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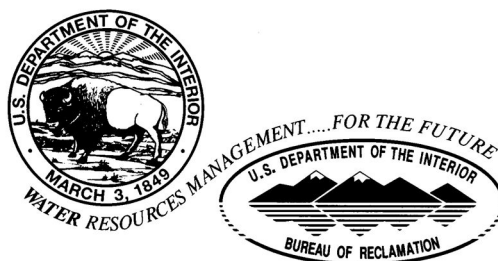
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**ELWHA RIVER
ECOSYSTEM AND FISHERIES
RESTORATION PROJECT,
Washington**

**ELWHA TECHNICAL SERIES
PN-95-9**

**SEDIMENT ANALYSIS AND
MODELING OF THE
RIVER EROSION ALTERNATIVE**

**U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
PACIFIC NORTHWEST REGION, BOISE, ID**



OCTOBER 1996

**Elwha Technical Series
PN-95-9**

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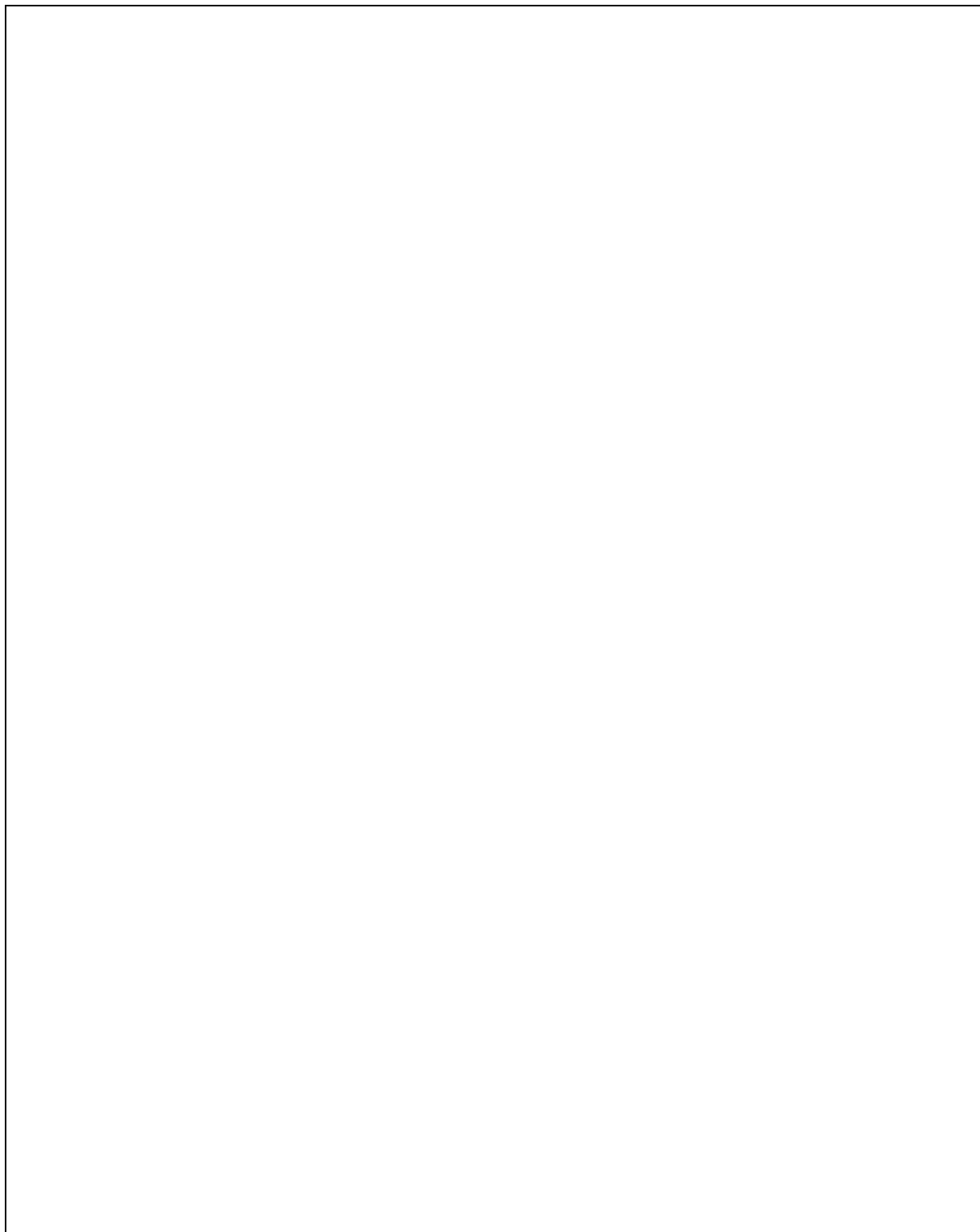
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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Location Map — Elwha River, Port Angeles, WA



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SUMMARY

Removal of two hydroelectric dams on the Elwha River of Washington's Olympic Peninsula is an alternative being considered to restore the ecosystem and native anadromous fisheries. Elwha and Glines Canyon Dams block anadromous fish passage to more than 70 miles of the Elwha River and its tributaries, limiting anadromous fish to the lower 4.9 river miles. Lake Aldwell, formed behind Elwha Dam in 1913, stores an estimated 4 million cubic yards (myd³) of sediment. Further upstream, Lake Mills was created in 1927 with the closure of Glines Canyon Dam and contains an estimated 14 myd³ of sediment.

Removal of these dams requires development and analysis of alternative plans to manage the reservoir sediment and analysis of the effects of re-establishing the natural sediment supply to the Elwha River downstream of the dams. Removing the dams in controlled increments and allowing reservoir sediment to erode and be transported downstream through natural processes is the alternative evaluated in this report. The impacts of this alternative on the river's sediment concentration, riverbed aggradation, and corresponding increases in flood stage were predicted from results of reservoir drawdown testing at Lake Mills and a series of computer models.

Model results predicted that 15–35 percent of the coarse sediment (sand, gravel, and cobbles) and about half of the fine sediment (silt- and clay-size particles) would be eroded from the two reservoirs because of dam removal. The remaining sediment would be left behind along the reservoir margins as a series of terraces. Fine sediment concentrations released from the reservoirs would be high during periods of dam removal, typically 200–1,000 ppm but occasionally as high as 30,000–50,000 ppm. Release concentrations would be relatively low — less than 200 ppm — during periods of high lake inflow when dam removal activities and lake drawdown would stop. After the dams are removed, fine sediment concentrations would be low and near natural conditions during periods of low flow. Concentrations would be high during progressively higher floodflows as erosion channels widen in the reservoir areas. Within 2 to 5 years, concentrations would return to natural levels.

Coarse sediment would aggrade in river pools in the relatively steep reach between the two lakes and would increase 100-year-flood stages up to 0.5 feet. In the more mild slope reach below Elwha Dam, general riverbed aggradation would occur which would likely cause the river to migrate laterally, especially near the mouth. Over the short term (up to five years), this could potentially increase river stages during the 100-year flood 0–3 feet, depending on location, with an average increase of less than 1 foot. Over the long term (50 years), aggradation could continue and increase existing river stages during the 100-year flood 0–5 feet (depending on location) with an average increase of 2.5 feet. Coarse sediment would enlarge the delta at the river's mouth to a size and character similar to that of predam conditions.

With monitoring and mitigation, the “river erosion alternative” constitutes a viable sediment management plan for the removal of Glines Canyon and Elwha Dams. Extensive monitoring and control of the dam removal rate are needed to manage or avoid problems with riverbed aggradation, flooding, and water quality.

PART I

INTRODUCTION, ISSUES, ALTERNATIVES, AND QUALITATIVE ASSESSMENT

CHAPTER I. INTRODUCTION

The U.S. Department of the Interior (Interior) is considering plans to purchase and remove two privately owned hydroelectric dams for the purpose of restoring the ecosystem and native anadromous fisheries. The dams are located on the Elwha River in and adjacent to Olympic National Park (Park), Washington. The construction of Elwha and Glines Canyon dams has blocked anadromous fish passage to more than 70 miles of the Elwha River and its tributaries, limiting anadromous fish habitat to the lower 4.9 river miles.

Congress passed the Elwha River Ecosystem and Fisheries Restoration Act (the Act), which became Public Law 102-495 when signed by the President in October 1992. The goal of the Act is the "...full restoration of the Elwha River ecosystem and native anadromous fisheries." The Act directed the Secretary of the Interior to study ways to restore the anadromous fisheries and the ecosystem of the Elwha River. The resultant study, named *The Elwha Report, Restoration of the Elwha River Ecosystem & Native Anadromous Fisheries* (Interior et al., 1994) determined that removing Elwha and Glines Canyon Dams was feasible and necessary to restore the fisheries and ecosystem. Removal of these dams requires the development and analysis of alternative plans to manage the reservoir sediment and analysis of the effects of re-establishing the natural sediment supply to the Elwha River downstream of the dams.

The "river erosion alternative" is removing the dams in controlled increments and allowing riverflows to erode the reservoir sediment and transport them downstream. Riverflow and sediment conditions of the reservoirs and river would be extensively monitored during and after dam removal. The rate of sediment release from the reservoirs would be controlled by controlling the rate of dam removal. The impacts of this alternative on the sediment concentration, riverbed aggradation (and any corresponding increases in flood stage), and the reservoir topography and landscape are evaluated in this report.

A. STUDY PURPOSE AND OBJECTIVE

The purpose of this study is to provide supporting information for the Olympic National Park's environmental impact statement on the implementation of Elwha River Ecosystem Restoration Project. The objective of this study is to evaluate and describe the sediment-related impacts of the river erosion alternative.

B. REPORT ORGANIZATION

This report is organized into four parts. Part 1 provides an introduction and overview of the physical setting, the sediment management issues to be considered, a description of the river erosion alternative, and a qualitative assessment of impacts. It is intended for those readers who have a general interest in the Elwha River Restoration Project.

Part 2 provides an overview of the basic data used in this report with references to other reports that provide more detail. It is intended for readers who have a basic understanding of hydrology or geomorphology.

Part 3 provides a detailed discussion of the analyses and various numerical (computer) models that were used to quantitatively predict impacts of the river erosion alternative. It is intended for those readers who have a good understanding of geomorphology and computer modeling.

Part 4 presents the overall report conclusions and is intended for those readers who have a general interest in the Elwha River Restoration Project.

C. EXISTING CONDITIONS

1. Basin hydrology and river channel characteristics — The Elwha River is a coarse-bed stream located on the Olympic Peninsula of northwestern Washington state. The river flows northward 45 miles from the base of Mount Olympus to the Strait of Juan de Fuca (Strait) near Port Angeles, Washington (location map). The river is steep (with an average slope of 1.9 percent) and falls about 4,500 feet in elevation. It is the fourth largest river on the Olympic Peninsula and its watershed includes more than 100 miles of stream channel. The watershed has a drainage area of 321 square miles — 83 percent of that in the Park (Federal Energy Regulatory Commission [FERC], 1993; Interior et al., 1994). The watershed upstream from Lake Mills is entirely within a federally designated wilderness area and also inside the Park.

The maritime climate of the area is characterized by mild, wet winters and relatively cool, dry summers. Annual precipitation in the watershed ranges from 220 inches in its upper reaches to 56 inches near the river's mouth. The average daily discharge is about 1,500 cubic feet per second (cfs) (U.S. Geological Survey [USGS], 1993). Minimum flows typically occur during summer and range from about 300 to 500 cfs. High flows are typical from November through February and from May through June. The 2-year flood is 13,000 cfs and the 100-year flood is 42,800 cfs (Reclamation, March 1995).

Elwha and Glines Canyon Dams were constructed on the Elwha River to provide hydroelectric power for development of the Olympic Peninsula in the early 1900's. The dams are operated as run-of-the-river facilities and provide 38 percent of the power used by the Daishowa America Co., Ltd. Port Angeles paper mill (FERC, 1993).

Elwha Dam, at river mile[†] (RM) 5, was constructed 1910–13. This 105-foot-high concrete gravity dam forms Lake Aldwell, which has a capacity of 8,000 acre-feet. Glines Canyon Dam, at RM 13.5, was constructed 1925–27. This 210-foot-high, concrete arch dam forms Lake Mills, which has a capacity of 40,500 acre-feet (FERC, 1993). Both lakes are maintained at or near full capacity and are not operated for flood control purposes.

[†] The river mile (RM) designation refers to the distance along the river channel, in miles, upstream from the mouth at the Strait of Juan de Fuca.

As of 1994, it was estimated that 13.8 million cubic yards (myd³) of sediment were trapped in Lake Mills — the upstream reservoir — and 3.9 myd³ of sediment was trapped in Lake Aldwell — the downstream reservoir (Reclamation, August 1995). Of the total 17.7 myd³ of sediment, about half (52 percent) is fine (clay- and silt-sized) and the other half (48 percent) is coarse (sand, gravel, and cobbles sediment). The division between fine and coarse sediment used in this report is 0.075 mm, which is the same standard used in *Alluvium Distribution in Lake Mills, Glines Canyon Project and Lake Aldwell, Elwha Project, Washington* (Reclamation, August 1995).

The Elwha River's slope is greatest at the headwaters (about 16 percent above RM 43) and is less steep downstream (Hosey, 1988). The river flows through several steep, narrow, bedrock canyons between wide alluvial reaches of more mild slope. The reach near the mouth has the widest floodplain and mildest slope.

The alluvial reaches of the Elwha River upstream from Lake Mills are dynamic. Bank erosion and channel migration create gravel and cobbles bars that erode and later re-form (Hosey, 1988). Downstream from the dams, which trap the coarse sediment, sands and gravels have been eroded and this once dynamic reach is now relatively stable.

Upstream from Lake Mills, riverbed material consists of sand, gravel, cobbles, boulders, and bedrock outcrops. The river bed has likely eroded sand, gravel, and small cobbles from the riverbed downstream from both dams, following dam closure, and now consists primarily of large cobbles, boulders, and bedrock. Because of riverbed armoring and the lack of gravel-sized sediment, current fish spawning habitat is limited to a few side channels near the mouth and riffles up to RM 3 (B. Winter, Olympic National Park, WA, oral communication, 1995).

Between Glines Canyon Dam (RM 13.5) and RM 4.0 (below Elwha Dam), bedrock controls the river gradient. Post-dam river flows have produced extensive armoring and stabilization of the active channel (Reclamation, March 1996). In this reach, almost 40 percent of the armor layer consists of boulders (300 mm or larger), about 50 percent is cobbles (75 to 300 mm), and about 10 percent is composed of gravel with traces of sand (less than 75 mm).

In the reach between the two lakes, the present river slope does not appreciably differ from the 1926 river slope, indicating that significant channel incision below Glines Canyon Dam has not occurred. Comparisons of channel configurations from present aerial photographs and pre-project river survey maps show that excessive channel migration has not occurred and the channel configuration has indeed been fixed by the canyon reaches (Reclamation, March 1996; Hosey, 1988).

The reach of the Elwha River between RM 4.0 and RM 2.5 was identified by Reclamation (March 1996) as a short transition reach between bedrock control of the upper reach and more alluvial reach downstream. Only about 10 percent of the armor layer consists of boulders, 75 percent is cobbles, and about 15 percent is gravel with traces of sand.

Between RM 2.5 and the mouth (RM 0.0), bedrock control of the river gradient is absent and post-dam river flows have produced moderate channel migration and channel down-cutting. The Elwha River channel widens and is entrenched in relatively easily eroded glacial deposits. Channel armoring is present in this reach, but is not as well-developed nor as coarse-grained as in the upper reach. No boulders were observed in the riverbed. About 55 percent of the bed is cobbles and about 45 percent is gravel with some sand.

There are four sets of fluvial terraces associated with the Elwha River (Reclamation, March 1996). Terrace deposits are generally exposed 3–18 feet above river level and adjacent to the river channel. These terraces predate the dams and represent predam sediment gradations along the floodplains of the Elwha River. The terraces contain few boulders, about 30 percent cobbles, about 35 percent gravel (5 to 75 mm), about 20 percent sand (0.075 to 5 mm), and about 10 percent silt- and clay-sized material (less than 0.075 mm). The elevations of these four terraces above river level are 3–4 feet, 5–7 feet, 10–12 feet, and 15–18 feet. The lower terraces may reflect erosion of the Elwha River bed following construction of the upstream dams.

Prior to dam construction, an extensive delta had formed at the mouth. For thousands of years, strong ocean currents in the Strait transported sediment from this delta eastward to form Ediz Hook — a spit of land that protects the natural harbor at Port Angeles. With completion of Elwha Dam in 1913, the amount of sediment reaching the river delta and Ediz Hook was significantly reduced and the delta and hook began to erode (Schwartz, 1994). Large boulders have been placed to protect the hook's shoreline from erosion. However, this shoreline protection measure requires long-term maintenance.

2. Existing infrastructure — All facilities and structures along the Elwha River are downstream from Glines Canyon Dam. These include:

- Roads and bridges (including county, State and Federal highways);
- Electrical transmission lines;
- Flood control levees;
- Private residences;
- A diversion dam and water intake for two Port Angeles mills;
- City of Port Angeles Ranney collector;
- Dry Creek Water Association well;
- Private wells;
- Washington Department of Fish and Wildlife (WDFW) Fish-rearing channel;
- Lower Elwha Klallam Tribe (the Tribe) lands, homes, tribal center, and fish hatchery; and
- Olympic National Park campgrounds, Elwha work station, ranger station, and park entrance.

3. Cultural resources — The Elwha River valley is rich in cultural resources with human occupation dating from prehistoric times. These cultural resources include historic and prehistoric archeological sites and tribal traditional cultural properties (including natural landforms and traditional fishing sites). Both Elwha and Glines Canyon Dams are listed on the National Register of Historic Places (National Park Service, 1994).

CHAPTER II. SEDIMENT MANAGEMENT ISSUES

Sediment management issues related to Elwha River restoration have been described by Randle and Lyons (1995). The amount and rate of reservoir sediment released downstream during and following dam removal influences both short- and long-term impacts. Over the short term, the release of fine lakebed sediment (silt- and clay-sized material) would affect water quality (suspended sediment concentration and turbidity). Release of coarse delta sediment would affect flood stage, channel migration, and the coastal shoreline including Ediz Hook (Schwartz, 1994). Gravels released from the reservoirs would help restore suitable fish habitat in downstream reaches. Over the long term, predam sediment regimes would be re-established. This would restore the river channel downstream from the dams to their predam character (i.e., a gravel-bed channel with more dynamic shifts in the bed and banks during floodflows).

A. WATER QUALITY AND GROUND WATER

Because of the pristine character of the watershed, water quality issues are primarily related to suspended sediment concentration and turbidity. This water quality issue is important to municipal, industrial, and private water users as well as to fish and the aquatic environment of the river and estuary. Water quality would primarily be affected by the erosion and release of silt and clay-sized sediment from the reservoirs and by re-establishment of the natural (predam) sediment loads downstream.

Landslides and short-duration floods result in episodic sediment loads in the Elwha Basin. Native anadromous fish evolved under these conditions and are expected to do well in a restored ecosystem. However, long-term water treatment for existing water users may be required because the present water supply infrastructure was developed since the dams were built and the reservoirs began trapping sediment. The Elwha River Ecosystem and Fisheries Restoration Act requires the "...protection of the existing quality and availability of water from the Elwha River for municipal and industrial uses from possible adverse impacts of dam removal."

Mitigation would be required to protect water quality for downstream water users, including the surface water diversions of two Port Angeles mills and the WDFW fish-rearing channel. Mitigation may also be necessary for wells adjacent to the river. Water quality and the proposed mitigation measures are addressed in *Water Quality Analyses and Mitigation Alternatives, Elwha River Dam Removal* (Reclamation, October 1996).

B. RIVERBED AGGRADATION, HABITAT, AND INCREASED FLOODING

Downstream from the dams, the riverbed primarily consists of boulders, cobbles, and bedrock. However, gravels are needed to provide suitable fish habitat. Gravels trapped in Lake Mills and Lake Aldwell are considered resources needed for restoration of fish habitat in downstream reaches and on floodplains which have been stripped of their sandy surface soils.

Because the Elwha River is a steep channel characterized by pools and riffles, pools may aggrade following dam removal but velocities in the riffles may be too high for significant aggradation. Pool aggradation alone would not substantially increase flood stage downstream of the dams.

An increase in bed-material load would be expected to result in a wider and more dynamic channel in the alluvial reaches. Other reaches are confined within bedrock canyons and the river channel cannot widen. In alluvial reaches, channel migration would erode river banks as a result of increased supply of bed material from upstream. Some historic homestead sites established in the early 1900's may be eroded if channel widening or lateral migration occurred. Mitigation might include documentation of the historic properties, relocation of certain artifacts or structures, and flood and streambank protection.

The rate of sediment release from the reservoirs can be controlled, to a certain extent, by controlling the rate of dam removal. A slow rate of dam removal would reduce short-term effects of riverbed aggradation but prolong the duration of impacts. A relatively fast rate of dam removal would shorten the duration of short-term impacts but might increase the amount of riverbed aggradation and the magnitude of suspended sediment concentrations. There is a concern that fish restoration efforts might be delayed if the duration of unnaturally high sediment loads is too long. For example, egg mortality could occur by disturbance or burial from unnaturally high sediment loads.

C. RESTORATION OF THE RESERVOIR AREA

During dam removal and draining of the lakes, the unvegetated reservoir bottoms would be exposed. Both lakebeds are expected to have large woody debris and other organic material. A revegetation program is anticipated to control dust, surface runoff, erosion, and to accelerate restoration of wildlife habitat and aesthetic land values.

CHAPTER III. RIVER EROSION ALTERNATIVE

Three basic sediment management alternatives for Elwha River restoration have been described by Randle and Lyons (1995). These sediment management alternatives include:

- River erosion and transport of sediment downstream to the Strait;
- Mechanical removal of sediment through a slurry pipeline to the Strait or a land disposal site (“dredge and slurry alternative”);
- Relocation and stabilization of sediment within the existing area of each reservoir.

Only the river erosion alternative is evaluated in this report. Elements of this alternative include:

- Removing features of the dams necessary to restore fish passage and ensure safety;
- Reservoir drawdown in controlled increments with periods of constant lake elevation in between;
- Short- and long-term monitoring of sediment concentration, water quality, aquatic ecology, and reservoir and river channel topography;
- Short- and long-term protection of municipal and industrial water supplies (including construction of infiltration galleries, a water treatment facility, and new wells);
- Mitigation of short- and long-term flood impacts caused by riverbed aggradation;
- Short-term protection of native fish stock;
- Revegetation of the reservoir areas.

