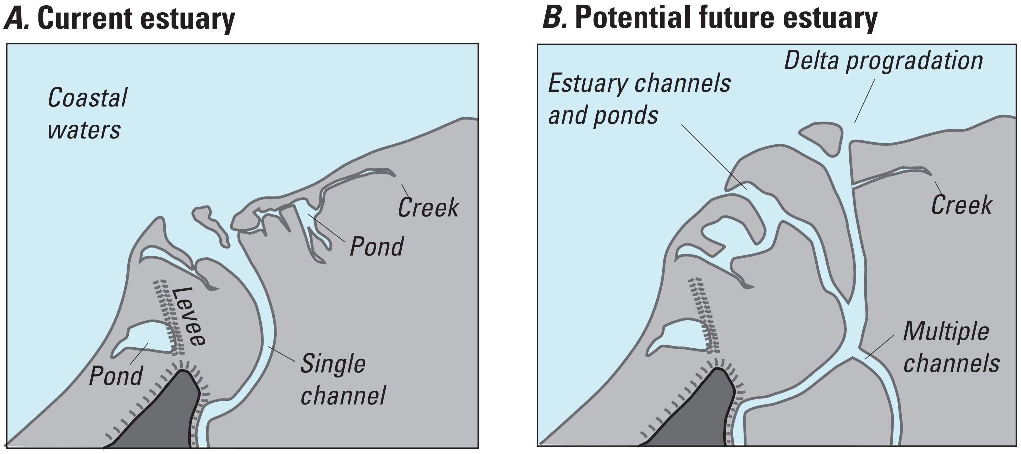


Figure 9.4. Schematic diagrams showing the (*A*) current estuary morphology and (*B*) potential morphologic changes to the estuary after several decades following dam removal and lower river sedimentation. The future changes to the estuary have not been predicted and therefore will not precisely mimic the patterns shown in (*B*); however, the future changes likely will exhibit many of the qualities shown in (*B*) such as multiple channels and delta progradation.

If phosphorous and nitrogen limit the biomass of primary producers in the Elwha River ecosystem, then increases in these nutrients may have important implications. Currently, the river is classified as oligotrophic (Munn and others, 1999; Duda and others, in press), and any increase in nutrient concentrations could significantly change the aquatic ecology of the river and estuary. Based on estimates of future salmon returns following full recovery, 1,275–10,900 kg of nitrogen and 210–1350 kg of phosphorous derived from salmon could be put into the river annually (estimates based on assumptions of Munn and others, 1999, and projected spawners presented by Ward and others, 2008). Although it is not likely that increased numbers of salmon will cause increases in dissolved water-column nutrients because of rapid flushing during the high flow season, salmon-derived nutrients may enter aquatic and riparian foodwebs through direct consumption by fish and aquatic invertebrates, or by indirect pathways like the guts of scavengers. This could provide temporal increases in the biomass and growth rates of resident biota (for example, Schuldt and Hershy, 1995; Bilby and others, 1996; Wipfli and others, 1998; Chaloner and Wipfli, 2002; Duda and others, in press).

Elwha River Beaches and Nearshore

The beaches and delta adjacent to the mouth of the Elwha River are the product of geomorphic processes that have continually formed and modified these landforms over multiple millennia. These processes include tectonic land-level changes, glaciation and related sea-level changes, erosion and sediment transport by the river, and coastal sediment transport by waves and currents (Warrick and others, 2011a, chapter 3, this report). Over the past century, the Elwha River beaches and nearshore have been modified by the presence of the two dams through a reduction in sediment delivery. Although coastal waters still receive sediment from the river, derived from erosion of channel-bank sediments deposited in the flood plains, most of the upriver sediment supply is intercepted by the reservoirs (Curran and others, 2009; Bountry and others, 2010). Several potential pathways for sediment discharged from the river exist, including along the beach, onto the nearshore submarine delta, and out into the deeper Strait of Juan de Fuca (fig. 9.5). The transport, fate, and implications of this sediment will be largely dependent on the physical processes and ecosystems within these settings (Miller and others, 2011; Warrick and others, 2011b, chapter 5, this report).