A. DAM REMOVAL PLANS

Both Elwha and Glines Canyon Dams would be removed in controlled increments (there are no plans to suddenly breach either dam). Because there is no low-level release capability from either dam, removal plans have focused on river diversion options. The details are described in *Plan for Removal of Elwha and Glines Canyon Dams, Elwha River, Washington* (Reclamation, May 1996b).

The plan to remove Glines Canyon Dam has focused on a “notch down” scheme. Riverflows would be diverted through notches cut into the dam allowing the part of the dam above the notches to be removed in the dry.

The removal of Elwha Dam is more complicated than the removal of Glines Canyon Dam. The alluvium under Elwha Dam eroded upon initial filling of Lake Aldwell. This resulted in the concrete gravity section being held in place by only the rock abutments of the canyon. The breach was repaired by filling the areas upstream and downstream of the dam with rock debris blasted from the canyon walls. Other fill material was subsequently placed upstream of the dam to control seepage including sand, a fir mattress, and a gunite cap. However, a large void still exists under the gravity section. This fill material is now considered part of the dam and its removal under full lake conditions could potentially cause another failure (water flowing under the dam). A sequence of cofferdams and a diversion channel is considered necessary to partially drain the reservoir and allow for the safe removal of Elwha Dam.

1. Glines Canyon Dam removal and lake drawdown — Initial drawdown of Lake Mills would begin in November of a given year, using the existing spillway and penstock (the low-level outlet is considered inoperable). The purpose of the initial drawdown of Lake Mills is to help control the

flows through Lake Aldwell while a diversion channel is excavated through the abutment of Elwha Dam. Due to the relatively high and variable flows that would be expected from November through January, there may be significant reservoir fluctuations in Lake Mills within the top 20–30 feet. These reservoir fluctuations would allow for the initial erosion and redistribution of delta sediment in the upstream portions of Lake Mills. High inflows from the spring snow melt are expected to refill the lake — at least to the spillway crest elevation. Final drawdown of Lake Mills would begin in July when riverflows returned to lower levels.

The top portion of the dam would be removed in the dry. Further dam removal and lake drawdown would be accomplished by cutting a sequence of notches (using drill and blast techniques) into the dam's concrete arch section. Notch openings would alternate on the dam's left and right sides. Each notch would be about 25 feet wide and 15 feet high. After each notch opening, the lake surface would drawdown as lake water drained through the notch. Lake drawdown would continue until outflow through the notch equaled lake inflow.

For an inflow of 1,400 cfs, water depth through the notch would be about 7.5 feet. This would expose a portion of the dam above the lake surface (about 7.5 feet) and allow removal under dry conditions. The next 15-foot-high notch would be on the dam's other side and would lower the lake another 7.5 feet. Lake inflows would have to be 1,400 cfs or less for a two-week period in order to complete work necessary to open another notch. Notch openings in the dam and removal of the upper 7.5 feet would continue about every two weeks during periods of low lake inflow (1,400 cfs or less).

Lake drawdown and dam removal would continue through the summer and early fall of the first year until lake inflows increased during the winter high flows, typically November through January. During these high flow periods, dam removal could not continue (because of inundation) and the lake level would remain relatively constant. Following a return to low flows, dam removal would continue again until high flows from spring runoff occurred — once again preventing dam removal. After spring runoff, the dam would be completely removed during the summer and fall of the second year.

2. Elwha Dam removal and lake drawdown schedule — Lake Aldwell would first be drawn down about 15 feet to an elevation of 182 feet[†] using the south spillway and penstocks (there is no low-level outlet). A diversion channel would be excavated through the bedrock of the left abutment at the present location of the north spillway channel. This would enable lowering the lake about 40 feet in August of a given year to an elevation of about 140 feet. The lake would remain near this elevation for a year while the exposed portion of the dam and upstream fill material are removed. Lake drawdown would resume in August of the next year and continue until complete removal in October. Lake drawdown would progress in 5-foot increments, as portions of the dam and fill material are removed, until complete removal at an elevation of 90 feet.

[†] All elevations in this report are referenced to mean sea level, 1929 National Vertical Geodetic Datum (NGVD).

B. SEDIMENT MANAGEMENT PLAN

The River Erosion Alternative would allow the sediment presently trapped in Lake Mills and Lake Aldwell to be eroded from the reservoirs (to the extent possible) and transported downstream to the Strait by natural processes. This sediment management alternative represents a minimum cost option. Except for controlling lake elevations during reservoir drawdown and the rate at which each dam is removed, the river would be allowed to erode reservoir sediment without mechanical intervention (such as hydraulic or mechanical dredging). However, some regrading of the remaining sediment to a stable slope may be desirable.

Each lake would be drawn down in stages in order to redistribute reservoir delta sediment within the remaining reservoir pool. Based on drawdown tests of Lake Mills in 1989 and 1994, a channel of some initial flow-dependent width would erode the deltas of each reservoir during drawdown. If the lake level is held constant for some period after a drawdown increment, the initial erosion width is expected to increase over time. Holding the lakes at a constant elevation after each drawdown increment would allow for some river channel meandering and migration, and induce lateral erosion of the delta to the extent practical for the riverflows at the time of drawdown. The rate of lateral erosion is expected to be greatest near the delta front and decrease upstream. The lakes would be drawn down in small increments so that the river would not deeply incise the deltas and leave large volumes of delta sediment behind with unstable banks.

For both lakes, fine-grained sediment would erode much faster than coarse-grained sediment. Boulders and cobbles present in the upstream portions of each delta may not erode at all. For a given peak riverflow during the initial erosion process, an armor layer of cobbles and boulders may develop that would prevent the erosion of finer sediment underneath. The potential armor layer and the underlying sediment would be eroded later by higher riverflows of sufficient duration. Because the volume of cobbles and boulders are relatively small, any armor layers that formed would be left to erode later by higher riverflows. If necessary, erosion of any armor layers could be initiated mechanically to allow upstream passage of fish.

Elwha and Glines Canyon Dams would be removed concurrently to minimize the duration of high sediment concentrations in the river. The rate at which sediment is released from the dam would depend on the rate of dam removal, lake inflow, and sediment particle size. High rates of sediment release would tend to reduce the duration of short-term impacts but increase their magnitude. Slow rates of sediment release would tend to reduce the magnitude of short-term effects but would increase the duration of those effects. However, even slow rates of sediment release may be lethal to fish or cause fish to avoid entering the river. Therefore, high-magnitude, short-duration impacts are preferred over low-magnitude, long-duration impacts.

River and estuary conditions (both physical and biological) and water intakes would be extensively monitored during the erosion of reservoir sediment. Monitoring information could be used to adjust the rate of dam removal and, therefore, the rate of sediment release. Sediment would be released as rapidly as possible to minimize the duration of impacts, but without exceeding the river's sediment transport capacity or the capacity to treat municipal and industrial water.

CHAPTER IV. QUALITATIVE ASSESSMENT

A. RESERVOIR SEDIMENT EROSION, REDISTRIBUTION, AND RELEASE DOWNSTREAM

The following qualitative assessment is based on results from the 1994 Lake Mills drawdown experiment (D. Childers, USGS, Cascades Volcano Observatory, Vancouver, WA, written communication, 1995; also see chapter V), analysis of suspended sediment concentration on the Toutle River after the eruption of Mt. Saint Helens (Smillie and Jackson, 1995), and published literature.

If the dams are removed, most of the sediment in these two reservoirs would remain in the area of the former reservoir and would be stable over the long term. Only a portion of the reservoir sediment would erode and be transported downstream because the reservoir widths (1,000 to 2,000 feet) are much larger than river widths upstream and downstream of the lakes (about 100 to 200 feet). Gregory Morris (1995) states:

“...Hydraulic scour will only excavate a narrow channel, leaving most of the reservoir filled with terraced sediments that will become increasingly stable and difficult to remove over time due to dewatering, compaction, and growth of vegetation. ... Hydraulic flushing can be highly effective in minimizing the rate of additional sediment accumulation in reservoirs of varied geometry but can effectively restore original capacity only in very narrow reservoirs.”

Presently, the coarse sediment (sand, gravel, and cobbles) of each reservoir is primarily stored within the lake deltas which are located at the upstream end of each reservoir (figure 1). The fine sediment (silt- and clay-sized material) is primarily stored along the existing lakebeds and closer to each dam. More energy is required of the river to transport the coarse sediment out of the existing reservoir areas and over greater distances than to transport the fine sediment. Fine sediment would be transported in suspension and coarse sediment would primarily be transported along the riverbed. Therefore, more fine sediment is expected to be transported out of the reservoir areas than coarse sediment.

The processes of reservoir sediment erosion, redistribution, and release downstream during dam removal are presented in four distinct phases (figure 2):

- **Phase 1: Redistribution of delta sediment** — This is also the first phase of dam removal and reservoir drawdown. By the end of this phase, enough of the dam would be removed so that the lake no longer existed. During this phase, the river would incise channels through the delta, eroding and redistributing coarse delta sediment within the reservoir area. Only fine delta sediment would be transported through the lake and past the dam.
- **Phase 2: First release of coarse delta sediment** — Dam removal would continue without a lake. The river would continue to incise channels through the reservoir sediment. As this occurred, a portion of the redistributed, coarse delta sediment and a portion of the fine lakebed sediment (exposed during previous delta erosion) would be eroded and transported past the dam.

Figure 1. Lake Mills Sediment Profile.

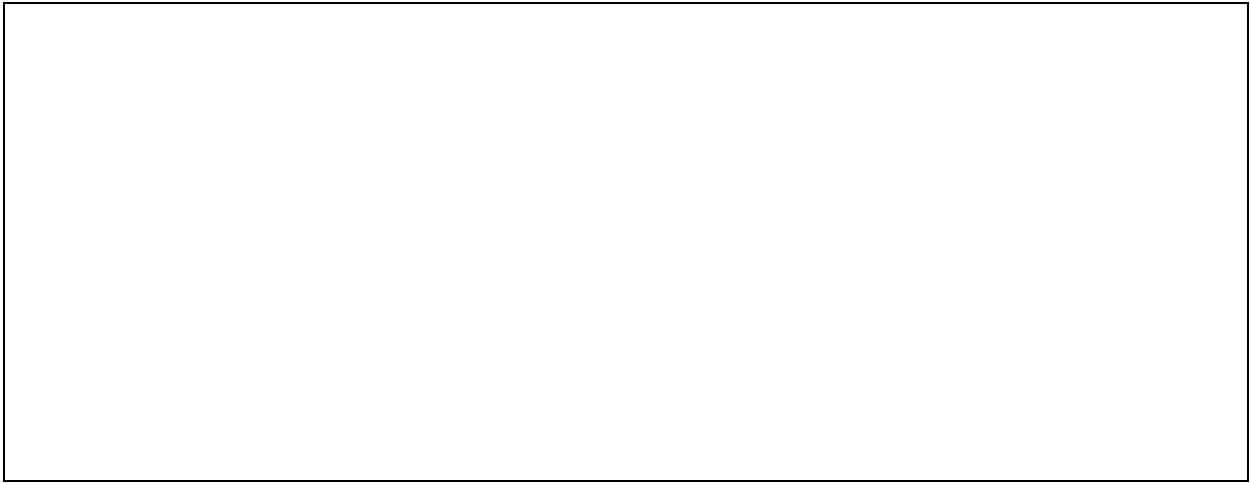
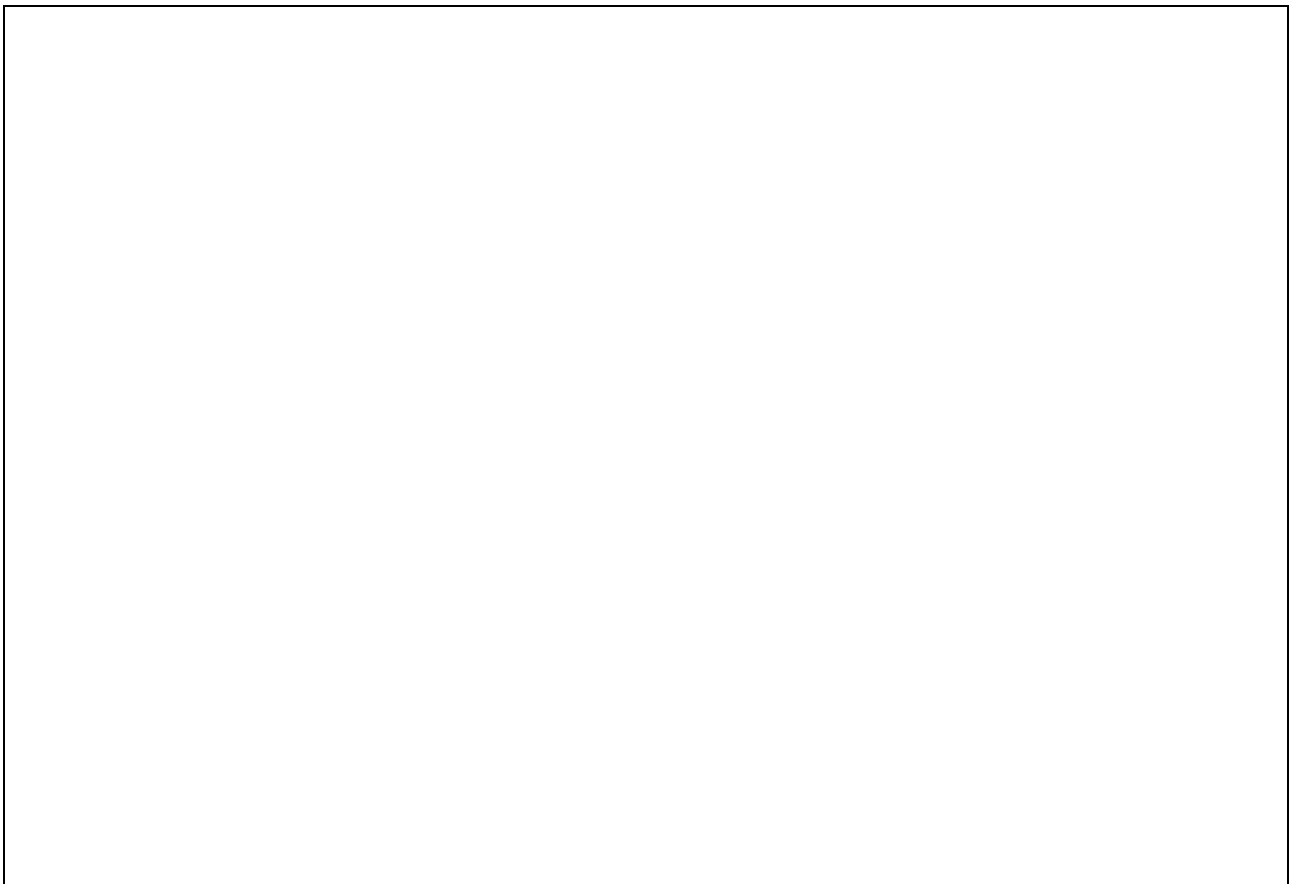


Figure 2. Lake Mills Sediment Profiles During Dam Removal.



- **Phase 3: First release of fine sediment deposited near the dam** — The river would incise channels through the fine lakebed sediment. As this occurred, the river would erode fine lakebed sediment near the dam and some of the coarse sediment through channel widening and transport them past the dam.
- **Phase 4: Post dam removal with sediment release during floodflows** — Through channel meandering and bank erosion, the river would erode and transport both coarse and fine sediment out of the reservoir area during progressively higher floodflows.

Figure 3. Photo of Delta Erosion Channel During the 1994 Lake Mills Drawdown Experiment.
Erosion channels incised through the reservoir delta leaving sediment terraces behind on both banks.



1. Redistribution of delta sediment (Phase 1) — In this first phase, portions of the delta would be eroded and redistributed downstream toward the dam. Coarse sediment would not be released past the dam site but would be redeposited within the remaining reservoir. Terraces of coarse sediment would be left behind along the reservoir margins (figure 3).

Fine sediment in the eroded delta would be re-suspended and would either be redeposited further downstream in the lake or be released past the dam. During the first few increments of dam removal,

the amount of fine sediment eroded and re-suspended from the delta would be small and would mix with a relatively large lake. Consequently, concentrations of fine sediment released downstream from the dams would be low. With each increment of dam removal and reservoir drawdown, water volumes in the lake would decrease due to the lower dam height and due to the redeposition of delta sediment into the remaining lake. As more fine sediment becomes accessible to erosion and is mixed with smaller water volumes in the lake, concentrations of fine sediment released downstream from the dams would increase. During periods of high lake inflow (greater than about 1,400 cfs), dam removal activities would stop. These high inflows would tend to flush the lake of high concentrations of suspended sediment, reducing the level of suspended sediment concentrations in the lake to that of the inflow.

During lake drawdown, delta sediments of both lakes would erode and redeposit downstream, forming a new delta which would temporarily cover the existing lakebed sediments. Deposition of delta sediment further downstream within the reservoir is expected to be uniform across the reservoir. The slope of the redeposited delta material would largely depend on the sediment particle size and river flow. Because there are no operable low-level outlets from either dam, coarse sediment would not be expected to be transported through the remaining lakes and past the dam sites.

As each lake is initially drawn down, the river would erode through a portion of the delta exposed above the receding lake. If the reservoir is held at a constant elevation for a long-enough period, then coarse delta sediment would redeposit all the way across the receded lake and extend the delta downstream. The coarse sediment would first redeposit where the erosion channels entered the receded lake; extending the delta downstream at that location. The redeposited delta sediment would induce rapid bank erosion of the newly exposed delta as the erosion channels moved laterally to reach deeper portions of the lake over the shortest possible distance. Erosion widths of the exposed delta would be almost equal to the lake width at the delta's downstream end, but would rapidly decrease upstream — leaving a terrace of delta sediment behind.

The reservoir would continue to drawdown with each increment of dam removal. During each reservoir drawdown increment, another portion of the delta would erode, coarse sediment would redeposit downstream, and the delta would continue to advance downstream to a lower elevation. The remaining portion of the exposed delta would be left behind in a series of terraces. As the delta continued to advance, fine sediment of the downstream lakebed would be covered (although some mixing would occur). The finer lakebed sediment would erode once the channels are able to erode through the overlying delta sediment. This process would continue until the advancing delta front had reached the dam.

2. First release of coarse delta sediment (Phase 2) — At the beginning of the second phase, coarse sediment from the delta would have reached the dam and covered the fine sediment of the lakebed. Once this occurred, the elevation of sediment would be about equal to the top of the remaining dam and the lake would no longer exist, but rather a stub dam with the remaining reservoir full of sediment. Coarse sediment would be released downstream with the next increments of dam removal and would no longer be redistributed within the lake (i.e., no new delta deposition).

The rate and amount of sediment release would depend on the increment or rate of dam removal, lake inflow, and sediment erosion slopes within the lakebed. Both fine and coarse sediment would be released downstream with each increment of dam removal. The rate at which sediment is transported past the dam would initially be high after a sudden increment of dam removal. This rate would decrease exponentially with time until the next dam removal increment. Erosion widths would be a

function of lake inflow, except that channel erosion widths at the damsite would be limited by bedrock controls. During periods of high riverflow into the reservoir area, dam removal operations would be suspended and sediment erosion and release downstream would occur primarily from channel widening.

3. First release of fine lakebed sediment near the dam (Phase 3) — The final stages of dam removal occur during the third phase. By now, dam removal would have progressed to a point where the river vertically eroded a channel through the layers of coarse, redeposited, delta sediment. The fine lakebed sediment near the dam would be exposed. The rate of fine sediment release past each dam initially would be high after a sudden increment of dam removal. This rate would decrease exponentially with time until the next dam removal increment.

The Elwha River would erode or incise through the reservoir sediment down to the predam river alluvium. The river would tend to seek the location of the predam channel. Tributaries such as Boulder Creek would also erode through reservoir sediment incising channels to their confluences with the Elwha River. Fine sediment along the reservoir rim is of minimal thickness (perhaps 1–4 feet). Some of this sediment would be transported further down into the reservoir during drawdown from tributary flow or surface runoff from rainfall. Woody vegetation, such as alder, would stabilize the remaining sediment within one to two years.

Heavy rains associated with high flows will cause surface erosion of exposed lakebed sediment and would result in increased turbidity levels downstream compared to predam background levels. However, turbidity levels of the Elwha River during heavy rains are somewhat naturally high and turbidity increases from surface runoff during these periods may not be much different when compared to predam background levels.

4. Post dam removal with sediment release during floodflows (Phase 4) — At the beginning of the fourth phase, the dam would have been removed and the river would have eroded down to predam alluvium. Relatively little reservoir sediment would be released during low-flow periods and the amount of coarse and fine sediment released downstream would approximately equal the upstream sediment supply over the short term (3–5 years). Additional release of reservoir sediment would occur due to channel widening during floodflows. After the first floodflow, significant channel widening would only occur during subsequently higher floodflows.

Erosion and transport of reservoir sediment downstream from the damsite is highly dependent on the magnitude and sequence of floodflows. In general, the amount of reservoir sediment eroded during floodflows would be expected to decrease exponentially with time. Reservoir sediment erosion rates initially would be high with the first floodflow following dam removal. Subsequent floodflows of progressively greater magnitude would be expected to cause additional channel widening but the volume of sediment erosion would tend to decrease with each floodflow. This is because channel width increases with riverflow, but at an ever-decreasing rate.

B. FINE SEDIMENT CONCENTRATIONS IN THE DOWNSTREAM RIVER CHANNELS

The removal of Elwha and Glines Canyon Dams would cause a rapid release of coarse and fine sediment from the reservoirs. Fine sediment would be transported in suspension and travel at near the velocity of the riverflow. Coarse sediment would tend to be transported along the riverbed and at a much slower rate, causing river pools and other slow velocity areas to aggrade.

The concentration of fine sediment released from each dam essentially would be the same in the river channels downstream. Initially, the concentration of fine sediment eroded and released past each dam would be small. Concentrations would generally increase through phase 1 of dam removal and then tend to decrease in phases 2, 3, and 4. Peak concentrations would coincide with each new opening in the dam in phases 1, 2, and 3 and with floodflows in phase 4. During dam removal (phases 1, 2, and 3), concentrations would tend to be low during periods of high lake inflow when dam removal activities are temporarily halted. During post dam removal (phase 4), concentrations would generally be low except for short periods during floodflows.

C. RIVERBED AGGRADATION AND FLOODING

Since construction of Elwha Dam in 1913 and Glines Canyon Dam in 1926, the supply of coarse sediment has been cut off to the river reaches downstream. Consequently, sand, gravel, and small cobbles (75–125 mm) have been eroded from the riverbed in these reaches, leaving an armor layer of large cobbles (125–300 mm) and boulders that prevent erosion of the finer, underlying sediment. The riverbed is now lower in places and the channel is more stable than under predam conditions.

The removal of these two dams would also restore the natural sediment supply to the river downstream. The lower river (below RM 3) has characteristics of an alluvial fan or delta and may have been aggrading under predam conditions. Restoration of the natural sediment supply to this reach may result in continued aggradation over the long term.

The river channel will become more active as coarse sediment loads increase. During and after dam removal, the river would achieve a straighter course and steeper slope and the rate of lateral channel migration (bank erosion) would increase. River slopes in the lower river (below RM 3) are less steep than upstream and side channels exist in addition to the main river channel. With increased loads of coarse sediment, the main river channel in the lower river may shift course to one or more of the side channels.

Neither dam presently provides flood control so dam removal would not significantly affect peak discharge during floods or floodflow frequency. However, flood stage for a given riverflow would increase locally due to riverbed aggradation. This would also cause the elevation at a given location to be flooded more frequently. Increases in river stage would be less than the amount of riverbed aggradation. This is because river stage at a given location depends on river stage at the next riffle downstream. Riffles are high-velocity areas of the river and least likely to aggrade. As long as riverbed aggradation does not occur at the riffles, only small increases in river stage would occur during floodflows from previous aggradation of river pools.

PART II

DATA COLLECTION

This part of the report provides an overview of the basic data used in this report with references to other reports that provide more detail. This part is intended for those readers who have a basic understanding of hydrology or geomorphology.

CHAPTER V. DATA COLLECTION

The basic data needed for the analysis of the river erosion alternative include:

- Geomorphology investigation to understand the dominant river system processes including the sediment sources and sinks.
- Predam and current reservoir topography of both lakes. These data are needed to determine the reservoir sediment volumes and their spatial distribution within each reservoir. This, in turn, would help determine how much sediment has the potential to be eroded from the reservoir area and how much would remain in a stable condition.
- The reservoir sediment characteristics of both lakes including particle-size distribution, bulk density, specific gravity, and any cohesion properties. These data are necessary for sediment transport computations and computer modeling. Computer modeling was used to predict erosion and redistribution of the reservoir sediment and downstream impacts to water quality and riverbed aggradation (part III of this report).
- Reservoir sediment erosion rates and characteristics. These data are necessary for computer model development, calibration, and verification.
- Cross section surveys of the river channel downstream from both dams to the Strait. These data are necessary to compute river hydraulics, sediment transport, and predict riverbed aggradation. The cross section data would also serve as the baseline from which to monitor and document changes during and after dam removal.
- Aerial photography of the river corridor and lakes. These photographs are needed to help evaluate existing conditions, identify cross section survey locations, and supplement cross section survey data.
- River discharge history and flow-frequency data. These data are necessary for computer model simulations.

A. PREVIOUS INVESTIGATIONS

The Elwha Report (Interior et al., 1994), the *Draft Staff Report* (FERC, 1993), and supporting documents contain a great deal of information, including topography and sediment size data for both reservoirs and the river channel.

Reservoir topography data includes a predam (1921) contour map of Lake Mills and 1989 contour maps for both Lake Aldwell and Lake Mills (Hosey, 1990). The volume of Lake Mills sediment was computed by taking the difference between the 1921 and 1989 contour maps (FERC, 1993; Summit Technology Consulting Engineers, Seattle, WA, written communication, June 28, 1994). No predam topography is available for Lake Aldwell. The volume of Lake Aldwell sediment was estimated from thickness probe and seismic refraction data (Hosey, 1990). Sediment size distribution data were available for both lakes from 2-inch (50 mm) core samples. However, data were unavailable for sizes greater than about 1.5 inches (38 mm).

In September 1989, Hosey (1990) conducted a drawdown test of Lake Mills to monitor sediment transport across the delta and document the delta's erosion. The lake drawdown began on September 6 with the lake starting at an elevation of 590 feet. The lake was lowered over a 4-week period at a rate of approximately 0.5 foot per day to an elevation of 572.4 feet. The lake was held near an elevation of 572.4 feet, with slight variations during a period of higher inflow, until October 22, when five days of high inflows caused the lake to rise to an elevation of 587 feet. Lake inflows from September 15 to October 20 were 228–530 cfs.

Cross sections of the Lake Mills delta were surveyed on September 21 and 27, October 2, 11, and 18. Stereo aerial photos of the delta were taken on September 29 and October 15 to provide additional information on channel development and volumes of sediment being transported through the delta. Suspended sediment samples and bedload sediment samples were taken by Ebasco Environmental during the drawdown (Hosey, 1988). These samples were analyzed for sediment concentrations and grain size.

From September 23 to October 15, the upstream half of the delta experienced little change. However, large portions of the downstream half of the delta were eroded and transported into Lake Mills. Up to 10 vertical feet of sediment were eroded from the downstream edge of the delta, with vertical erosion depths decreasing upstream.

There was no further significant delta erosion until the high flows October 22–27, when much more erosion took place and the headcut moved upstream almost to the head of the delta (where the inflowing river splits into two channels). The flows, estimated at 2,863 cfs, were able to transport the gravel and cobbles sediment on the upstream half of the delta. The gravel and cobbles were not moved by previous flows of up to 649 cfs. During the high flows, the lake levels rose to an elevation of 587 feet, completely changing the base elevation to which the delta was adjusting, so the study was discontinued.

Cross sections for the reach of river from the mouth to Glines Canyon were available from a variety of sources: U.S. Army Corps of Engineers (Corps) (J. Lencioni, Corps, Seattle District, Seattle, WA, oral communication, 1995); Federal Emergency Management Agency (FEMA, 1980); and Hosey (1990). However, these different data sets were not necessarily linked to common horizontal or vertical datums. Measurements of riverbed material (both armor and sub-armor layers) at various locations from the mouth to about RM 40 were made by Hosey (1988).

The USGS has operated a stream gauge on the Elwha River since 1918 at the McDonald Bridge site at RM 8.6, located between the two dams. In addition to discharge measurements, some water quality and sediment data are available for this gauge.

Additional data collection efforts necessary to address sediment management issues primarily focused on:

- The establishment of a new stream gauge upstream from Lake Mills;
- A second drawdown test of Lake Mills;
- Additional reservoir surveys of Lake Aldwell and Lake Mills forebay;
- A geologic investigation of Lake Aldwell sediment;
- Aerial photography of the river corridor; and
- Topographic surveys and geologic mapping of the river channel and reservoirs.

B. NEW STREAM GAUGE

A new stream gauge above Lake Mills (near the mouth of Rica Canyon) was established by the USGS under a cost-sharing agreement with the Tribe. The gauge is providing information on natural river discharge, sediment load, and water quality. Should the dams be removed, the stream gauge would have to be relocated above Rica Canyon (at Goblins Gate) to support the long-term monitoring program.

C. 1994 LAKE MILLS DRAWDOWN TEST

1. Objectives — Another 18-foot drawdown experiment of Lake Mills was conducted in April 1994 to determine the erodibility characteristics of the delta (channel development, erosion of armor layers, etc.) and the size distribution of the sediment. This data was later used in the development, calibration, and verification of computer models (chapter VIII). Data were also collected to define ambient water quality and the effect of delta erosion on subsequent water quality. Procedures and results of this experiment are documented by Childers et al. (D. Childers, USGS, Cascades Volcano Observatory, Vancouver, WA, written communication, 1995). Compared to the 1989 drawdown test, data collection during this experiment was much more frequent and comprehensive and was conducted during a period of higher lake inflow.

2. Methods — The lake's water level was lowered 18 feet over a 1-week period (more than five times the proposed average rate of dam removal) and then held at a constant elevation for one week before refilling. Lake inflows during the drawdown test were below average for April, between 900 and 1,800 cfs.

Data collection was conducted jointly by Reclamation, USGS, NPS, and the Tribe. Data collection included daily stream gauging (streamflow, suspended sediment, bed material, and bedload), repeat cross-section surveying, geologic mapping of the delta surface, time-lapse photography, and aerial photography.

3. Summary of results — The Lake Mills delta was found to consist mostly of sand and fine gravel (less than 19 mm). These sediments were likely derived from upstream shale beds and consisted of platelets and rod-shaped particles.

During lake drawdown the delta eroded both vertically and laterally. Eroded banks were almost vertical with no signs of seepage-based erosion. After the full 18-foot drawdown, the delta erosion became primarily lateral as the stream had adjusted to the new base level. The eroded sediment redeposited across the receded lake and extended the delta front about 300 feet downstream but at a lower elevation. As the coarse delta sediment eroded and redeposited in the receded lake, the erosion channels eroded laterally to reach deeper areas of the lake. The total eroded width at the initial delta front was equal to the reservoir width and decreased rapidly with distance upstream. Only a slight increase in suspended-sediment concentration (relative to pretest conditions) was found downstream from Glines Canyon Dam during the drawdown test.

D. BATHYMETRIC SURVEYS OF LAKE MILLS AND LAKE ALDWELL

- 1. 1989 bathymetric surveys** — Bathymetric and topographic maps for both Lake Mills and Lake Aldwell were prepared using similar procedures and equipment (Hosey, 1990). The bathymetric survey was conducted from a boat using a depth recorder and microwave positioning system.
- 2. 1994 bathymetric surveys** — Sediment deposits of both lakes were mapped in order to help determine the reservoir sediment volume and size distribution. Reservoir sediment sampling and drilling locations were surveyed and new bathymetric maps were made to support the reservoir sediment investigations (Reclamation, August 1995). Comparison of these new bathymetric maps with a predam map of Lake Mills and recent drill hole data from Lake Aldwell were used to determine the volume and spacial distribution of the reservoir sediments.

The Lake Aldwell survey revealed that a landslide had occurred about 700 feet upstream from Elwha Dam and now blocks the original river channel under the lake. The volume of the landslide was estimated by Reclamation (May 1996a) to be 15,000 yd³. This landslide occurred since dam construction but the year of occurrence is unknown. There is no indication of continuing slope movement in the upslope area. This landslide is a natural dam (now submerged) about half the height of Elwha Dam. Release of sediment from Elwha Dam would be impeded until the Elwha River had re-established its channel through the landslide mass. Mechanical excavation of the landslide may be required to ensure timely release of reservoir sediment and reduce impacts to downstream fish habitat and maintain project schedules (Reclamation, May 1996a).

E. RESERVOIR SEDIMENT VOLUME SUMMARY

Detailed information on the reservoir sediment volumes and size distributions for Lake Mills and Lake Aldwell can be found in *Alluvium Distribution in Lake Mills, Glines Canyon Project and Lake Aldwell, Elwha Project, Washington*. (Reclamation, March 1996). Reservoir sediment volume, grain size gradations, and post-dam sediment distribution estimates for both lakes were made using geologic data collected in 1989 (Hosey, 1990) for project owner James River II, Inc. and data from 1994 explorations conducted by Reclamation.

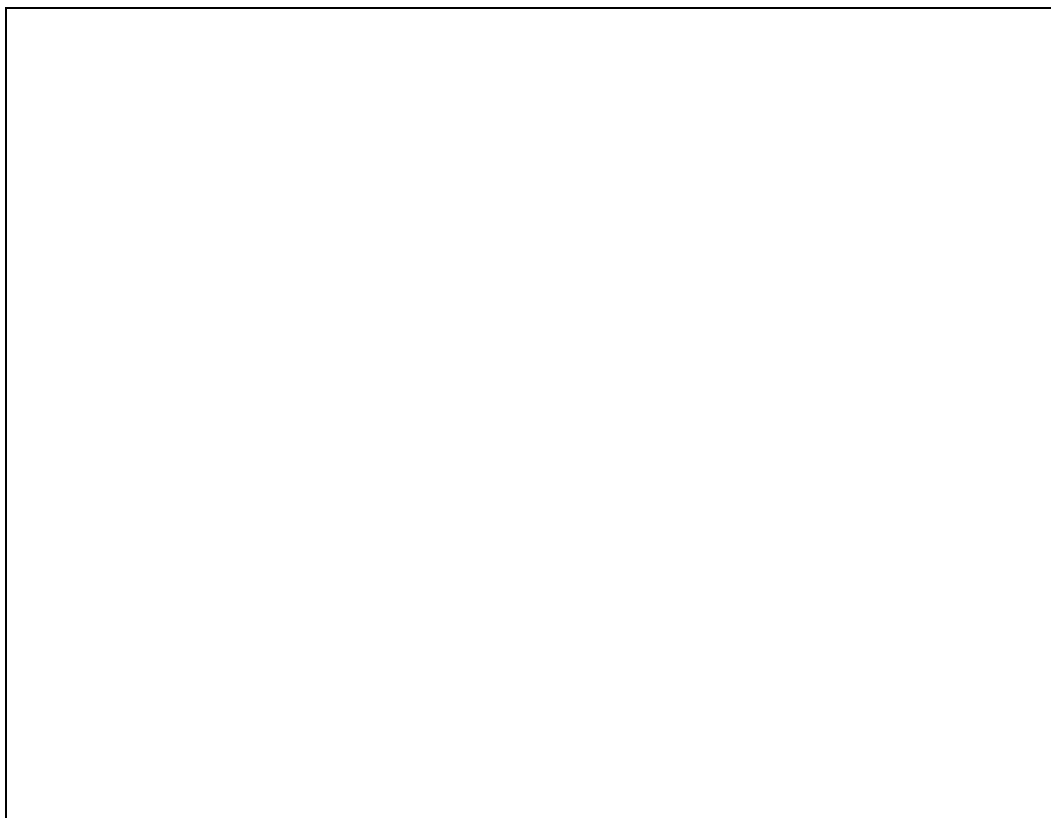
Of the total 17.7 myd³ of reservoir sediment, 78 percent (13.8 myd³) are in Lake Mills and 22 percent (3.9 myd³) are in Lake Aldwell. Of the sediment in Lake Mills, about half is considered fine grained (silt and clay) and about half is considered coarse grained (sand, gravel, and cobbles) (table 1 and figure 4). Most of the coarse sediment of Lake Mills (94 percent) is in the delta located at the upstream end of the reservoir. The Lake Mills delta, with a volume of 8.5 myd³, is mostly sand and gravel, with some silt and clay, and a small amount of cobbles. The lakebed sediments, with a volume of 5.3 myd³, are mostly silt- and clay-sized material (92 percent) with some fine sand.

Of the sediment in Lake Aldwell, about two-thirds is considered fine and about one-third is considered coarse (table 1 and figure 4). Most of the coarse sediment of Lake Aldwell (82 percent) is in the delta located at the upstream end of the reservoir. The Lake Aldwell delta, with a volume of 1.8 myd³, is mostly sand, with silt and clay, gravel, and a small amount of cobbles. The lakebed sediment, with a volume of 2.1 myd³, are mostly silt- and clay-sized material (89 percent) with some sand and a minor amount of gravel.

Table 1. Estimated Reservoir Sediment Volumes and Size Distribution.

(modified from Reclamation, August 1995)

Reservoir	Clay and Silt		Sand		Gravel		Cobbles		Total	
	myd ³	percent	myd ³	percent	myd ³	percent	myd ³	percent	myd ³	percent
Lake Mills	6.62	47.8	5.16	37.3	1.85	13.4	0.21	1.5	13.84	100
Lake Aldwell	2.59	66.8	1.08	27.8	0.16	4.1	0.05	1.3	3.88	100
Total	9.21	52	6.24	35.2	2.01	11.3	0.26	1.5	17.72	100

Figure 4. Reservoir Sediment Size Distribution for Lake Mills and Lake Aldwell

1. Lake Mills sediment — Reservoir sediment volume estimates for Lake Mills were made using surface and subsurface data and a comparison of post-dam (1989 and 1994) topography and predam (1921) topography. Data collected by Hosey and Associates in 1989 included drill hole drive samples in the Lake Mills delta. In addition, they collected piston core samples and thickness probe tests in the reservoir. Investigations in 1994 included surface mapping, photography, hand-dug test pits, sediment sampling, contaminant sampling, and video recording.

Since construction of Glines Canyon Dam 69 years ago, the Elwha River has built a 3,000-foot-long delta at the head of Lake Mills, which has a maximum thickness of 70–80 feet. Sediment distribution in the Lake Mills delta ranges from predominantly gravel, cobbles, and boulders in the upstream reach, through cobbles, gravel, and sand in the central reach, to mostly sand and minor fine gravel in the lower reach. Post-dam sediment on the lakebed forms a long, gently sloping wedge of fine sand, silt, and clay that extends to Glines Canyon Dam. Based on average percentages of fines, sand, and coarser sediments, the Lake Mills reservoir basin was subdivided into 7 sedimentation areas (Reclamation, August 1995):

- Area 1. Rica Canyon
- Area 2. Cat Creek fan
- Area 3. Boulder Creek fan
- Area 4. Pro-delta sediments
- Area 5. Reservoir floor sediments
- Area 6. Lake Mills delta (upstream portion)
- Area 7. Lake Mills delta (downstream portion)

The total volume of post-dam fluvial sediment in the Lake Mills basin was determined to be 13.83 myd³. Approximately 51 percent (6.97 myd³) of this total sediment volume is concentrated in the main delta, while about 38 percent (5.30 myd³) mantles the reservoir floor and side slopes. The remaining 11 percent (1.56 myd³) of the reservoir sediment is distributed within Rica Canyon and at the mouths of Cat Creek and Boulder Creek.

Of the total post-dam sedimentation volume, 48 percent (6.62 myd³) is silt- and clay-sized particles and 52 percent (7.21 myd³) is sand, gravel, and cobbles (coarse sediment). Of this coarse sediment, 72 percent is sand size, 26 percent is gravel size, and 3 percent is cobble size).

2. Lake Aldwell sediment — A geologic investigation of Lake Aldwell was conducted by Reclamation (August 1995). Post-dam sediment volumes for Lake Aldwell were estimated using 1989 and 1994 topography data and limited subsurface data. Topography of Lake Aldwell was not obtained prior to the construction of Elwha Dam. Data collected by Hosey in 1989 included vibro-core sampling, piston core sampling, seismic refraction survey, ground-penetrating radar survey, and thickness probe tests on the delta and reservoir. Reclamation investigations in 1994 included surface mapping, photography, limited drill sampling, hand-dug test pits, and an underwater dive examination. Surface mapping and core drilling revealed that previous volume estimates of the delta were too large and that volume estimates of the lakebed sediments were too low. The previous volume estimates for the delta included predam channels and terraces consisting of cobbles and boulders. The previous volume estimates for the lakebed were found to underestimate the sediment thickness by 50 percent when compared with the 1994 drill-hole information. This difference may be due to the relatively small equipment used to measure sediment thickness in the previous volume estimates. These early thickness measurements, based on refusal of the equipment, probably

represent minimum values. (Refusal of the equipment was likely the result of skin friction rather than encountering coarse predam alluvium.)

In the 83 years since construction of Elwha Dam, the Elwha River has formed a narrow, 2,500-foot-long, 18- to 24-foot-thick delta at the head of the Lake Aldwell reservoir basin. The post-dam delta is nested in older river terrace deposits that are locally up to 16 feet above normal reservoir level (elevation 197 feet). Sediment distribution in the Lake Aldwell delta ranges from gravel, cobbles, and some boulders at the delta head, to predominantly sand and silt near the delta front. Sediment on the reservoir floor forms a long, gently sloping wedge of fine sand, silt, and clay that extends to Elwha Dam. Based on average percentages of fines, sand, and coarser sediments, the Lake Aldwell reservoir basin was subdivided into 9 sedimentation areas (Reclamation, August 1995):

- Area 1. Lake Aldwell delta (upstream portion)
- Area 2. Lake Aldwell delta (downstream portion)
- Area 3. Indian Creek delta and similar sediments
- Area 4. Delta margin sediments
- Area 5. Pro-delta Sediments
- Area 6. Reservoir floor sediments (upstream portion)
- Area 7. Reservoir floor sediments (gooseneck portion)
- Area 8. Reservoir floor sediments (downstream portion)
- Area 9. Reservoir rim sediments

The total volume of post-dam fluvial sediment in the Lake Aldwell basin was determined to be about 3.88 myd³. Of this total sediment volume, 46 percent (1.78 myd³) is concentrated in the delta area, while about 54 percent (2.1 myd³) mantles the reservoir floor and side slopes. Approximately 67 percent of the total post-dam sedimentation volume consists of silt- and clay-size particles, and 33 percent consists of sand, gravel, and cobbles (coarse sediment). Of this coarse sediment, 84 percent is sand size, 12 percent is gravel, and 4 percent is cobbles.

F. AERIAL PHOTOGRAPHS

Photographs of the river corridor were obtained under contract by the Tribe. Photographs from the river's mouth to Glines Canyon Dam were taken in March 1994 and from Glines Canyon Dam to the base of Mount Olympus in April 1994.

G. RIVER CROSS SECTION SURVEYS AND GEOLOGIC MAPPING

New river cross sections from the river's mouth to Glines Canyon Dam were surveyed (with consistent horizontal and vertical datums) to supplement existing information and document recent changes near the mouth. Geologic mapping of the riverbed and terraces was also performed at the same time (chapter I, section C-1; also Reclamation, March 1996).

Existing river cross section data were produced by combining (and adjusting) data from two surveys in 1994 and one in 1983. Cross section data from the river mouth (RM 0) to RM 3 were supplied by the Corps (J. Lencioni, Corps, Seattle District, Seattle WA, written communication, 1994). These cross section data were combined from surveys of the main river channel in the fall of 1994 and surveys of the floodplains and side channels in 1983. The channel lengths between cross sections, measured in 1983, were included with these data. Because of some changes in the river channel location and

alignment since 1983, reach lengths for the lower reach (RM 0 to RM 3) were re-measured from the 1994 aerial photographs. Cross section data from RM 3 to RM 5 (Elwha Dam), including data for the computation of reach lengths, were measured by Reclamation's Ephrata (WA) Field Office survey crew in September 1994.

In the upper portion of the lower reach (above RM 3), additional cross sections were interpolated to account for variations in river hydraulics through riffles and pools. The floodplain portion of the cross section at RM 0.8 was modified to straighten out a dog-leg in the original survey that was too far downstream.

PART III

SEDIMENT ANALYSIS AND COMPUTER MODELING

CHAPTER VI. MODELING INTRODUCTION

To mitigate water quality degradation, fish loss, and reduced flood protection, knowledge is required of the suspended sediment concentration released from the two lakes (including magnitude, duration, and timing) and the amount of riverbed aggradation and channel widening that is expected to occur.

This part of the report provides a detailed discussion of the analyses and various numerical (computer) models that were used to predict the impacts of the river erosion alternative. It is intended for those readers who have a good understanding of geomorphology and computer modeling.