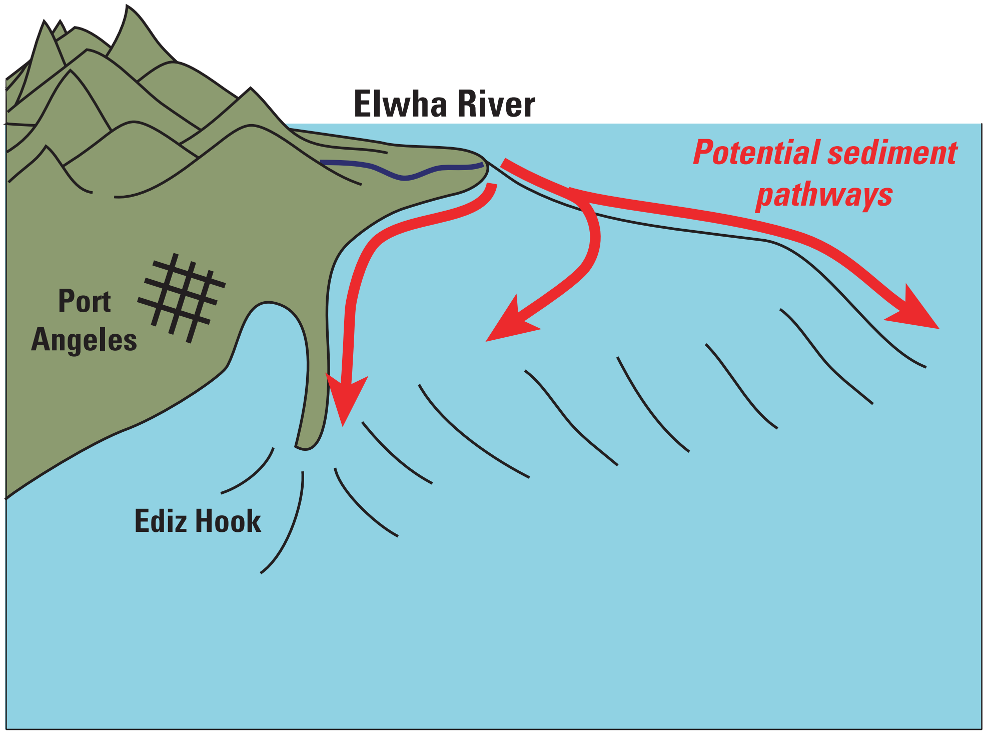


Figure 9.5. Schematic diagram showing the potential transport pathways for sediment offshore of the Elwha River mouth, Washington. Actual transport directions will be determined by sediment grain size and the strength, direction, and persistence of coastal currents and waves.

Discharge from the Elwha River enters the Strait of Juan de Fuca as a buoyant freshwater plume, influencing the water properties of the nearshore from Freshwater Bay to Ediz Hook and Port Angeles. The position of the freshwater plume is largely determined by tidal conditions. Warrick and Stevens (2011) examined the behavior of the freshwater plume and determined that about 50 percent of the time the plume is directed toward the east, and about 40 percent of the time the plume maintains a radial spread from the river mouth. The remainder of the time, less than 10 percent, the river plume is directed toward the west (fig. 9.6). These tidally influenced river plume conditions have implications for sediment dispersal and nearshore conditions during and after dam removal. As millions of cubic meters of sediment are released from the reservoirs, the fine-grained material will be transported in the river plume and arrive in the nearshore. Warrick and Stevens (2011) suggest that the nearshore area within 1 km of the Elwha River mouth will see the greatest suspended sediment and turbidity levels.