Combinations of three computer models were used to predict the amount of sediment eroded from each reservoir and the resulting effects on sediment concentration and riverbed aggradation in the river downstream. The three are:

- STARS model: Sediment Transport and River Simulation (Reclamation, 1987).
- HEC-6 model: Scour and Deposition in Rivers and Reservoirs, Version 4.1A (Corps, 1993).
- Elwha Reservoir model: a new reservoir sediment erosion model developed to predict the erosion, redistribution, and downstream release of sediment during concurrent removal of both dams and corresponding lake drawdown. This model is based in part on the concepts described by Smillie and Jackson (1995) and results from the 1994 Lake Mills drawdown test.

Both STARS and HEC-6 are one-dimensional, movable boundary, open-channel flow models designed to simulate and predict changes in river profiles resulting from scour and deposition. A special version of the STARS model was used to compute coarse-sediment transport capacity of the river channels downstream from both dams. The Elwha Reservoir model is empirically based and was developed specifically for this study. These three models each have certain advantages and disadvantages. All of the models were used and the results were combined to maximize the advantages of each. For example, the STARS model could be easily customized for simple applications, but was slow for long-term simulations. The HEC-6 model was very fast for long-term simulations, but neither the STARS nor HEC-6 models could predict channel erosion widths. The Elwha Reservoir model worked well for the two lakes but required input from the other two models. Separate (but almost identical) versions of the Elwha Reservoir model were created for Lake Mills and Lake Aldwell.

All three models were used to make predictions for Lake Mills. Some of the STARS model results were used in the HEC-6 model and some of the results from both models were used in the Elwha Reservoir model (figure 5). Results of the Elwha Reservoir model for Lake Mills provided input to the STARS model when it was applied to the river reach below Glines Canyon Dam and to the Elwha Reservoir model when it was applied to Lake Aldwell. Results of the Elwha Reservoir model from Lake Aldwell were used as input to the STARS and HEC-6 models when they were applied to the river below Elwha Dam.

During dam removal and the reservoir drawdown, various portions of the delta sediment were assumed to erode and redeposit farther downstream over the lakebed sediment of the remaining reservoir. Although the delta sediments are primarily sand and gravel, there is a small portion of silt- and clay-sized sediment. Some of this silt- and clay-sized sediment would be eroded from the delta, mix with the remaining lake, and be released downstream in reduced concentrations. This process

would be expected to continue until eroded delta sediment had reached the dam and the remaining reservoir was full of sediment. At this time, additional dam removal would result in the downstream release of coarse delta sediment (in addition to the release of fine sediment).

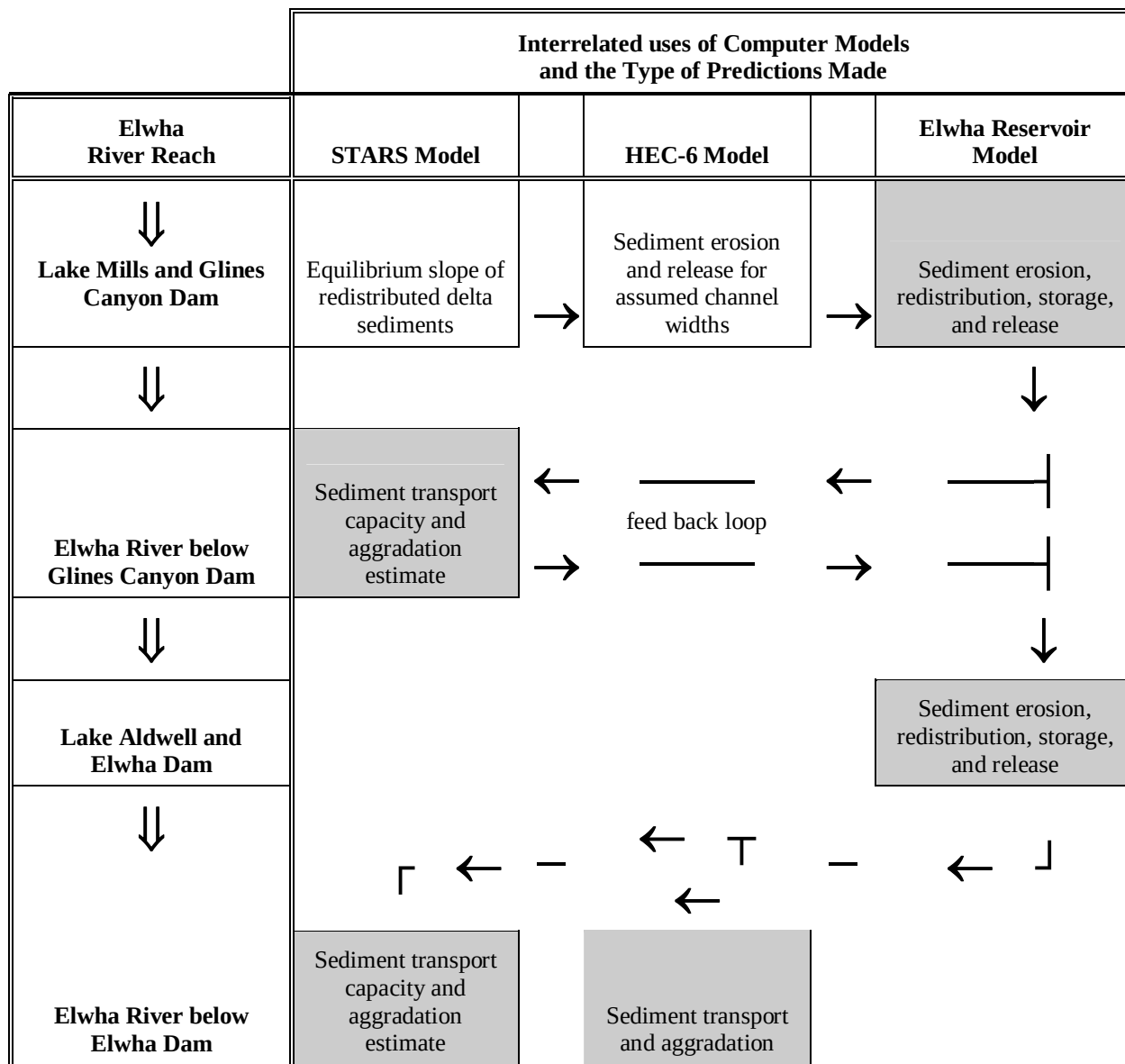
For Lake Mills, the elevation of the redeposited delta sediment when it first reaches the dam was estimated from mass-balance calculations (chapter VII, section B). This elevation is important for the preparation of dam removal plans and for determining when coarse delta sediment would be first released downstream. The STARS model was used to determine the equilibrium slope of the redistributed delta sediment. The hydraulic properties table feature of the STARS model was also used to assist in the mass-balance calculations. The computed profile for the eroded and redeposited delta sediment upstream from Glines Canyon Dam was used as the initial conditions for the HEC-6 model. The general pattern of sediment release between successive increments of dam removal was predicted using HEC-6 (chapter VII, section C) and was used as input to the Elwha Reservoir model (chapter VIII). Using the equilibrium slope from the STARS model, the general pattern of sediment release from the HEC-6 model, and observations during the 1994 Lake Mills drawdown test, the Elwha Reservoir model predicted the erosion, redistribution, storage, and downstream release of both coarse and fine sediment.

Any silt- and clay-sized sediments released from the reservoir were assumed to be rapidly transported downstream to the river mouth and into the Strait. Although some silt- and clay-sized sediment may deposit along channel margins, the river channel is too steep for significant aggradation to occur from material this size. Therefore, the predicted sediment hydrographs for silt and clay released past the dam sites were applied downstream without modification for lag time or attenuation.

For the Elwha River reach below Glines Canyon Dam, the STARS model was used to compute sediment transport capacity for a range of sand- and gravel-size sediment (chapter IX). These transport capacities were then compared with the sediment release rates from Lake Mills (predicted by the Elwha Reservoir model) to estimate the potential riverbed aggradation. As a conservative assumption, the predicted sediment release rates from Lake Mills were used directly as input to the Elwha Reservoir model when it was applied to Lake Aldwell. The HEC-6 model was not applied to this very steep reach because the large number of required river cross sections were not available.

For the more mild reach below Elwha Dam, both the STARS and HEC-6 models were used to predict the amount of riverbed aggradation. The STARS model was used to compute sediment transport capacity for a range of sand- and gravel-size sediment (chapter IX). These transport capacities were then compared with the sediment release rates from Lake Aldwell (predicted by the Elwha Reservoir model) to estimate the potential riverbed aggradation. STARS model results were then used later to compare with results from the HEC-6 model. The HEC-6 model was used to simulate the transport and deposition of sand and gravel from Lake Aldwell for a 3.3-year period during and after dam removal and over the following 50 years (Chapter X).

Figure 5. Modeling sequence and interrelated uses of computer models
(The shaded boxes indicate which model results were used in the final conclusions.)



CHAPTER VII. INITIAL SEDIMENT ANALYSIS AND MODELING FOR LAKE MILLS

A. NATURAL COARSE SEDIMENT SUPPLY

The natural supply of coarse sediment (bed-material load) from the Elwha River and the development of a sediment-discharge rating curve are discussed in this section.

About 7.2 myd³ of coarse sediment (sand, gravel, and cobbles) have been deposited upstream of Glines Canyon Dam in the Lake Mills Delta, which extends into Rica Canyon (Reclamation, August 1995). This delta has accumulated over the 67 years (1927–94) since Glines Canyon Dam was completed and began storing water. This coarse sediment volume of 7.2 myd³ translates into an average annual sediment load of about 110,000 yd³ per year — the natural supply of coarse sediment entering Lake Mills.

A sediment-discharge rating curve for the natural supply of coarse sediment was developed from the following data:

- The volume of coarse sediment accumulated in Lake Mills;
- A flow-duration analysis for the period of sediment accumulation (1927–89); and
- Provisional suspended and bedload measurements reported by Childers et al. (D. Childers, USGS, Cascades Volcano Observatory, Vancouver, WA, written communication, 1995) for the Elwha River gauge above Lake Mills (USGS No. 12044900).

1. Procedure — An iterative procedure was used to develop a bed-material load (coarse sediment) rating curve such that when it was applied to the flow-duration analysis, the resulting sediment yield would agree with the volume of coarse sediment trapped within Lake Mills:

- **Step 1:** Results from suspended sediment load measurements were combined with bedload measurements to compute the total bed-material load. The sand-size portion of the measured suspended load was added to the results of the bed load measurement made on the same day (table 2). Cobbles up to 128 mm in size were captured in the bed-load sampler. Only 1 percent of the sediment in the Lake Mills delta is larger than 125 mm. For the purposes of this report, total bed-material load will be referred to as coarse sediment load.
- **Step 2:** River discharge (Q) and the corresponding coarse sediment load (Q_s) data were plotted on Log-Log paper (figure 6). A regression analysis of the logarithms was performed to determine the sediment-discharge rating curve (Q_s = a Q_w^b) for flows less than 1,970 cfs.
- **Step 3:** The sediment concentration was then calculated for the largest coarse sediment load of the measured data, which is 428 tons/day and corresponds to a discharge of 1,380 cfs. The concentration C is:

$$C = Q_s/Q_w = \frac{\text{dry wt. of sediment}}{\text{wt. of water} + \text{dry wt of sediment}} \approx \frac{\text{dry wt. of sediment}}{\text{wt. of water}}$$

$$C = \frac{(428 \text{ tons/day})(2,000 \text{ lbs/ton})(1 \text{ day/24 hrs})(1 \text{ hr/3,600 sec.})}{(1,380 \text{ cfs})(62.4 \text{ lbs/ft}^3)}$$

$$C = \frac{9.9074 \text{ lbs/s (coarse sediment)}}{86,112 \text{ lbs/s (water)}} = 0.000115 = 115 \text{ parts per million (ppm)} \approx 115 \text{ mg/L}$$

• **Step 4:** For flows greater than 1,970 cfs, the sediment-discharge rating curve matched the lower curve at a discharge of 1,970 cfs. The slope of the curve above 1,970 cfs (Figure 6) was computed by trial and error. As an initial guess, the concentration of 115 ppm (calculated in step 3) was used to compute the coarse sediment load for a discharge of 19,000 cfs as 5,890 tons/day (figure 6). This was the highest mean daily discharge for the period of record (1927–94) and is only exceeded 0.01 percent of the days. The slope of the upper sediment-discharge rating curve was then computed to also pass through the point corresponding to the high discharge of 19,000 cfs.

• **Step 5:** The equations defining the lower and upper sediment-discharge rating curves were used to calculate the coarse sediment load for Lake Mills by applying the flow-duration analysis results (Reclamation, 1951). A flow-duration analysis for mean daily flows of the Elwha River at McDonald Bridge was obtained from the USGS WATSTOR database for the period 1927–94 (table 3). The coarse sediment load (corresponding to a certain flow or discharge increment) was multiplied by the frequency of days in which that flow increment historically occurred. This product of coarse sediment load and flow frequency was totaled for a range of flows from 12 cfs to 19,000 cfs to compute the average annual coarse sediment yield. This annual yield was then multiplied by the number of years of reservoir operation to compute the total amount of coarse sediment entering Lake Mills.

The total sediment yield was then converted to a volume using an average density of 110 lbs/ft³ and compared to the measured coarse sediment volume in Lake Mills.

• **Step 6:** A new sediment concentration for a discharge of 19,000 cfs was assumed and steps 4 and 5 were repeated until the computed sediment volume matched the measured volume.

2. Results — The computed sediment concentration for a discharge of 19,000 cfs was 1,900 mg/L and the equations defining the lower and upper sediment-discharge rating curves are:

- Lower curve (for flows less than 1,970 cfs):

$$Q_s = 1.915379 \text{ E-10 } (Q_w^{3.734454})$$
 - Upper curve (for flows between 1,970 cfs and 19,000 cfs):

$$Q_s = 3.470206 \text{ E-06 } (Q_w^{2.441953})$$
- where:
- Q_s is the coarse sediment load, in tons per day, and
 Q_w is the mean daily discharge or riverflow, in cfs.

Table 2. Measured Discharge and Sediment Loads of the Elwha River above Lake Mills.

Date	Time	Discharge (cfs)	Suspended Sediment (tons/day)	Bedload (tons/day)	Total Coarse Sediment (tons/day)
4/08/94		1190	N/A	51.0	51.00
4/09/94	1500	1150	27.8	63.8	91.60
4/09/94	1505	1150	2.4	63.8	66.20
4/11/94		1020	0.7	19.2	19.90
4/12/94		1080	N/A	41.3	41.30
4/14/94		918	1.4	16.9	18.30
4/16/94	0825	915	2.1	15.1	17.20
4/16/94	0845	918	1.1	15.1	16.20
4/17/94	0825	1090	1.5	24.7	26.20
4/17/94	0830	1090	1.7	24.7	26.40
4/18/94		1450	5.2	67.3	72.50
4/19/94	1035	1830	39.7	200.0	239.70
4/19/94	1040	1830	32.1	200.0	232.10
4/20/94	1525	1470	6.8	79.7	86.50
4/20/94	1530	1470	36.5	79.7	116.20
4/21/94	1030	1490	13.7	95.6	109.30
4/21/94	1055	1480	8.3	95.6	103.90
4/22/94		1380	5.8	422.0	427.80
4/25/94		1150	N/A	61.8	61.80
4/26/94		1090	1.4	47.8	49.20
4/27/94		1080	1.9	62.6	64.50
5/11/94		1970	N/A	436.0	436.00
5/31/94		1090	N/A	54.9	54.90
6/21/94		1160	N/A	119.0	119.00

Table 3. Computation of Natural Coarse Sediment Supply Rate.

(Sediment rating curves were derived for the natural coarse sediment supply rate and applied to the flow-duration table (below) to compute the average annual supply rate. The sediment rating curves were adjusted until there was agreement between the computed and measured average annual sediment supply rates. The computed average annual coarse sediment supply rate is 164,000 tons (448.65 tons/day x 365 days) or 110,000 yd³ assuming a density of 110 lbs/ft³.)

Frequency range (percent-days)		Interval (percent-days)	Frequency midpoint (percent-days)	Mean daily discharge (cfs)	Coarse sediment transport capacity (tons/day)	Discharge-frequency product (cfs)	Sediment-frequency product (tons/day)
0.00	0.02	0.02	0.01	19,000	97,469.9	3.8	19.49
0.02	0.10	0.08	0.06	14,500	50,375.6	11.6	40.30
0.10	0.50	0.40	0.30	9,314	17,092.3	37.3	68.37
0.50	1.50	1.00	1.00	5,974	5,778.5	59.7	57.79
1.50	5.00	3.50	3.25	4,073	2,267.8	142.6	79.37
5.00	15.00	10.00	10.00	2,810	916.1	281.0	91.61
15.00	25.00	10.00	20.00	2,090	444.6	209.0	44.46
25.00	35.00	10.00	30.00	1,710	226.8	171.0	22.68
35.00	45.00	10.00	40.00	1,440	119.4	144.0	11.94
45.00	55.00	10.00	50.00	1,220	64.3	122.0	6.43
55.00	65.00	10.00	60.00	1,040	35.4	104.0	3.54
65.00	75.00	10.00	70.00	855	17.0	85.5	1.70
75.00	85.00	10.00	80.00	676	7.1	67.6	0.71
85.00	95.00	10.00	90.00	499	2.3	49.9	0.23
95.00	98.50	3.50	96.75	359	0.7	12.6	0.02
98.50	99.50	1.00	99.00	237	0.1	2.4	0.00
99.50	99.90	0.40	99.70	78	0.0	0.3	0.00
99.90	99.98	0.08	99.94	22	0.0	0.0	0.00
99.98	100.00	0.02	99.99	12	0.0	0.0	0.00
Totals						1,504.2	448.65

B. MASS-BALANCE CALCULATIONS

Mass-balance computations were performed to solve for the surface elevation at which the eroding delta sediment would first reach the dam as the lake is being lowered during dam removal, the end of phase 1 (chapter IV, section A). This sediment elevation would also equal the top elevation of the partially removed dam. The predicted sediment surface at the damsite is a function of the reservoir and sediment topography, and the erosion and redeposition slopes. Time is not considered nor is the release of sediment downstream. Results from these computations were used as the initial conditions to the HEC-6 sediment transport model (chapter VII, section C).

In this analysis, the delta sediment is assumed to erode and redeposit downstream along a surface of constant longitudinal slope (figure 7). The elevations of this new sediment surface are determined such that the volumes of eroded and redeposited sediment are equal. All or a portion of the delta sediment above this new sediment surface are assumed to erode and then redeposit downstream over existing lakebed sediment that is below the longitudinal slope. Deposition is assumed to occur laterally across the entire reservoir and up to the new sediment surface.

The slopes of the sediment erosion and redeposition surfaces were both set equal to an equilibrium slope where the sediment transport capability matches the upstream rate of sediment supply. Actual erosion slopes would likely be greater so that the use of an equilibrium slope tends to be conservative in that it overestimates the sediment surface elevation at the damsite just prior to the release of coarse sediment. An equilibrium slope of 0.00052 was computed by trial and error such that the computed coarse sediment load would match the upstream supply. The techniques, data, and assumptions used to compute the equilibrium slope included:

- STARS model (Reclamation, 1987);
- The Yang sediment transport function for sand and gravel (Yang, 1973 and 1984);
- Composite bed-material size gradation of the Lake Mills delta;
- An assumed wide channel cross section of rectangular shape (generally 800 feet wide);
- A constant lake water inflow of 1,500 cfs (the mean daily flow) and a corresponding coarse sediment inflow of 139 tons/day.

Reservoir cross sections were developed from predam and post-dam topographic maps of Lake Mills. The locations of these cross sections are shown in figure 8. Tables of cross-sectional area versus elevation were developed for each reservoir cross section using the hydraulic properties program HYDTAB, a part of the STARS model. The volume of sediment eroded was calculated by multiplying the erosion area of each cross section by a total of one-half the distance to the next upstream and next downstream cross sections. Erosion areas at each cross section were computed using the predam (1921) geometry and by taking the area difference between the current thalweg elevation (1989) and the new thalweg determined from the erosion slope. The sediment redeposition volume was calculated in a similar manner.

Because the river would probably not erode all of the delta sediment, four different portions of delta sediment were assumed to erode and redeposit within the reservoir downstream: all, two-thirds, one-half, and one-third (figures 7, 8, 10, and 11). It is also assumed the most conservative result is that all the delta sediment above the erosion surface would erode to the predam topography and redistribute across the lower lake, assuming that one-third of the delta sediment would erode was the lower limit evaluated. Table 4 summarizes the four cases considered.

Table 4. Volume of Lake Mills Sediment Erosion and Redeposition and the Sediment Surface Elevation at the Dam Site.

Case	Volume of Sediment Eroded/Redeposited (million cubic yards)	Sediment Surface Elevation at Damsite
All	8.7	504
Two-thirds	5.9	493
One-half	4.4	487
One-third	3.0	481

The original riverbed elevation at the damsite is estimated to be 400 feet (D. Gathard, Summit Technology Consulting Engineers, Seattle, WA, written communication, 1995). Based on these computations, the maximum sediment surface elevation at the damsite would range from 55–43 percent of the dam’s height.

Figure 6. Natural Supply of Coarse Sediment Entering Lake Mills versus River Discharge.

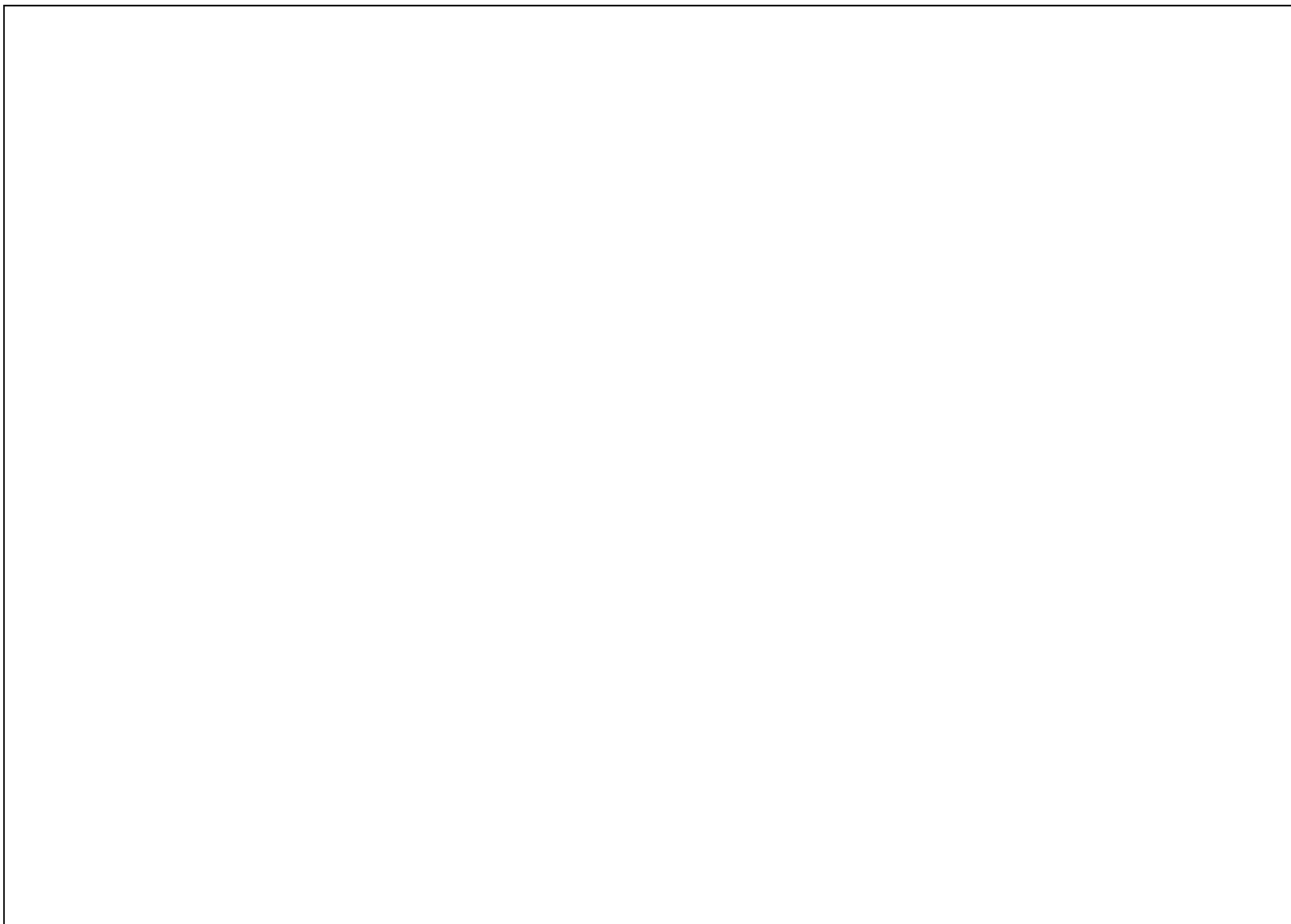


Figure 7. Lake Mills, Reservoir Sediment Redistribution Profile.
(Assuming that all sediment is eroded above the erosion slope and
Redeposited downstream.)



Figure 8. Lake Mills, Location of River Cross Sections.

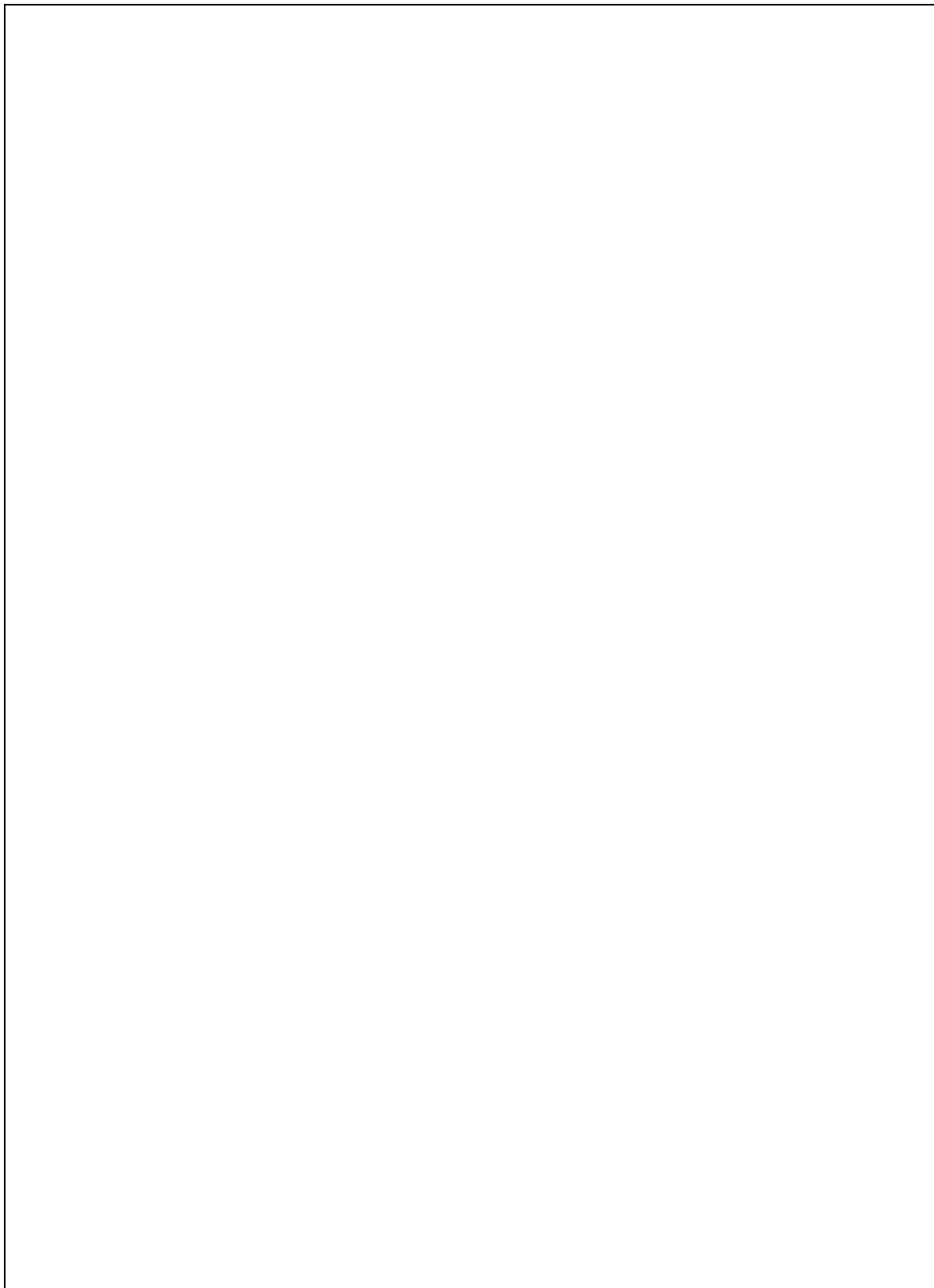


Figure 9. Lake Mills, Reservoir Sediment Redistribution Profile.

(Assuming that two-thirds of the sediment is eroded above the erosion slope and redeposited downstream)



Figure 10. Lake Mills, Reservoir Sediment Redistribution Profile.

(Assuming that one-half of the sediment is eroded above
the erosion slope and redeposited downstream.)



Figure 11. Lake Mills, Reservoir Sediment Redistribution Profile.

(Assuming that one-third of the sediment is eroded above
the erosion slope and redeposited downstream.)



C. HEC-6 MODELING OF LAKE MILLS SEDIMENT RELEASE

The river's capacity to vertically incise a channel through the redistributed delta sediment of Lake Mills during removal of Glines Canyon Dam was numerically modeled with HEC-6 to determine sediment release rates over time during phases 2 and 3 of dam removal (chapter IV, section A). Simulations of various steady flows for several channel widths were used for initial predictions of the erosion channel geometry. Sensitivity testing of the rate of dam removal was combined with the steady flow simulations to bracket the amount and timing of sediment transport past Glines Canyon Dam expected during dam removal.

1. Model input data

• **Cross-section data** — The reach modeled extended 2 miles upstream from Glines Canyon Dam to the mouth of Rica Canyon. The maximum spacing between cross sections was 300 feet. Results from the simple mass-balance calculations (chapter VII, section B) were used to define the initial sediment elevations at each cross section. In the early HEC-6 model simulations, the initial bed elevations were based on the case where all of the sediment above the erosion slope is eroded and redistributed downstream — the most conservative case. The results of the one-third redistribution case were judged to better represent what would actually occur and therefore used in subsequent simulations. Existing and predam cross-section data of the reservoir were obtained from the 1989 and 1921 topographic maps. Vertical channel erosion was limited to the elevation of the predam reservoir valley, based on the 1921 topographic map.

Within the wide areas of the reservoir, a narrower 5-foot-deep rectangular channel was assumed for the initial cross-section geometry to initiate reservoir sediment erosion during model simulations of dam removal. Cross sections in the bedrock canyon near the dam were already sufficiently narrow to produce velocities capable of transporting the delta sediment. Because the HEC-6 model does not predict width changes, a trial-and-error procedure was conducted for each flow simulated to determine the channel width that would result in progressive erosion from the downstream to the upstream end of the reach. Initially, a 787-foot-wide channel was assumed (based on a measurement from the 1994 Lake Mills drawdown experiment) but erosion at the downstream end did not progress more than one-third of the total distance upstream. Narrower widths were tried (which increased the channel velocity) until the erosion progressed to near the upstream end of the reach.

• **Sediment data** — The Yang sediment transport equations were selected because of their applicability to both sand- and gravel-size sediment. Size gradations were developed based on data obtained from the existing delta and lakebed (Reclamation, August 1995). The size gradation of the redistributed sediment was assumed to be sorted longitudinally with the coarser sediment deposited upstream and the finer sediment deposited downstream. The percentage of silt and clay-sized sediment was added to the very fine sand size range for both the redistributed delta sediment and for the lakebed sediment. The value of 2.7 for the specific gravity of sand particles and a dry unit weight of 110 lbs/ft³ were specified based on measurements from the 1994 drawdown experiment; otherwise, model default parameters were used. No adjustment was made for sediment particle shape factor.

• **Hydrologic data** — Steady flows of 500, 1,500, and 5,000 cfs were assumed. The downstream boundary water surface elevation (at the damsite) was calculated assuming the notch opening in the dam acted as a weir (critical depth at the notch). Flows of 500 and 1,500 cfs were contained within the notch opening. However, flows of 5,000 cfs overtopped the remaining dam crest. Temperature was held at a constant 50 °F. Either 1-hour or ½-hour time steps were used in these simulations.

2. Model results — Sediment loads released through several successive notches for a given flow and channel width are presented in Table 5. As would be expected, the predicted amount of released sediment increased with discharge. The results also show that the rate of sediment release increases as more of the dam is removed. The predicted sediment loads released from each dam-removal increment were averaged over 15 days.

Table 5. Lake Mills, HEC-6 Simulations of Sediment Release During Removal of Glines Canyon Dam.

Notch elevation (feet)	75	200	200	400	Channel width (feet)
	500	1,500	1,500	5,000	Flow (cfs)
	3.75	3.75	7.50	7.50	Notching rate (feet per 15 days)
468.20	85,836	159,748	160,751	41,301	Sediment discharge past Glines Canyon Dam for various notch openings (tons)
464.45	67,926	159,514			
460.70	76,064	180,600	216,315	335,501	
456.95	80,898	193,070			
453.20	65,489	189,834	228,358	490,730	
449.45	—	237,826			
445.70	—	235,901	283,128	518,216	
Total (tons)	376,213	1,356,493	888,552	1,385,793	Total (tons)
Elapsed Time (days)	75	105	60	60	Elapsed Time (days)
Average load (tons/day)	5016	12,919	14,809	23,097	Average load (tons/day)

Sensitivity tests conducted to determine the effect of increasing the time between successive 7.5-foot notch openings revealed that on average 82 percent of the total degradation experienced after 40 days occurred within 14 days in the 1,500 cfs steady flow simulations (table 6). This percentage rose to 92 in the 5,000 cfs simulations. Therefore, 14-day dam-removal increments appear to allow sufficient time to erode the majority of the available delta sediment. Table 6 contains additional data from this testing.

Table 6. Percent of Total Erosion Versus Time for a Single Notch Opening.

Flow simulations (cfs)	Percent of total erosion after specified time			
	after 7 days	after 14 days	after 21 days	after 40 days
1,500	57	82	88	100
5,000	72	92	100	100

Figure 12 shows the sediment released past the dam as a function of time for the simulation case of one-third initial sediment redistribution, 200-foot-wide channel, and 1,500 cfs steady flow. Sediment

loads peak at 15-day intervals and they exponentially decay after each sudden notch opening. The results from nine successive notches are depicted in the figure. Average and peak sediment loads increase with each notch. The large increase shown corresponding to the seventh notch (about 90 days) resulted from the channel accessing the finer-grained lakebed sediment. Shortly after the ninth and final notch opening, the dam has been effectively removed, all accessible delta and lakebed sediments have been eroded, and the natural sediment inflow is simply being transported downstream. Progressive thalweg profiles resulting from the same 1,500 cfs steady-flow simulations are shown on figure 13.

Figure 12. Lake Mills, HEC-6 model results: Predicted Rates of Sediment Erosion and Release Versus Time.

(Assuming initial conditions of figure 11, one-third sediment redistribution, 200-foot-wide erosion channel, and constant inflow of 1,500 cfs. The sediment transport rate peaks correspond to each notch opening in the dam.)

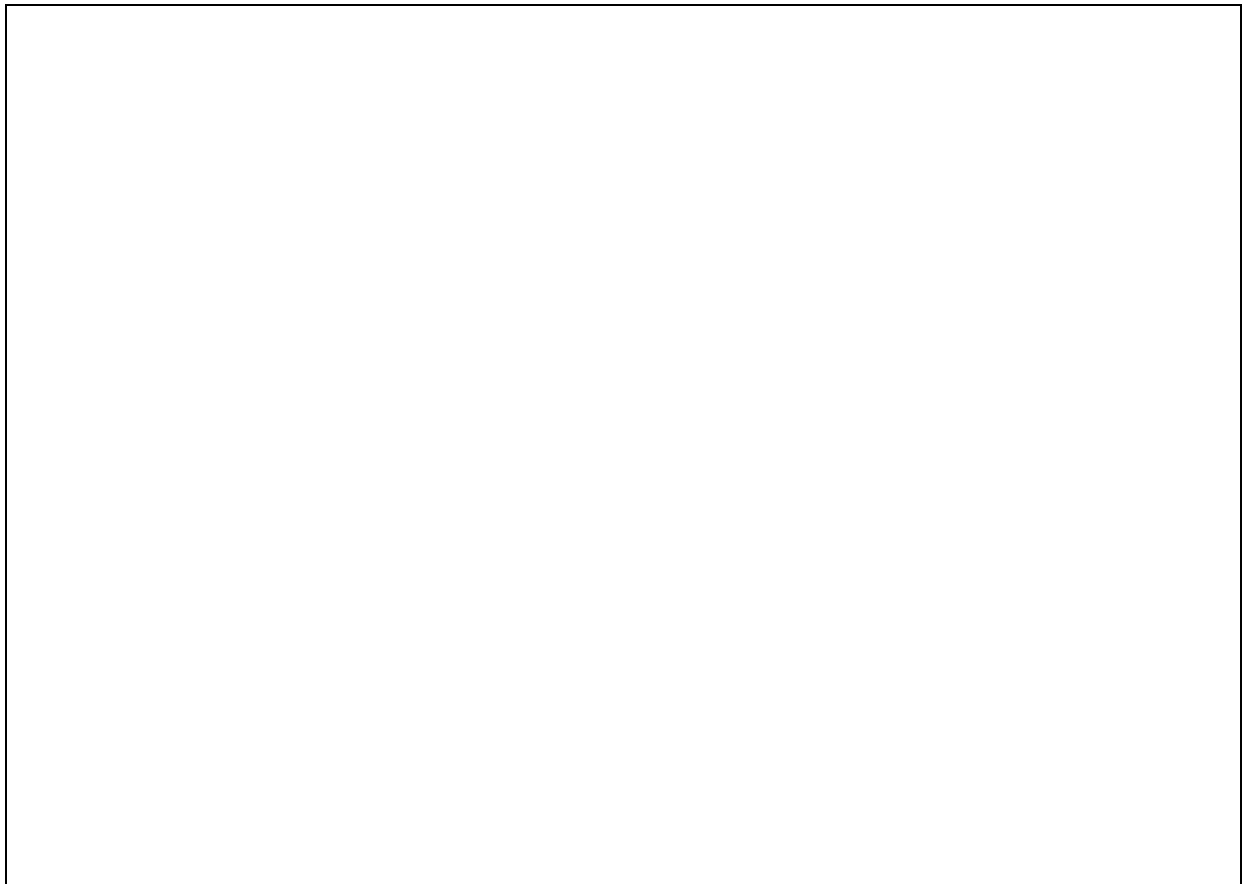


Figure 13. Lake Mills, HEC-6 model results: Predicted sediment erosion profiles 2 weeks after each notch opening in the dam.

(Assuming initial conditions of figure 11, 200-foot-wide erosion channel, and constant inflow of 1,500 cfs. The shaded profiles represent the amount of sediment eroded from each dam removal increment.)



D. DISCUSSION

1. Natural coarse sediment supply — The average annual coarse sediment yield of 110,000 yd³ per year is based on actual measurements from Lake Mills and can be used to represent long-term (greater than 10 years) conditions. However, flow and sediment yields from the Elwha River are highly variable and are usually different from average values. For example, sediment loads immediately after a landslide in the upper watershed would be temporarily high. There are some oral accounts that a large portion of the Lake Mills delta formed after the occurrence of a single landslide in the upstream watershed (at the foot of the Grand Canyon of the Elwha) in the mid-1960's. The computed sediment yield may be overestimated if the recurrence of large landslides is much greater than 67 years.

The sediment rating curves approximate average loads for a given flow. The lower sediment-discharge rating curve is based on 24 sediment loads measured during April, May, and June of 1994 — a small data set with a short duration. The upper curve covers two log cycles and was computed by trial and error such that, when applied to the flow duration analysis, the resulting sediment yield equaled the volume measured from the reservoir. Until a long-term sediment record is established, these sediment rating curves represent the best available predictor of sediment yield. These rating curves can be verified and improved as more data from the new stream gauge above Lake Mills become available.

2. Mass-balance calculations — The mass-balance technique is an easy way to determine the maximum possible range of sediment elevations at the dam. The computed sediment-surface elevations at Glines Canyon Dam are significant — from 55 to 43 percent of the dam's height. These computed elevations likely are high because they are based on a very mild erosion-and-deposition slope. The computed sediment elevation at the damsite was sensitive to the assumed erosion-and-deposition slope but not to the assumed portion of the delta eroded above the erosion slope (i.e., all, two-thirds, one-half, or one-third).

3. HEC-6 modeling of Lake Mills sediment release — HEC-6 model results provide information concerning how sediment release rates would vary between notch openings in the dam. However, channel erosion widths must be provided to the model. Therefore, development and application of a new mathematical model for the reservoir sediment is justified (chapter VIII).

CHAPTER VIII. ELWHA RESERVOIR SEDIMENT MODEL — RESERVOIR SEDIMENT EROSION, REDISTRIBUTION, AND RELEASE DOWNSTREAM

The HEC-6 model was used to predict how sediment release rates would vary between notch openings in Glines Canyon Dam. However, the HEC-6 model cannot predict the erosion width through the sediment nor does it predict sediment terrace development in the reservoir during the erosion process. Therefore, the Elwha Reservoir model was developed and used to simulate the erosion of coarse and fine sediment from both Lake Mills and Lake Aldwell.

The Elwha Reservoir model integrates empirical relationships for the erosion and redeposition of coarse sediment with a mixing cell model for fine sediment developed by G. Smillie and W. Jackson (1995). Not all of the reservoir sediment is expected to erode during dam removal. Some portion of the sediment would remain stable in the reservoir area over the long term because the reservoirs are much wider than the river. Therefore, predicting erosion widths during dam removal is critical to determining how much sediment could be eroded downstream. Observations from the 1994 Lake Mills drawdown test were used to develop an empirical relationship for the erosion and redistribution of coarse sediment within the delta.

A. MODEL INPUT AND OUTPUT

The following data are necessary to run the Elwha Reservoir model:

- Lake cross section data for existing and predam conditions including thalweg and tables of elevation and cross-section width;
- A current table of water volume versus lake elevation;
- The vertical distribution of coarse and fine sediment within the delta defined by a simple table of coarse- and fine-sediment percentages for various ranges of elevation;
- Exponent of the delta erosion width function (defined later in this section);
- Longitudinal erosion slopes for coarse and fine sediment;
- Coefficients to distribute sediment release over time within a reservoir drawdown increment;
- A water and sediment inflow hydrograph for the reservoir; and
- The amount and frequency or schedule of reservoir drawdown increments. For Lake Mills, a dam removal and lake drawdown increment is assumed to occur every two weeks when average lake inflow is less than or equal to 1,400 cfs. For Lake Aldwell, a schedule of drawdown increments was provided rather than a set frequency.

Model output includes:

- Longitudinal reservoir sediment profiles for each drawdown increment;
- Cross-section erosion widths for each drawdown increment;
- Mean daily release of water discharge, coarse sediment, and fine sediment from the dam site; and
- The total volume of coarse and fine sediment released.

B. MODEL ASSUMPTIONS AND PROCEDURE

The Elwha Reservoir model uses the following general assumptions:

- A single erosion channel can be used to simulate any multiple erosion channels that may actually occur;
- Vertical erosion would stop at the predam alluvium (reservoir bottom elevation);
- All reservoir sediment can be treated as two distinct sizes: coarse and fine;
- A daily time step is assumed to be adequate for model predictions; and
- Any tributary flow entering the reservoir can be ignored.

The Elwha Reservoir model simulates sediment erosion, redistribution, and release downstream in four phases of dam removal and lake drawdown described in chapter IV, section A.

1. Redistribution of delta sediment (Phase 1) — This is also the first phase of dam removal and reservoir drawdown. By the end of this phase, enough of the dam would be removed so that the lake no longer existed. During this phase, the river would incise channels through the delta eroding and redistributing coarse delta sediment within the reservoir area. Only fine delta sediment would be transported through the lake and past the dam.

In the first phase, the model computes the erosion and redistribution of delta sediment. The Elwha Reservoir model assumes that for a given drawdown increment, only a portion of the exposed delta is eroded. Erosion widths are assumed to be of some minimum value at the upstream end and increase at a parabolic rate with distance downstream to a maximum value — equal to the reservoir width at the delta front (figure 14). Erosion widths are assumed to be symmetrical about the center of the reservoir. The delta erosion slope is assumed to be constant over time so that the erosion depth is equal to the lake drawdown increment.