The reduced sediment supply to the Elwha River nearshore has changed the physical character of the delta and nearshore sea floor, which in turn has changed the biological assemblages dependent upon this habitat. The shoreline and submarine areas of the Elwha River delta are dominated by coarse sediment (gravel, cobbles, and boulders; Warrick and others, 2008; 2011b, chapter 5, this report). A time-series analysis of historical aerial photographs and contemporary topographic surveys of the beaches have identified significant coastal erosion since dam construction (Warrick and others, 2009). Net erosion rates have increased over time, from 0.8 m yr^{-1} from 1936 to 1990 to 1.4 m yr^{-1} during 1990–2006 and local erosion rates as much as 3.8 m yr^{-1} during 2004–07 (Warrick and others, 2009). It is uncertain whether a lack of fine sediment supply from the river also has resulted in a coarsening of the beaches over time.

These physical changes have influenced the plants and animals living in the nearshore environment. Recent scuba dive surveys (Rubin and others, 2011, chapter 6, this report) determined that a species-rich and biologically diverse community that included 10 kelp species, each with different growth forms and habitat affinities, inhabited the Elwha River nearshore. Community structure, including density, taxa richness, and habitat associations, was controlled in part by substrate composition, seafloor relief, and depth. Taxa richness (total number of kelp, invertebrate, and fish taxa) was more strongly associated with seafloor relief than with substrate type, although because relief usually was present in the form of scattered boulders perched on mixed sand, gravel, and cobble substrate, substrate also indirectly contributed to this relation. On average, 12 (59 percent) more taxa occurred where boulders were present compared to areas lacking boulders but with otherwise similar conditions.

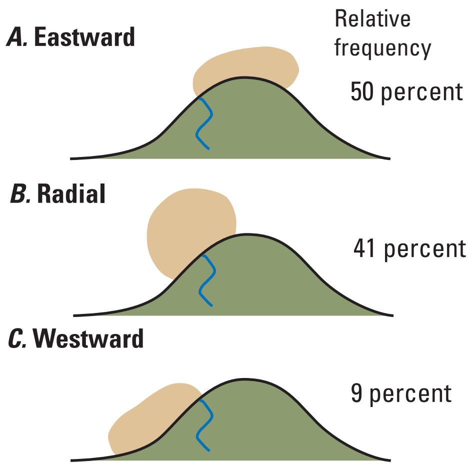


Figure 9.6. Schematic diagrams showing the behavior of the buoyant coastal plume of the Elwha River, Washington. (After Warrick and Stevens, 2011). The plume is bent toward the east (*A*) and west (*C*) during strong tidal currents, and is radial (*B*) during weak currents. Oceanographic observations suggest that the plume is bent toward the east more frequently than toward the west.

Four main species-habitat associations were identified in the Elwha River nearshore zone. The highest kelp density and taxa richness were in bedrock/boulder reefs, and were characterized by a surface canopy of bull kelp and a secondary canopy of perennial kelp 1–2 m above the seafloor. Mixed sand and gravel-cobble habitats with moderate relief had the highest density of invertebrates and a taxa richness nearly as high as in bedrock/boulder reefs. Mixed sand and gravel-cobble habitats with low relief were areas lacking in boulder cover (which generally reduced relief scores and excluded species that preferred seafloor relief) supported a moderate density of kelp (primarily annual species with blades close to the seafloor) and the lowest invertebrate density among the four habitat types. Sand habitats in localized sand bodies were limited in extent. These sandy areas had the lowest kelp density and kelp taxa richness, with a moderate density of invertebrates. Sandy substrate along the west side of Freshwater Bay supported eelgrass meadows, an important habitat for juvenile salmon and other fish species.

A significant amount of the sediment released by the dam removal project eventually will be discharged into the Strait of Juan de Fuca at the Elwha River mouth (fig. 9.2). Waves and currents that move sediment along and across the delta will dictate the fate of this sediment. The waves of the Elwha River delta region are primarily from the northwest.