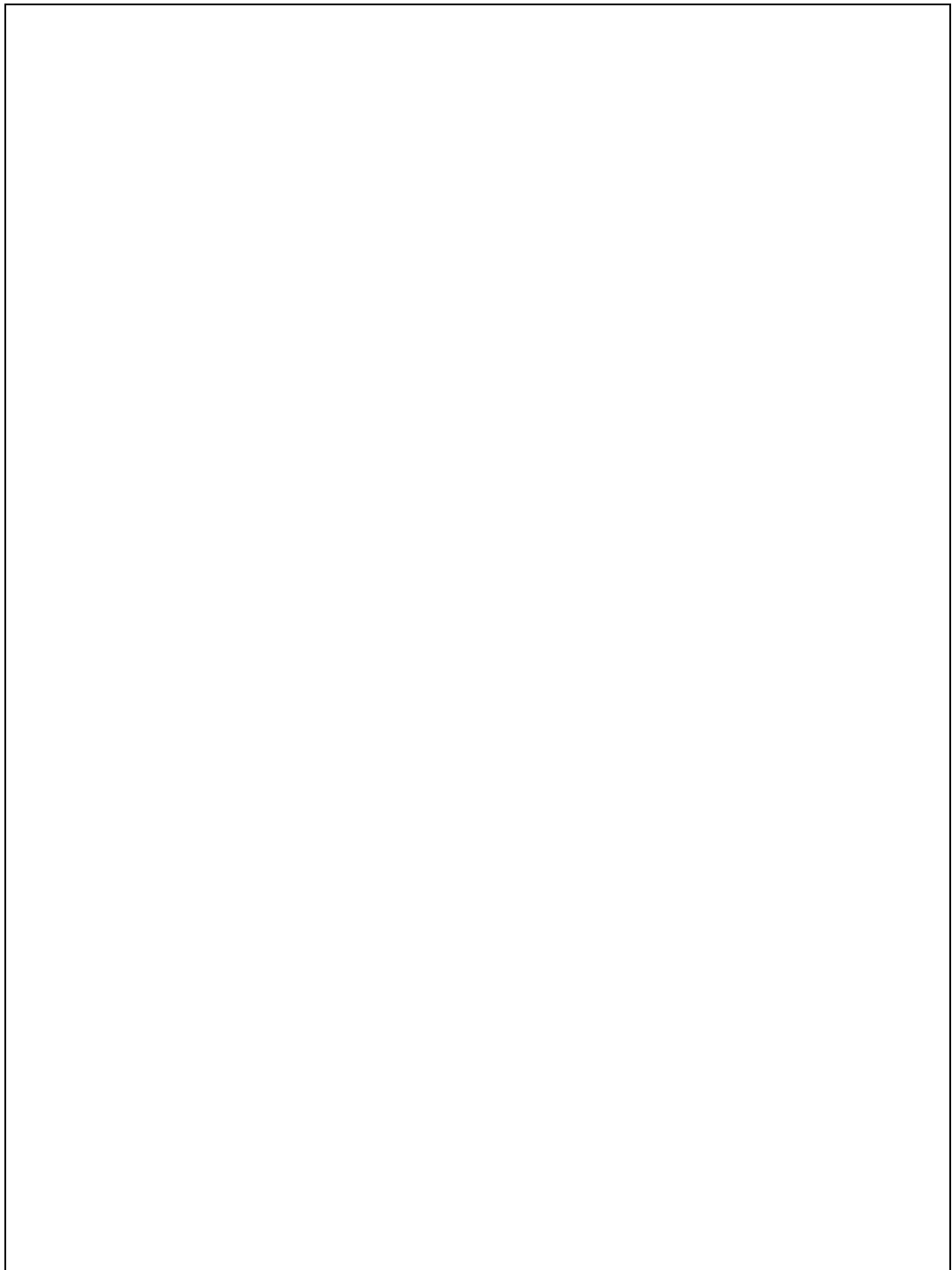
The frequency and amount of the reservoir drawdown increments are defined by the user. The model assumes that the lake is held at a constant elevation and for a long enough duration so that erosion and redistribution of the computed erosion volume has occurred.

For a given lake drawdown increment, delta erosion widths are computed for each reservoir cross section using equation 1:

- **Eq. 1** $EW = 2[aX^b + EW_{min}/2]$
where:
EW is the erosion width at a distance X,
X is the erosion channel length (increasing in the downstream direction),
a is a coefficient calculated by the model such that EW is equal to the lake width at the delta front,
b is a user defined exponent, and
EW_{min} is the minimum erosion width.

Figure 14. Elwha Reservoir Model: Example plan and profile plots of the Lake Mills delta erosion and redistribution after three increments of lake drawdown.

(After the first drawdown increment, the river has eroded and redistributed a portion of the delta downstream. Erosion widths increase at a parabolic rate with distance downstream, leaving a sediment terrace behind on both sides of the lake (area 1 and profile 1). After the second drawdown increment, another portion of the delta is eroded leaving a narrow, lower-level terrace on each side (area 2 and profile 2). After the third drawdown increment, a third terrace is left on each side (area 3 and profile 3), the river has eroded down to profile 4 and the delta front has advanced downstream. Some terrace levels may be lost later due to channel widening during subsequently higher lake inflows.)



In equation 1, the erosion width (EW) is a minimum at the upstream end of the erosion channel ($X = 0$) and is a maximum at the delta front. The upstream end of the erosion channel is where the erosion slope intersects the predam reservoir bottom. In the case of Lake Mills, the upstream end is limited by the mouth of Rica Canyon and the erosion in Rica Canyon is computed separately.

The minimum erosion width is assumed to be a function of discharge and is computed using equation 2 — a regime equation:

- **Eq. 2** $EW_{\min} = c Q_w^{0.41}$
 where:
 $EW_{\min}$ is the minimum erosion width (in feet),
 c is a channel width coefficient and
 Q_w is the river discharge (in cfs).

A regime equation is used to predict channel widths that would be achieved over a period of years or decades. In the case of the Elwha River forming a channel through the reservoir delta, use of the regime equation is expected to over predict actual erosion widths and volumes.

The exponent of 0.41 has been theoretically derived by Yang, Song, and Woldenberg (1981) and agrees well with rivers in the United States. The coefficient “c” was computed separately for a range of discharge values using measured width and discharge data from the Krause Bottom reach of the Elwha River ($c = Q_w^{0.41}/EW_{\min}$). This is a natural alluvial reach upstream from Lake Mills and Rica Canyon. Krause Bottom was subjected to a large sediment supply from a natural landslide that occurred a short distance upstream in the mid-1960's. The river in this reach exhibits characteristics of a braided channel and the active channel widths are relatively wide. Data from this reach were chosen to estimate the erosion widths.

Active channel widths in this reach were measured from an aerial photograph taken April 16, 1994. The widest active width of 530 feet was associated with the 2-year flood of 13,100 cfs (Reclamation, March 1995). The widest wetted channel width of 200 feet was also measured from the photograph and associated with discharge of 930 cfs (measured at the Elwha River stream gauge above Lake Mills on the same day the photograph was taken).

From these data, equations 3 through 5 were developed for three discharge ranges.

For discharges (Q_w) less than or equal to 10,000 cfs:

- **Eq. 3** $EW_{\min} = [200 \text{ ft} / (930 \text{ cfs})^{0.41}] Q_w^{0.41} = 12.1 Q_w^{0.41}$

For discharges between 10,000 and 13,100 cfs:

- **Eq. 4** $EW_{\min} = 530 \text{ ft}$

For discharges greater than or equal to 13,100 cfs:

- **Eq. 5** $EW_{\min} = [530 \text{ ft} / (13,100 \text{ cfs})^{0.41}] Q_w^{0.41} = 10.9 Q_w^{0.41}$

These functions are shown graphically in figure 15. Erosion widths increase more slowly than corresponding increases in discharge. For example, a 20-percent increase in discharge from 15,000

to 18,000 cfs results in a 7.7-percent width increase from 562 to 605 feet. The channel width is constant (530 feet) for discharges between 10,000 and 13,100 cfs because almost-vertical river banks prevent wetted widths from increasing until the river stage has overtopped the bank.

**Figure 15. Elwha Reservoir Model Input:
Width-discharge Relationship for Krause Bottom Reach.**



For each lake drawdown increment, the surface erosion area is computed using equation 6, which is the integral of equation 1:

- **Eq. 6** $EA = 2\{[a/(b+1)]X^{(b+1)} + (EW_{min}/2)X\}$
 where:
 EA is the surface erosion area.

Erosion volume is computed using equation 7, which is simply the erosion area times the erosion thickness:

- **Eq. 7** $EV = (EA)(TK)$
 where:
 EV is the total erosion volume for a given drawdown increment and
 TK is the erosion thickness and equal to the lake drawdown increment.

If the computed erosion width for any cross section (of a given drawdown increment) is greater than a previously computed erosion width for that cross section, then any overlying sediment is also eroded and the correspond volume is added to the total erosion volume.

The coarse and fine sediment erosion volumes are computed as percentages of the total erosion volume. The distribution of the erosion volumes over the days of the drawdown increment are computed from erosion distribution coefficients. These coefficients — one for each day of the drawdown increment — are defined by the user. The sum of these coefficients must total 1.

The coarse-sediment erosion volume is assumed to deposit immediately downstream of the delta front and up to the drawn-down lake elevation. The deposition volume is computed using equation 8 and is equal to the coarse-sediment-erosion volume plus the upstream supply of coarse sediment:

- **Eq. 8** $DV = (EV)(pc) + QSc_{up}$
 where:
 DV is the deposition volume of coarse sediment,
 pc is the percentage of coarse sediment from the eroded delta, and
 QSc_{up} is the upstream coarse-sediment supply for the drawdown increment.

The width of the redeposited coarse sediment is assumed to be equal to the lake width. The thickness and downstream length are computed from the reservoir geometry using an iterative procedure. The table of water volume versus lake elevation is updated to account for redeposition of the coarse delta sediment into the lower lake.

The fine-sediment erosion volume is assumed to be resuspended in the lake and remain suspended until transported past the dam. This assumption means that the fine sediment never settles out on the margins of the reservoir and consequently over-estimates the concentration of fine sediment released downstream.

The lake concentration is computed using equation 9:

- **Eq. 9** $L_{conc} = (VOL_{sed}/VOL_{wat})(W_f/W_w)(1,000,000)$
where:
 L_{conc} is the fine sediment lake concentration (ppm by weight),
 VOL_{sed} is the cumulative volume of fine sediment suspended in the lake,
 VOL_{wat} is the volume of water and suspended sediment in the lake,
 W_f is the unit dry weight of fine sediment, and
 W_w is the unit weight of the water-sediment mixture (chapter VIII, section B-5).

The cumulative volume of fine sediment suspended in the lake (VOL_{sed}) tends to increase with dam removal as more material is eroded and resuspended into the lake. The volume of water in the lake (VOL_{wat}) decreases with dam removal and with deposition of coarse sediment transported from the upstream delta.

The volume of water released from the dam on a given day is computed using equation 10, a function of lake inflow, the lake drawdown volume (if any that day), and the lake volume displaced by the accumulation of coarse sediment from upstream.

- **Eq. 10** $QW_{out} = QW_{in} + DR + (DV)(C_{day})(1-n)$
where:
 QW_{out} is the daily lake outflow volume of water,
 QW_{in} is the daily lake inflow volume of water,
 DR is the daily lake drawdown volume,
 DV is the coarse sediment deposition volume for the drawdown increment,
 C_{day} is the coefficient or fraction of the coarse sediment volume deposited that day, and
 n is the porosity of the coarse sediment (ratio of the volume of voids or pores to the total volume of sediment).

With each increment of dam removal, the lake is assumed to drawdown over a one-day period. Therefore, the drawdown volume (DR) only applies to the first day in which an increment of the dam is removed.

Lake water is released from the lake surface over the top of the dam. Because fine sediment concentration would be less near the surface than at depths, release concentrations were empirically reduced by the inverse of the residence time and computed using equation 11 (Smillie and Jackson, 1995):

- **Eq. 11** $R_{conc} = L_{conc}(1/RT)$
where:
 R_{conc} is the fine sediment release concentration (ppm by weight),
 L_{conc} is the fine sediment lake concentration, and
 RT is the lake residence time, in days.

The lake residence time is the number of days for water to travel through the lake, not less than 1, and is computed using equation 12:

- **Eq. 12** $RT = VOL_{wat} / QW_{in}$
where:
 QW_{in} is the mean lake inflow rate over the drawdown increment.

The volume of fine sediment released each day is computed using equation 13, which is the fine sediment release concentration multiplied by the released volume of water:

- **Eq. 13** $QSf_{out} = R_{conc} QW_{out}$
where:
 QSf_{out} is the volume of fine sediment released from the dam.

2. Release of coarse delta sediment (Phase 2) — Dam removal would continue without a lake. The river would continue to incise channels through the reservoir sediment. As this occurred, a portion of the redistributed, coarse delta sediment and a portion of the fine lakebed sediment (exposed during previous delta erosion) would be eroded and transported past the dam.

At the beginning of the second phase, coarse sediment from the delta would have reached the dam and covered the fine sediment of the lakebed. Once this occurred, the elevation of sediment would be about equal to the top of the remaining dam and the lake would no longer exist, but rather a stub dam with the remaining reservoir full of sediment. Coarse sediment would be released downstream with the next increments of dam removal and would no longer be redistributed within the lake (i.e., no new delta deposition).

Because delta sediment has reached the dam in this phase, eroded sediment is now released downstream from the dam and no new delta deposits are created. Channel erosion widths at the damsite are limited by bedrock controls. Regime equations 3, 4, and 5 are used to compute erosion widths of the exposed sediment with each increment of dam removal. Erosion volumes for coarse and fine sediment are computed from equations 14 and 15, respectively:

- **Eq. 14** $EV_c = X_c (EW) TK$
where:
 X_c is the length of the erosion channel through coarse sediment (limited to the distance between the dam and where the channel intersects the predam riverbed);
 EW is the erosion width computed from equations 3, 4, or 5; and
 TK is the erosion thickness and equal to the lake drawdown increment.
- **Eq. 15** $EV_f = X_f (EW) TK$
where:
 X_f is the length of the erosion channel through fine sediment (limited to the distance between the dam and where the channel intersects the predam riverbed);

The total of X_c and X_f equals X which is the total length of the erosion channel between the dam and where the channel intersects the predam riverbed.

Erosion widths are computed to increase with discharge. For the case of a constant discharge, the model would compute a vertically incised channel of constant width. When the discharge increases, so to does the width of the erosion channel. Any overlying sediment is also eroded and added to the total erosion volume.

Coarse and fine sediment erosion volumes are distributed over the days of the drawdown increment using a user-supplied coefficient for each day. In this phase of dam removal, the fine sediment concentration released downstream is computed using equation 16:

- **Eq. 16** $R_{conc} = [(C_{day}) EV_f + Qsf_{up}] / (QW_{out})(W_f/W_w) (1,000,000)$
 where:
 R_{conc} is the fine sediment release concentration (ppm by weight),
 C_{day} is the coefficient or fraction of sediment released that day,
 EV_f is the erosion volume of fine sediment,
 Qsf_{up} is the fine sediment volume supplied from upstream, and
 QW_{out} is the daily water discharge volume past the damsite — equal to the inflow of the former lake area.

The amount of coarse sediment released to the river downstream is computed using equation 17 which is the coarse sediment erosion volume plus the amount of coarse sediment supplied from upstream:

- **Eq. 17** $RV_c = (C_{day}) (EV_c) + QSc_{up}$
 where:
 RV_c is the daily release volume of coarse sediment,
 QSc_{up} is the upstream sediment supply of coarse sediment volume.

3. Release of fine lakebed sediment near the dam (Phase 3) — The final stages of dam removal occur during the third phase. At the beginning of the third phase, dam removal would have progressed to a point where the river has vertically eroded a channel through the layers of coarse, redeposited delta sediment. The fine lakebed sediment near the dam would be exposed. The rate of fine sediment release past each dam would be initially high after a sudden increment of dam removal. This rate would decrease exponentially with time until the next dam removal increment.

In phase 3, the model only computes vertical erosion through the fine lakebed sediment. The erosion volume of fine lakebed sediment is computed from equation 15. The erosion channel length, X_f , is equal to X , the distance between the dam and where the channel intersects the predam riverbed, and X_c is equal to zero. The release concentration of fine sediment is computed from equation 16. The erosion and release of any overlying coarse sediment are only computed from channel widening and only when the previous maximum discharge has been exceeded.

4. Post dam removal with sediment release during floodflows (Phase 4) — At the beginning of the fourth phase, the dam would have been removed and the river would have eroded down to predam alluvium. Through channel meandering and bank erosion, the river would erode and transport both coarse and fine sediment out of the reservoir area during progressively higher floodflows.

In phase 4, the model no longer computes vertical erosion through the reservoir sediment. Erosion of coarse and fine sediment only occurs through channel widening. Otherwise, the transport of coarse and fine sediment past the damsite are limited to the amount entering the reservoir area from upstream.

5. Unit weight of sediment — No reliable data were available on either sediment porosity (ratio of void volume to total sediment volume) or dry unit weight for the fine sediment of Lake Mills. These data are difficult to obtain in reservoirs. In addition to logistical problems of sampling in deep water, the sediment was easily compacted during sampling.

The correction factor, W_f/W_w , was computed to convert sediment concentrations from ppm by volume to ppm by weight. However, the computed correction factor was almost equal to one ($1.15 \approx 1$). A correction factor of one ($W_f/W_w = 1$) was actually used because of the basic uncertainty of the computed dry unit weight and of the general process being modeled and because the computed factor is close to one. The following discussion describes how the factor W_f/W_w was computed.

The average dry unit weight of lakebed sediment in Lake Mills was calculated using the procedure described in *Reservoir Sedimentation* (Reclamation, 1982). This guideline provides initial dry unit weights for clay, silt, and sand for various reservoir operating practices and also provides an equation to account for compaction over time.

The initial weights and compaction factors for Lake Mills were obtained from the guideline assuming that the sediment is almost always submerged (table 7). The percentages of sediment type in the lakebed were based on average-size gradation analyses of samples collected from Lake Mills (D. Gathard, Summit Technology Consulting Engineers, Seattle, WA, written communication, 1995).

Table 7. Reservoir Sediment Initial Weights and Compaction Factors.

Sediment type	Initial unit weight (lbs/ft ³)	Compaction factor — K	Percentage in lakebed
clay	26	16	23
silt	70	5.7	77
sand	97	0.0	0

The equation for computing the average initial weight is:

• **Eq. 18** $W_o = W_c p_c + W_m p_m + W_s p_s$

where

W_o is the average initial dry unit weight;

W_c, W_m, W_s are the initial dry unit weights of clay, silt, and sand; and

p_c, p_m, p_s are the percentages of clay, silt, and sand.

Using equation 18, the initial dry unit weight for lakebed sediment of Lake Mills is:

$$W_o = 26 \text{ lbs/ft}^3 (0.23) + 70 \text{ lbs/ft}^3 (0.77) = \mathbf{60 \text{ lbs/ft}^3}$$

However, the sediment would have compacted over time. Part of the sediment deposited during each year of operation and each year's deposit would have a different compaction time. The average dry unit weight of all sediment deposited in "T" years of operation is:

• **Eq. 19** $W_T = W_o + 0.4343 K \{[T/(T - 1)] \ln(T) - 1\}$

where

W_T is the average dry unit weight after T years of operation and

K is a compaction factor based on the type of reservoir operation and sediment size.

The compaction factor K is computed from equation 20.

• **Eq. 20** $K = K_c p_c + K_m p_m + K_s p_s$

where

K_c, K_m, K_s are correction factors for clay, silt, and sand based on the type of reservoir operation (table 7).

Using equation 20, the composite K-factor for Lake Mills, assuming normally submerged conditions, is:

$$K = (16)(.23) + (5.7)(.77) + (0)(0) = \mathbf{8.1}$$

Over the 68 years of reservoir operation from 1927–95, the average dry unit weight of fine lakebed sediment (using equation 19) is:

$$W_f = W_T = 60 \text{ lbs/ft}^3 + (0.4343)(8.1)[\{68/(68 - 1)\} \ln_e(68) - 1] = \mathbf{71.5 \text{ lbs/ft}^3}$$

Therefore, the computed correction factor to convert the concentrations to ppm by weight is: $\underline{W_f}$

$$= \frac{71.5 \text{ lbs/ft}^3}{62.4 \text{ lbs/ft}^3} = 1.15 \approx 1$$

C. LAKE MILLS SEDIMENT MODELING DURING REMOVAL OF GLINES CANYON DAM

The Elwha Reservoir model was used to simulate the sediment erosion, redistribution, and release downstream from Lake Mills during removal of Glines Canyon Dam. Concurrent removal of Glines Canyon and Elwha Dams was simulated by using model output from Lake Mills as model input for the simulation of Lake Aldwell.

1. Lake Mills model input — The timing of dam-removal increments would depend on lake inflow and any seasonal restrictions to mitigate impacts on migrating fish. The Elwha Reservoir model assumes that drawdown of Lake Mills could begin as early as June 1st of a given year (chapter III, section A) if riverflows into the lake are low enough. Drawdown increments were assumed to occur every 14 days if the root-mean-squared inflow (equation 21) for each 14-day period was less than or equal to 1,400 cfs. Otherwise, the model assumes that dam removal operations would be suspended due to high flow conditions and the lake is assumed to remain at a constant elevation. Other than high flow periods, the model assumes that there are no other seasonal restrictions on dam removal.

- **Eq. 21** $Q_{RMS} = [\{\Sigma (Q_{wi})^2\}/n]^{0.5}$
 where,
 Q_{RMS} is the root-mean-squared lake inflow (discharge),
 Q_{wi} is the mean daily discharge, and
 n is the number of days over which the average is computed ($n = 14$).

The root-mean-squared discharge was computed, rather than a simple average, to give more weight to the high discharge values.

Lake drawdown increments of 15 feet were assumed between lake elevations of 590 to 530 feet. This corresponds to the period when the lake elevation can be drawn down by penstock releases. The drawdown increment was reduced to 7.5 feet between lake elevations of 530 to 425 feet — the period corresponding to dam removal by notching. The arch portion of the dam would be completely removed down to an elevation of 400 feet. However, the last 25 feet of dam removal are not simulated because there is negligible storage or water or sediment behind the dam at an elevation of 425 feet.

Reservoir sediment cross section data for Lake Mills were obtained from the 1921 (predam) and 1989 topographic maps. A total of 14 cross sections were established on the 1921 and 1989 maps from just upstream of the damsite to the mouth of Rica Canyon. The location of these cross sections are shown on figure 8. A table of predam (1921) and current (1989) thalwegs were constructed from the cross section data. In addition, the table includes cross-sectional area versus lake elevation for each cross section (table 8).