This occurs for swells (10–18 second wave periods), which are derived from storms in the North Pacific Ocean, and wind waves (2–6 second wave periods), which are generated in the Strait of Juan de Fuca from westerly winds (Warrick and others, 2008; 2011b, chapter 5, this report). The oblique direction of these waves results in strong littoral transport along the delta, driving sediment transport toward the east (Miller and others, 2011). The currents offshore of the beaches are driven primarily by the tides; however, the shape of the delta influences water that must flood and ebb past the Elwha River delta due to these tides. Eddies that are 2–5 km in diameter are formed on the downstream sides of this deltaic headland during most tidal floods and ebbs. These currents influence the location of the turbid river plume, the location of the initial sediment settling, and subsequent movement of sediment (Gelfenbaum and others, 2009).

A flood on December 3, 2007, foreshadowed the potential changes that dam removal may bring to the Elwha River mouth and nearshore area. A large scale rain-on-snow storm caused rivers of the Olympic Peninsula to swell, with the peak discharge on the Elwha River recorded as 1,020 m^3/s, and an estimated 40-year recurrence interval (Draut and others, 2011; Duda and others, 2011a, chapter 1, this report). Detailed mapping of elevations of the Elwha River mouth in September 2007, and again in September 2008, revealed an accumulation of about 34,000 m^3 of sediment directly offshore of the river mouth. This sediment accumulation likely was associated with the peak discharge from the intervening December 2007 flood. It also changed salmon access to the east estuary, as revealed by observations on the ground and changes in fish community structure and density (Shaffer and others, 2009; Duda and others, 2011b, chapter 7, this report).

A calibrated hydrodynamic and sediment transport model described by Gelfenbaum and others (2009) provides some predictions of the fate of sediment during and following dam removal. Forced with waves, currents and river discharge, the model predicts the dispersal of fine-grained silt and sand across the delta. Model simulation results indicate that a larger sediment supply, such as that which is expected following dam removal, would spread in a zone to the east and west of the river mouth, largely driven by tidal currents (fig. 9.7). Because of the asymmetry in the tidal currents off the river mouth, sand will be mostly deposited east of the river mouth, whereas silt will be more evenly deposited to east and west of the river mouth. The weaker tidal currents directed to the west should be strong enough to transport silt in this direction, but probably are not strong enough to transport much sand to the west. Thin accumulations of silt and sand are expected across most of the delta, with thicker accumulations in deep water off the eastern edge of the delta and east of Ediz Hook, just inside of Port Angeles harbor.

The initial large sediment influx to the nearshore zone from released reservoir sediments will stress nearshore communities, but in the long-term, the communities should benefit from restoration of the natural, pre-dam sediment delivery regime (fig. 9.8). Separating the short-term effects from long-term benefits will be a primary challenge facing scientists in the years following dam removal. In the short term, negative effects will be greatest for species most vulnerable to deposited and suspended sediments. Kelp, for example, are vulnerable because they require relatively sediment-free surfaces for spore settlement. Their microscopic gametophyte and young sporophyte life stages also are susceptible to burial. Plants that can propagate vegetatively, on the other hand, may be resistant to sedimentation because they bypass these vulnerable juvenile life stages.

As high sediment transport and increased turbidity continue for 2–3 years during dam removal, community composition of plants and invertebrates is likely to change (Airoldi, 2003), and species richness may decline. The spatial extent, vertical thickness, frequency, duration, seasonal timing, and particle characteristics (for example, grain size and shape, mineral and chemical composition) of deposited sediment will largely determine the ecological response. Of the four main community-habitat associations described, each will have different responses to increased sedimentation. Bedrock/boulder reefs may be most vulnerable if deposited sediments bury organisms attached to the reef or prevent establishment of their propagules. On the other hand, vertical surfaces of hard substrate, such as the sides of large boulders, will not collect sediment and may serve as refugia for some reef-adapted taxa. If localized accumulations of sediment are great enough, some areas could convert from hard substrate to soft substrate, causing dramatic community shifts and decreasing habitat heterogeneity. Accumulations of very fine sediment (silt and clay) could benefit tube-building amphipods (*Ampelisca* spp.), which provide food for various other organisms (see Rubin and others, 2011, Chapter 6, sidebar 6.1, this report).