Original lake capacity data were digitized from a plot of elevation versus reservoir capacity (Thebo, Starr, and Anderson, 1926). Current lake capacity data were computed using the original lake capacity and sedimentation volume from Reclamation (August 1995). This sedimentation volume was distributed throughout the lake using a sediment distribution design curve from *Reservoir Sedimentation* (Reclamation, 1982) for the case where the sediment is almost always submerged. A current lake capacity curve could have also been digitized from the 1989 topographic map but the value added from this effort was judged not to be worth the additional work.

Table 8. Lake Mills Cross Section Tables.
(Predam [1921] and post-dam [1989] cross-section thalwegs and reservoir cross-sectional areas [see figure 8 for map].)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Station (feet)	0	1160	2640	3900	4900	6020	6900	7780	8180	8380	8720	9200	9960	10680
1921 thalweg elevation (feet)	425	441	457	464	468	476	485	495	500	503	508	511	515	518
1989 thalweg elevation (feet)	445	450	465	475	490	500	520	530	540	580	580	580	590	590
Elevation (feet)	1989 Cross-Sectional Area (ft²)													
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
445	0	0	0	0	0	0	0	0	0	0	0	0	0	0
455	3056	2163	0	0	0	0	0	0	0	0	0	0	0	0
465	6988	12538	0	0	0	0	0	0	0	0	0	0	0	0
475	11431	26113	7088	0	0	0	0	0	0	0	0	0	0	0
485	16338	40531	22494	4075	0	0	0	0	0	0	0	0	0	0
495	21706	55625	39850	12263	5550	0	0	0	0	0	0	0	0	0
505	27450	71294	58275	21225	17206	1788	0	0	0	0	0	0	0	0
515	34056	87363	77513	30838	29256	12444	0	0	0	0	0	0	0	0
525	41363	103919	97450	40881	41656	24869	2925	0	0	0	0	0	0	0
535	49419	121013	118006	51269	54413	37669	10900	1775	0	0	0	0	0	0
545	58606	138619	139200	61919	67556	50825	20931	12869	4775	0	0	0	0	0
555	69188	156788	161000	72813	81063	64400	31944	26044	15863	0	0	0	0	0
565	81125	175631	183400	83919	94956	78600	43300	39681	28300	0	0	0	0	0
575	94544	195119	206425	95275	109194	93725	54956	53719	41713	0	0	0	0	0
585	108963	215144	230219	106931	123700	109675	67240	68438	56581	7638	5427	543	0	0

The entire lakebed was assumed to consist of fine silt- and clay-sized sediment. The delta was also known to contain some silt- and clay-sized sediment. Reclamation (August 1995) provided sediment volume and size data for the Lake Mills delta. From this data, a simple table of delta elevation range and fine-sediment percentage was developed (table 9).

Table 9. Lake Mills Delta Elevation Range Versus Average Percentage of Fine Sediment.

Delta elevation range (feet)	Average percentage of fine sediment
> 552	5.15
552 to 527	13.87
< 527	47.53

During lake drawdown, the delta erosion width was assumed to increase at a parabolic rate with distance downstream (equation 1). An exponent of 2 agreed well with erosion widths observed during the 1994 Lake Mills drawdown experiment and was used in Elwha Reservoir model simulations.

The longitudinal erosion slopes for coarse and fine sediment were set equal to the computed equilibrium slope for the delta (0.00052; see chapter VII, section B). The fine sediment erosion slope was assumed to be controlled by coarse delta sediment and therefore equal to the coarse sediment erosion slope.

The erosion volume of coarse and fine sediment released downstream from the dam is computed for each drawdown increment. The daily-release coefficients used to distribute this erosion volume over the days of the drawdown increment are presented in figure 16.

In the first phase of dam removal, portions of the lake delta are eroded and redistributed downstream toward the dam. Based on the 1994 Lake Mills drawdown experiment, lake drawdown initiates vertical erosion of the delta followed by lateral erosion near the delta front. Delta sediment therefore erodes at a relatively uniform rate. The erosion rate of coarse and fine sediment was assumed to decrease linearly over time so that the erosion rate on the 14th day of the drawdown cycle was 30-percent less than the erosion rate on the first day (figure 16). In subsequent phases of dam removal and lake drawdown, sediment release rates were assumed to have an exponential decay with time. High sediment release rates would occur immediately after a notch opening in the dam. These high rates would rapidly decrease as head cut erosion progressed upstream followed by lateral erosion. An exponential decay curve was developed based on HEC-6 modeling of sudden notch openings in the dam (chapter VII, section C; also figure 12). The coefficients to distribute sediment release over time within a reservoir drawdown increment were taken from this exponential decay curve.

Figure 16. Elwha Reservoir Model Input: Daily Sediment Release Coefficients.

(Sediment is eroded at an almost constant rate when coarse delta sediments are redepositing across the lake [first phase of dam removal]. Sediment erosion rates decay exponentially after the coarse delta sediments have reached the dam [subsequent phase of dam removal].)



2. Lake Mills model results — Model simulations were performed using both constant and variable lake inflow.

- **Constant lake inflow** — A simulation was performed using a low constant lake inflow of 1,000 cfs. This simulation is helpful for understanding model procedure and capability. Simulation results of fine and coarse sediment released downstream are shown in figure 17.

During dam removal (phases 1, 2, and 3), the predicted fine-sediment-concentration pattern follows the pattern of notch openings in the dam and subsequent lake drawdown. After the delta front reaches the dam (phase 2), the predicted pattern of coarse sediment release also follows the pattern of notch openings in the dam and subsequent lake drawdown. Release rates of fine and coarse sediment tend to be highest immediately after each notch opening, then decrease with time until the next notch opening. During the entire dam removal process, fine sediment release concentrations are initially low, then tend to increase with time as more sediment is eroded and lake water volumes decrease. Sediment terraces within the lakebed and delta areas are predicted and shown in figure 18.

Figure 17. Elwha Reservoir Model Results During Removal of Glines Canyon Dam Assuming a Constant Inflow of 1,000 cfs.

(Lake surface elevation versus time; water discharge versus time; fine sediment concentration versus time; and coarse sediment load versus time.)

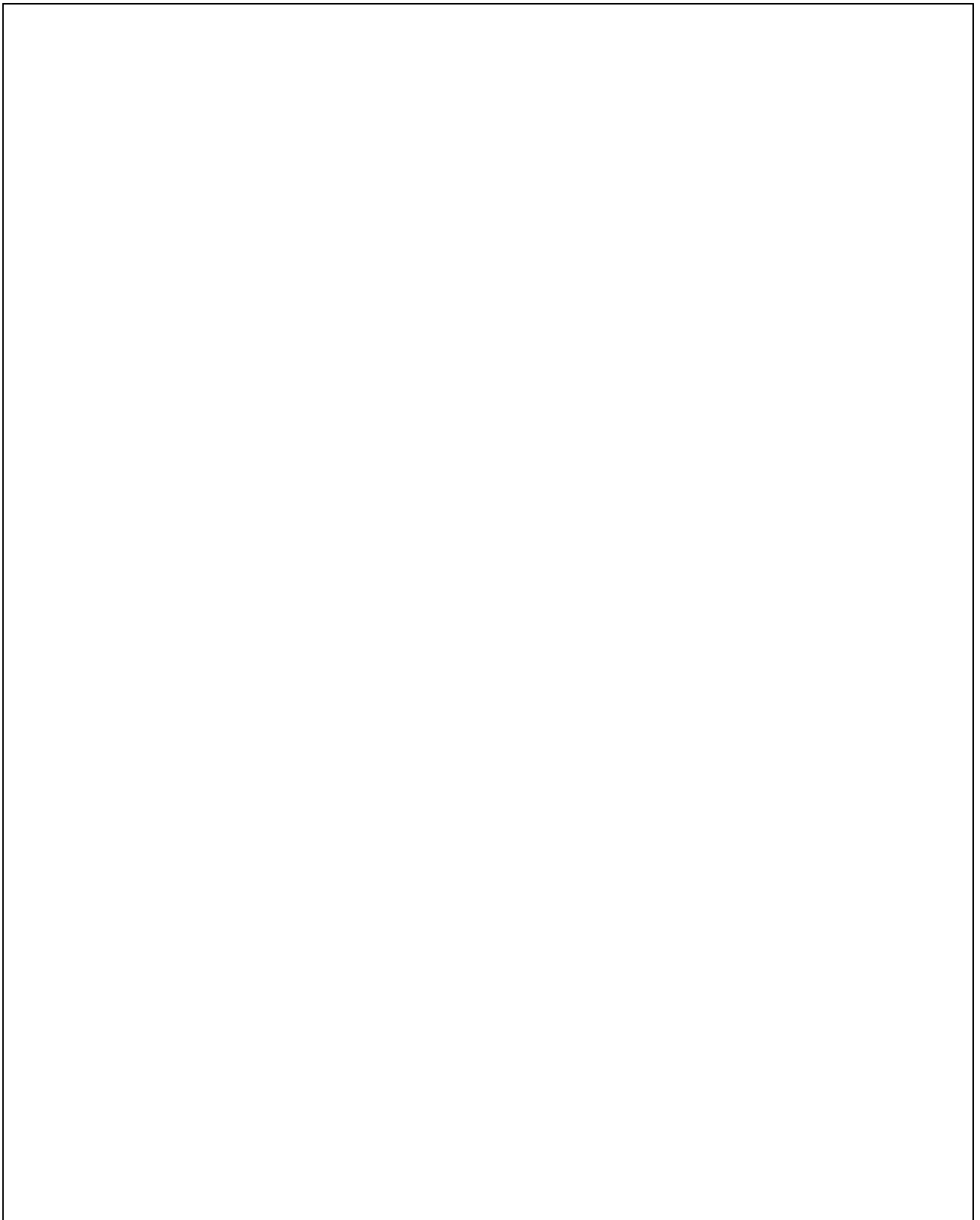
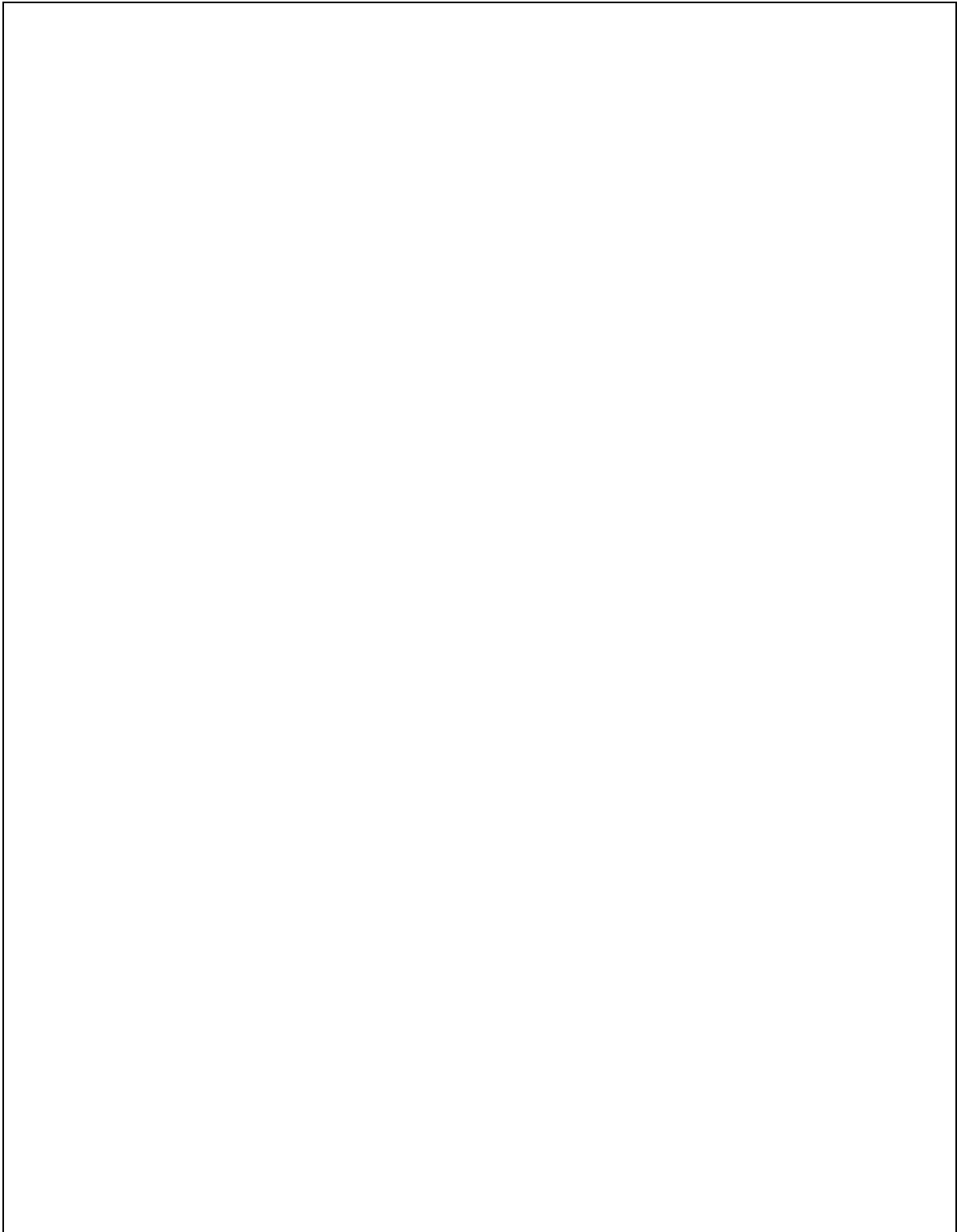


Figure 18. Elwha Reservoir Model Results for a Constant Inflow of 1,000 cfs.
(Reservoir sediment terraces remaining in Lake Mills after removal of Glines Canyon Dam.)



· **Variable lake inflow and hydrologic scenarios** — In the Elwha Reservoir model, sediment erosion widths and total erosion volumes increase with lake inflow. Therefore, model simulations were performed using historic flows as the lake inflow. Historic mean daily discharges for the Elwha River were obtained from USGS measurements at the McDonald Bridge gauging station. Four different hydrologic scenarios were simulated, each based on 3 years 4 months of historic flow:

- Hydrologic scenario 1. June 1, 1968 to September 30, 1971
- Hydrologic scenario 2. June 1, 1950 to September 30, 1953
- Hydrologic scenario 3. June 1, 1971 to September 30, 1974
- Hydrologic scenario 4. June 1, 1989 to September 30, 1992

Each of these historic periods were selected based on annual peak mean daily discharges (table 10 and appendix B). Hydrologic scenario 1 includes the lowest peak discharges for any three consecutive water years of record. Scenario 4 includes the highest peak discharges for any three consecutive years of record. Scenarios 2 and 3 were arbitrarily chosen to represent the range between the extremes of scenarios 1 and 4. Scenario 2 includes a year of relatively high annual-peak discharge followed by a year of relatively low and then moderate annual-peak discharge. Each year of scenario 3 has a progressively higher annual-peak discharge. A hydrograph plot of each scenario is presented in figure 19.

Table 10. Mean Daily Peak Discharges for Each Hydrologic Scenario.

Hydrologic scenario	Water year		Annual peak mean daily (cfs)
	Year	Months	
1	1968	Jun-Sep	4,000
	1969	Oct-Sep	5,440
	1970	Oct-Sep	4,830
	1971	Oct-Sep	5,490
2	1950	Jun-Sep	5,500
	1951	Oct-Sep	11,800
	1952	Oct-Sep	3,860
	1953	Oct-Sep	9,150
3	1971	Jun-Sep	4,250
	1972	Oct-Sep	6,420
	1973	Oct-Sep	10,300
	1974	Oct-Sep	18,100
4	1989	Jun-Sep	2,850
	1990	Oct-Sep	12,400
	1991	Oct-Sep	21,400
	1992	Oct-Sep	14,600

Figure 19. Elwha Reservoir Model Input: Lake Inflow Hydrographs for 4 Hydrologic Scenarios.
(Mean daily flows are from Elwha River stream gauge measurements at McDonald Bridge.)

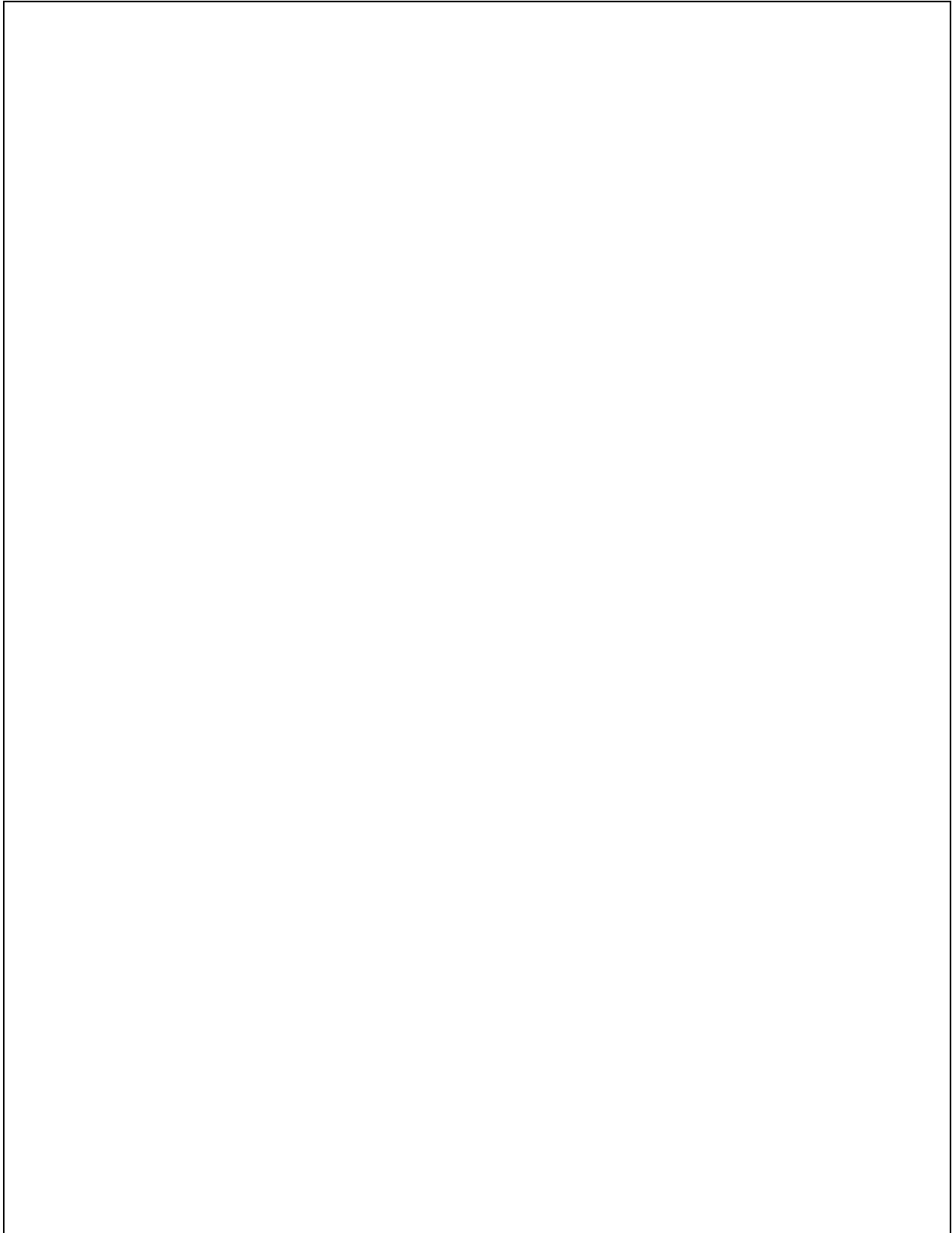


Figure 20. Elwha Reservoir Model Results for Hydrologic Scenario 1.
(Lake Mills drawdown and the release of water, fine sediment concentration, and coarse sediment load versus time during the removal of Glines Canyon Dam.)

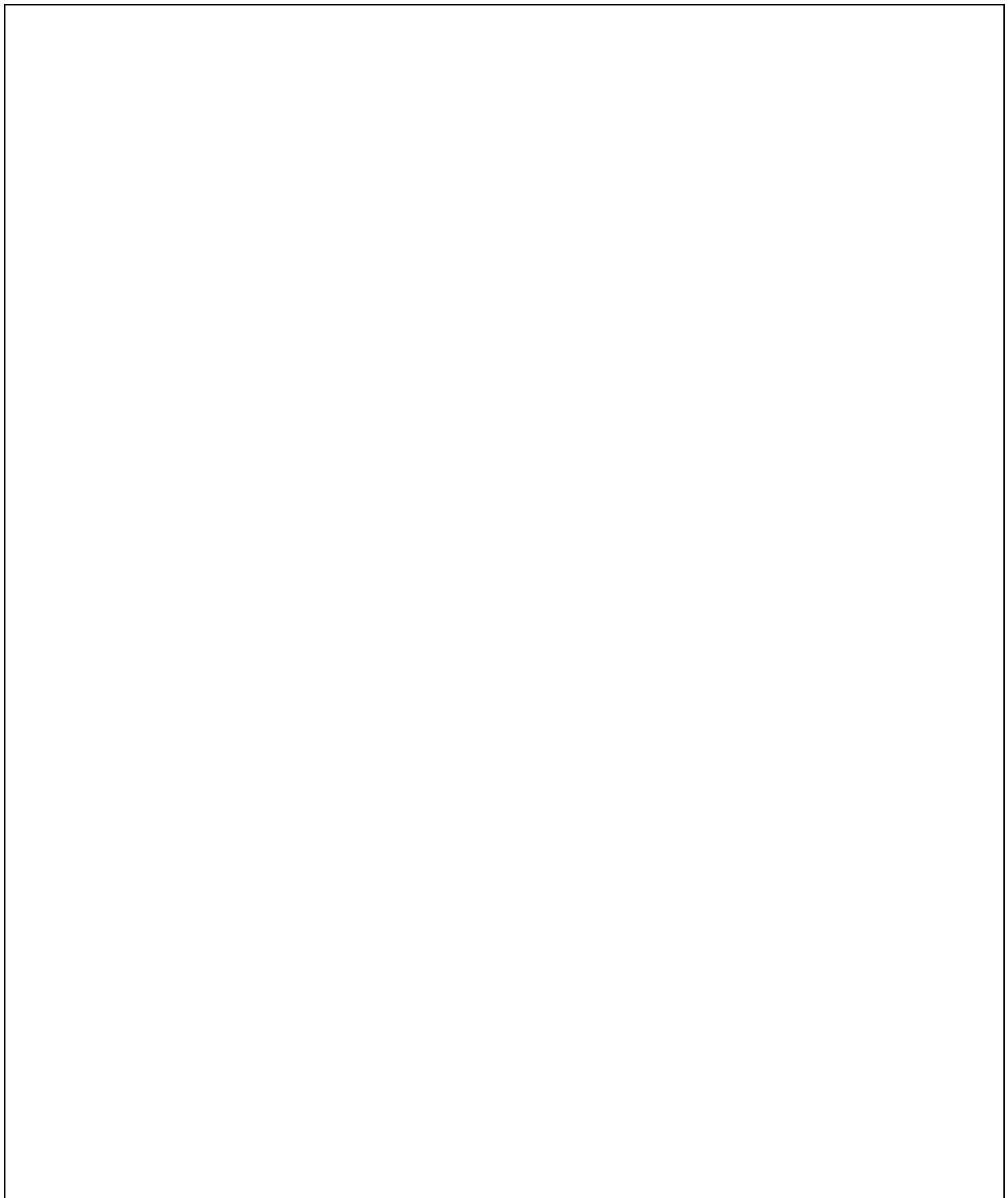


Figure 21. Elwha Reservoir Model Results for Hydrologic Scenario 2.
(Lake Mills drawdown and the release of water, fine sediment concentration, and coarse sediment load versus time during the removal of Glines Canyon Dam.)