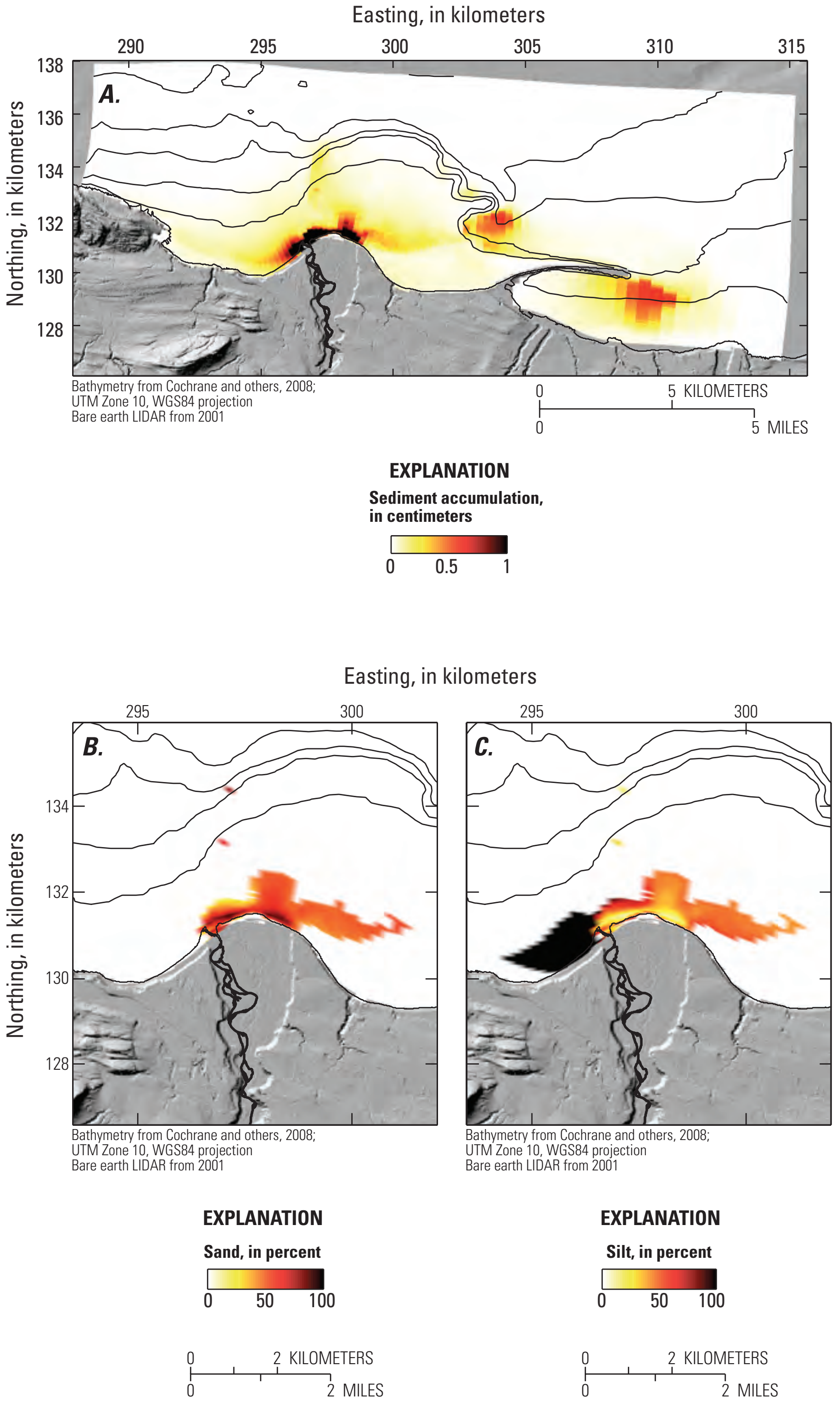


Figure 9.7. (*A*) simulated sediment accumulation offshore of the Elwha River mouth, Washington, after flood event from the river. (After Gelfenbaum and others, 2009). Results derived from a three-dimensional hydrodynamic model of water and two classes of sediment, sand, and silt. The sand (*B*) preferentially accumulates east of the river mouth, and the silt (*C*) accumulates on both sides of the river mouth.

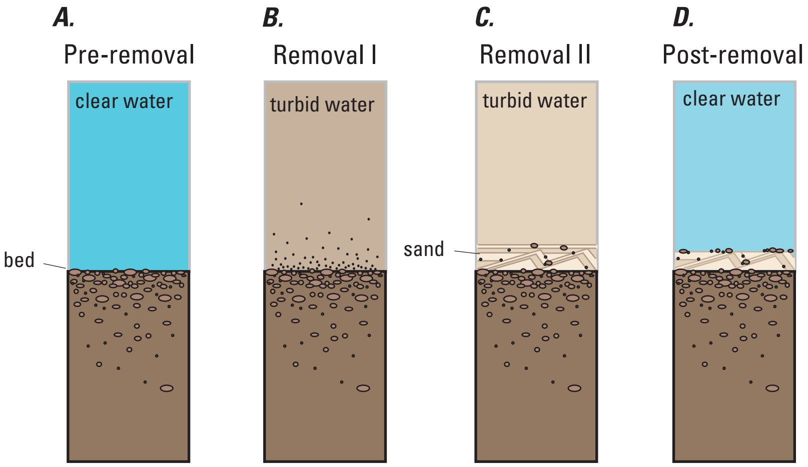


Figure 9.8. Schematic diagram showing the coastal water and seafloor near the Elwha River mouth, Washington, and hypothetical changes before, during, and after dam removal. (*A*) The pre-removal condition has relatively clear water and a gravel bed. (*B*) Sediment loading during removal initially will increase suspended-sediment concentrations and turbidity in the water column. (*C*) Sand introduced to the coastal waters likely will accumulate and change the grain size of the seafloor. (*D*) Several years following the dam removal, the coastal waters will be much less turbid, although the grain size of the seafloor likely will be sandier than observed before the dam removal.

Summary

The Elwha River dam removal and ecosystem restoration project is an unprecedented opportunity for scientific discovery. It also is inherently multidisciplinary, with changes to the physical and biological components of the ecosystem expected. The multidisciplinary team assembled as part of this project has attempted to develop baseline information about the river from multiple perspectives. From species diversity in the nearshore region to vegetation communities in the estuary, and growth, habitat use, and migratory patterns of juvenile salmon, many species will be affected by the dam removal project. Complex interactions among trophic levels and the environments upon which they depend are expected during and after dam removal. As environments change due to sediment release from the reservoirs, species will reassemble into new configurations in the estuary and nearshore environments. Similarly, the hydrology, geomorphology, and coastal oceanography will change in the river, estuary, and nearshore zone below the dams. The largest controlled release of sediment in history, characterized by high suspended sediment in the near term followed by more gradual movement of larger material over the coming decades, will also bring about changes. These changes to the physical habitat and biological characteristics of the ecosystem will need to be monitored to allow for a full evaluation of the restoration of the Elwha River.

Acknowledgments

Funding for this work came from the U.S. Geological Survey, Coastal Habitats in Puget Sound project. We are grateful to all of the authors who contributed to this report. Their dedication and passion for improving the scientific understanding of large-scale ecosystem change associated with the Elwha River Restoration Project is evident in their work. We thank the Lower Elwha Klallam Tribe for valuable discussion and insights into the Elwha River and estuary. This chapter benefited from conversations with Steve Rubin and Christopher S. Magirl.

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