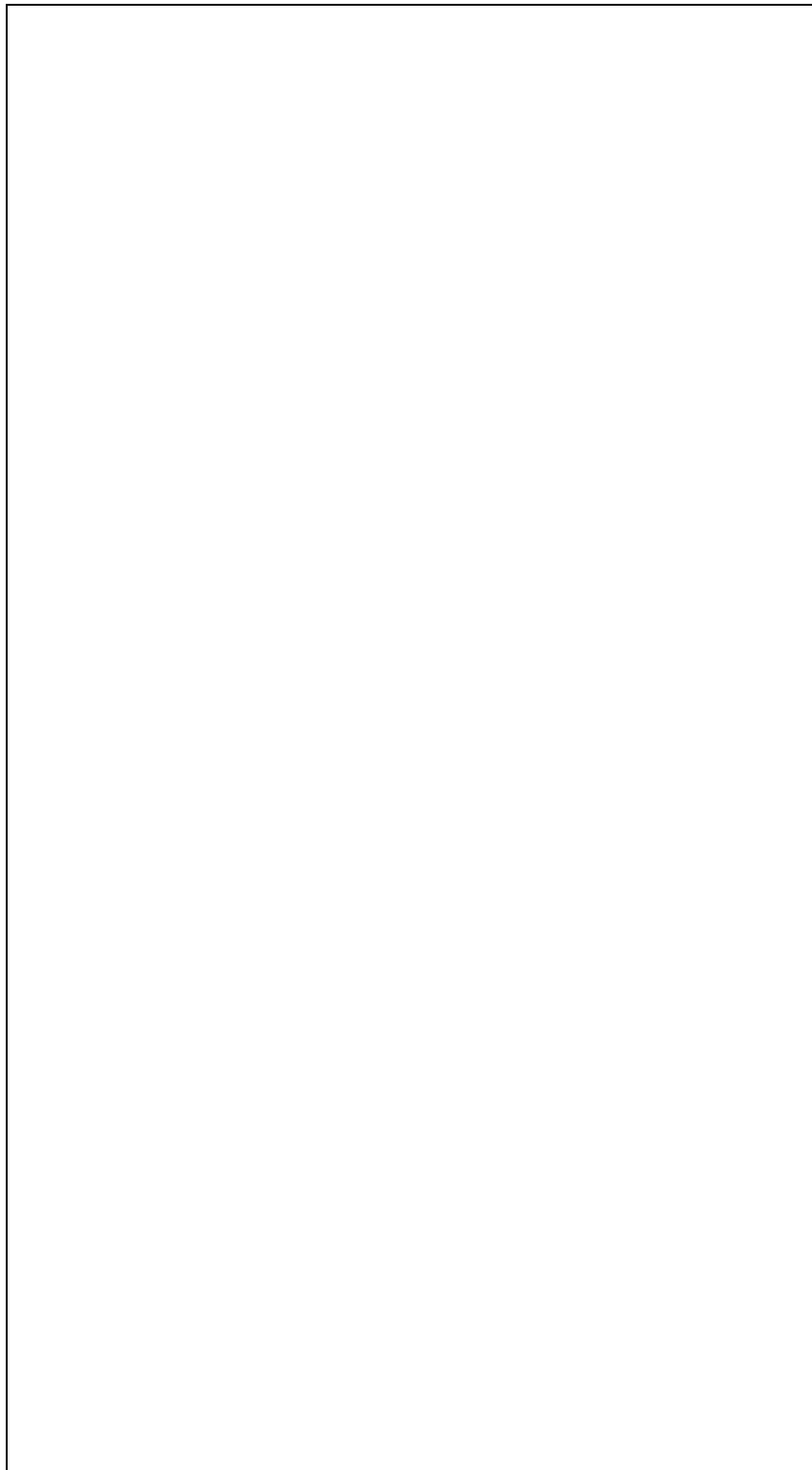


Figure 22. Elwha Reservoir Model Results for Hydrologic Scenario 3.
(Lake Mills drawdown and the release of water, fine sediment concentration, and coarse sediment load versus time during the removal of Glines Canyon Dam.)

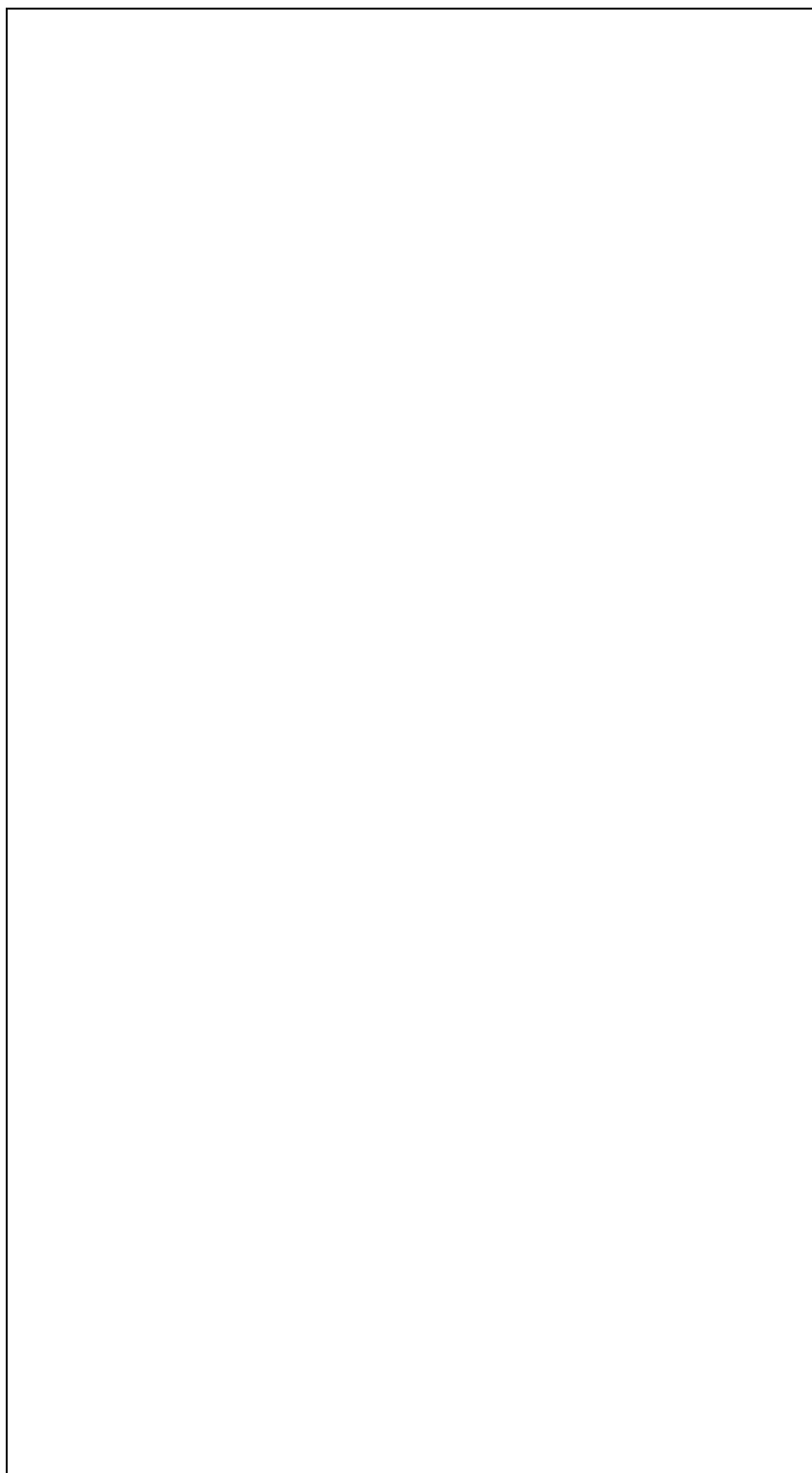
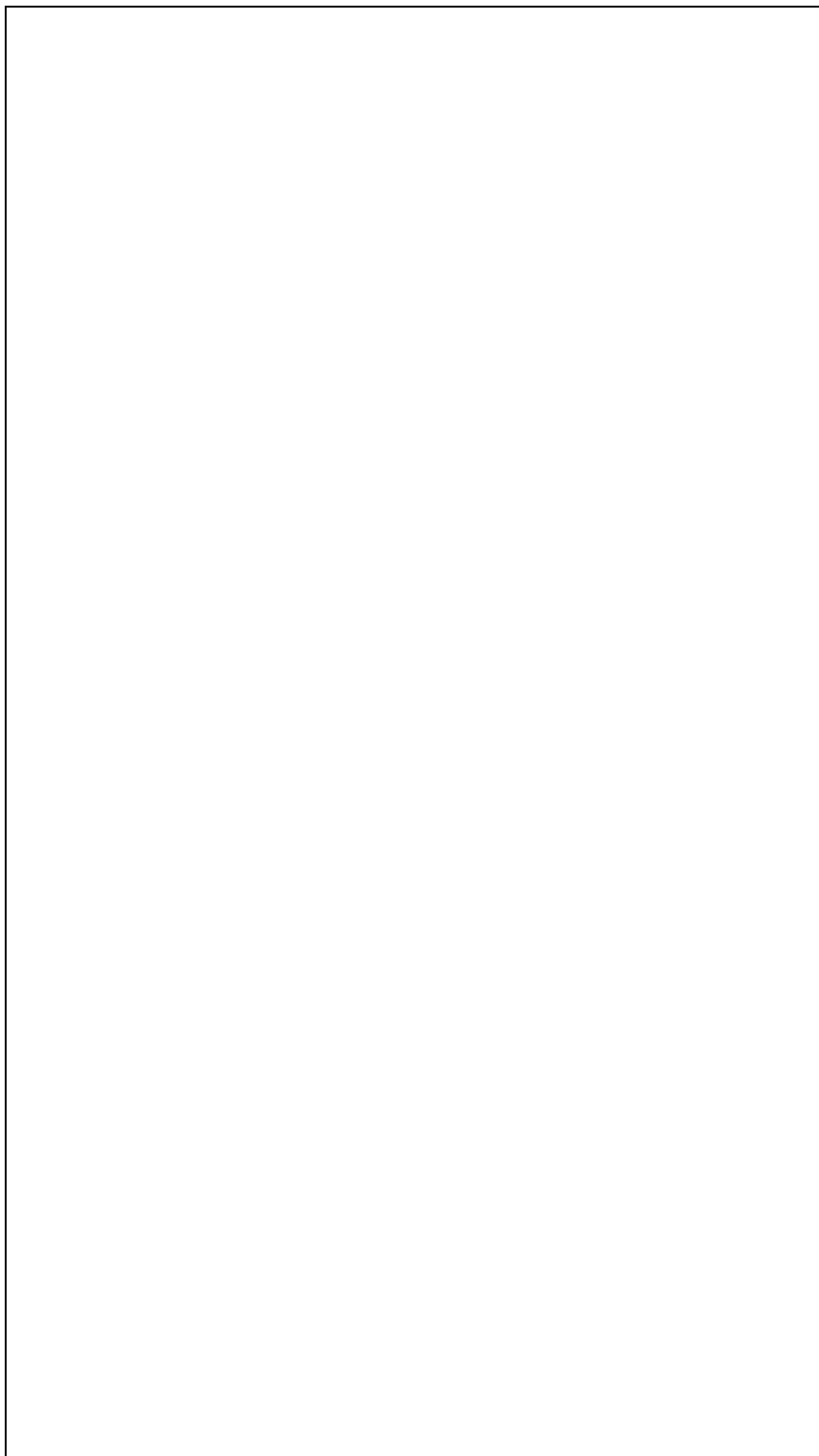


Figure 23. Elwha Reservoir Model Results for Hydrologic Scenario 4.
(Lake Mills drawdown and the release of water, fine sediment concentration, and coarse sediment load versus time during the removal of Glines Canyon Dam.)



Model results of water, fine sediment concentration, and coarse sediment load released downstream from Lake Mills, during removal of Glines Canyon Dam, are presented for each hydrologic scenario in figures 20 through 23. In each case, the model predicted that the sediment surface elevation would be 462.5 feet when the eroding delta front first reached the dam. The predicted volumes of fine and coarse sediment released downstream are listed in table 11.

Table 11. Summary of Model Results for Fine and Coarse Sediment Release from Lake Mills.

FINE SEDIMENT RESULTS				
Lake Mills	Hydrologic Scenario			
	1	2	3	4
Peak mean daily discharge (cfs)	5,490	11,800	18,100	21,400
Sediment inflow (yd ³)	156,000	158,000	352,000	571,000
Sediment outflow (yd ³)	3,861,000	3,723,000	4,366,000	4,712,000
Net Erosion (yd ³)	3,706,000	3,565,000	4,014,000	4,140,000
Percent of 6,620,000 yd ³	56	53	60	63
COARSE SEDIMENT RESULTS				
Lake Mills	Hydrologic Scenario			
	1	2	3	4
Peak mean daily discharge (cfs)	5,490	11,800	18,100	21,400
Sediment inflow (yd ³)	156,000	158,000	352,000	571,000
Sediment outflow (yd ³)	1,161,000	977,000	1,760,000	2,334,000
Net erosion (yd ³)	1,005,000	819,000	1,408,000	1,763,000
Percent of 7,210,000 yd ³	14	11	20	25

The eroded sediment volumes tend to increase with each hydrologic scenario. However, the model predicted slightly more sediment erosion from scenario 1 than from scenario 2. This is because larger lake inflows were occurring in scenario 1 during the spring snowmelt of the second water year (when compared with scenario 2). The higher spring snowmelt flows of scenario 1 were eroding more sediment terrace levels when compared with scenario 2. Although scenario 2 contained a higher peak flow for all water years, the largest peak occurred early in the second water year and eroded fewer sediment terraces than compared to the higher spring flow of scenario 1, which occurred later in the water year.

The predicted release of fine and coarse sediment from Lake Mills for each of the four hydrologic scenarios has many similarities to the previous simulation of constant lake inflow. Five distinct periods are evident for each of these four hydrologic scenarios (appendix C).

- **Begin lake drawdown for dam removal (phase 1)** — This period would be from June through October of the first year. Fine sediment concentrations released downstream would be initially low and then increase as drawdown continues. Concentrations would be less than 500 ppm most days with maximum concentrations of 1,100–34,000 ppm (lasting 1–3 days), depending on lake inflows. Coarse sediment from the delta would erode and redeposit in the lower lake but no coarse sediment would be released downstream.
- **Stop lake drawdown and dam removal during winter high flows (phase 1)** — This period likely would be from November through January of the second year. Exposed delta sediment would continue to erode but none would be released downstream. The remaining lake would be flushed by the high lake inflows and fine sediment concentrations released downstream would be low and close to natural conditions.
- **Continue dam removal and lake drawdown after winter high flows (phase 1)** — This period would probably be from February through April of the second year. Fine sediment concentrations released downstream would be 1,000–10,000 ppm most days with maximum concentrations of 6,400–13,000 ppm (lasting 1–3 days). Coarse sediment from the delta would be approaching the dam but no coarse sediment would be released downstream.
- **Stop dam removal and lake drawdown during spring high flows (phase 1)** — This period would likely be from May through June of the second year. Coarse delta sediment would almost reach the dam but none would yet be released downstream. The remaining lake would be small and flushed by the high lake inflows. Fine sediment concentrations released downstream would be similar to natural inflows.
- **Finish dam removal after spring high flows (phases 2 and 3)** — This period would likely be from July through September or October of the second year. Coarse sediment from the delta would reach the dam and be released downstream. Coarse sediment release rates would initially be high but decrease rapidly with time. Fine sediment concentrations released downstream would be 1,000–5,000 ppm most days with maximum concentrations of between 6,400–27,000 ppm (lasting 1 to 3 days), depending on lake inflow.
- **Reservoir sediment erosion and release following dam removal (phase 4)** — This period would begin during October of the second year and continue for about two more years (model simulations continued through September of the fourth year). The erosion and release of coarse and fine sediment would be low and close to natural conditions most of the time. However, floodflows of progressively higher magnitude would continue to widen erosion channels through the reservoir and produce high rates of both coarse and fine sediment release downstream. Peak concentrations of fine sediment would be 17,000–29,000 ppm. Peak concentrations would typically be of short duration (1–3 days) and the magnitudes of these events would tend to decrease with time.

During dam removal, maximum coarse sediment loads released downstream for each simulation ranged 80,000–160,000 tons per day with a duration of a few days. Maximum coarse sediment loads were greater after dam removal in all model simulations. This is because the model assumed that all of the sediment within the computed erosion width is released downstream over a one-day period. During actual dam removal, the sediment would likely erode over several days.

The Elwha Reservoir model simulations predict sediment terraces development within the lakebed and delta areas. The lower elevation terraces are subject to widening during floodflows. Computed channel erosion widths at the predam thalweg are listed in table 12 for each hydrologic scenario. Figures 24 through 27 show the final reservoir topography for cross sections K, F, and C (figure 8 for cross section locations) for each hydrologic scenario. In general, model results predict that lower elevations terraces would be lost to bank erosion during floodflows and channel bank heights would be greater.

Table 12. Maximum Computed Channel Erosion Widths at the Predam Thalweg of Lake Mills for Each Hydrologic Scenario.

Hydrologic scenario	Highest peak discharge (cfs)	Maximum erosion width (feet)
1	5,490	410
2	11,800	510
3	18,100	610
4	21,400	650

Figure 24. Elwha Reservoir Model Results for Hydrologic Scenario 1.
(Reservoir sediment terraces remaining in Lake Mills after removal of
Glines Canyon Dam.)

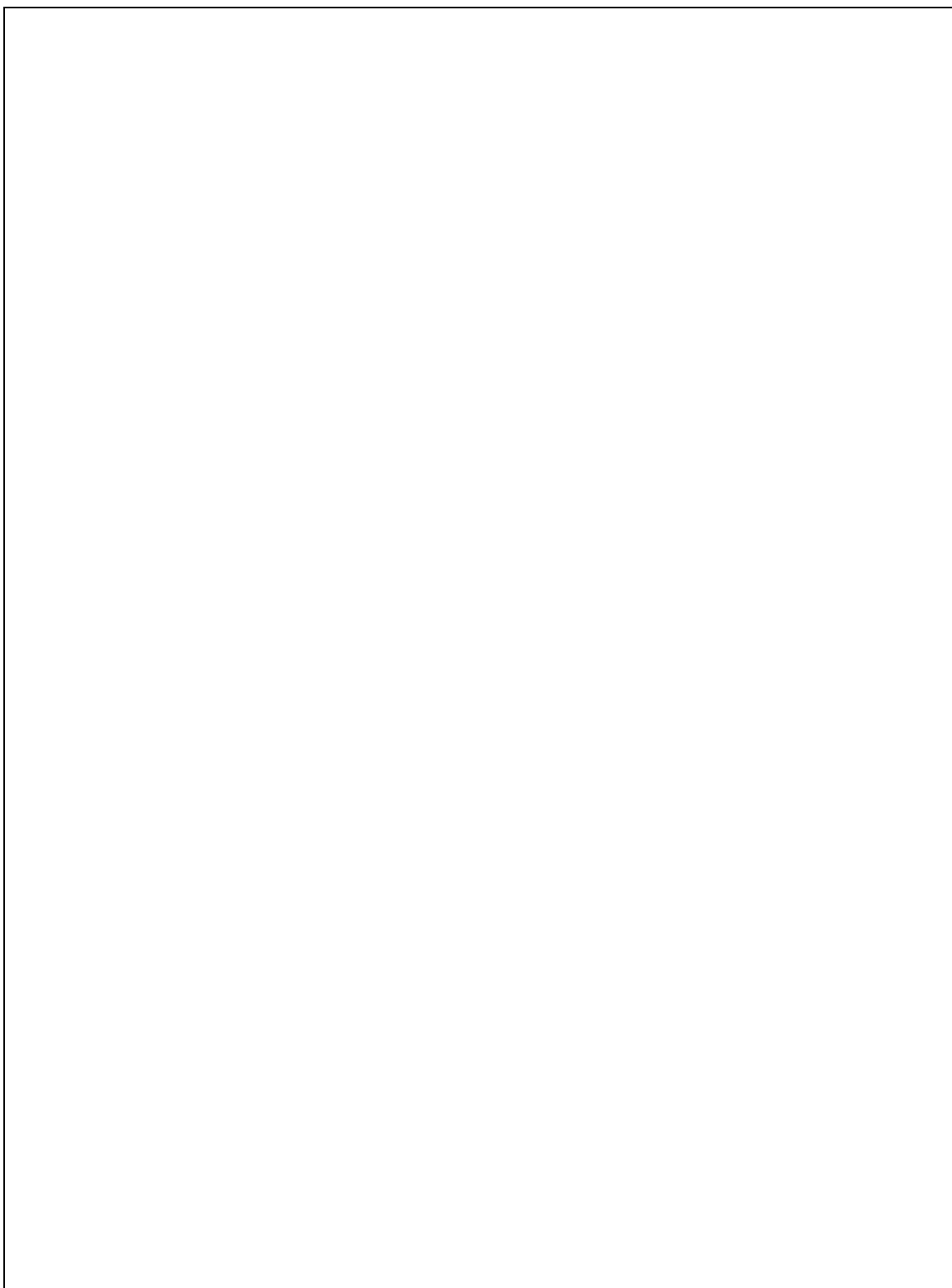


Figure 25. Elwha Reservoir Model Results for Hydrologic Scenario 2.
(Reservoir sediment terraces remaining in Lake Mills after removal of
Glines Canyon Dam.)

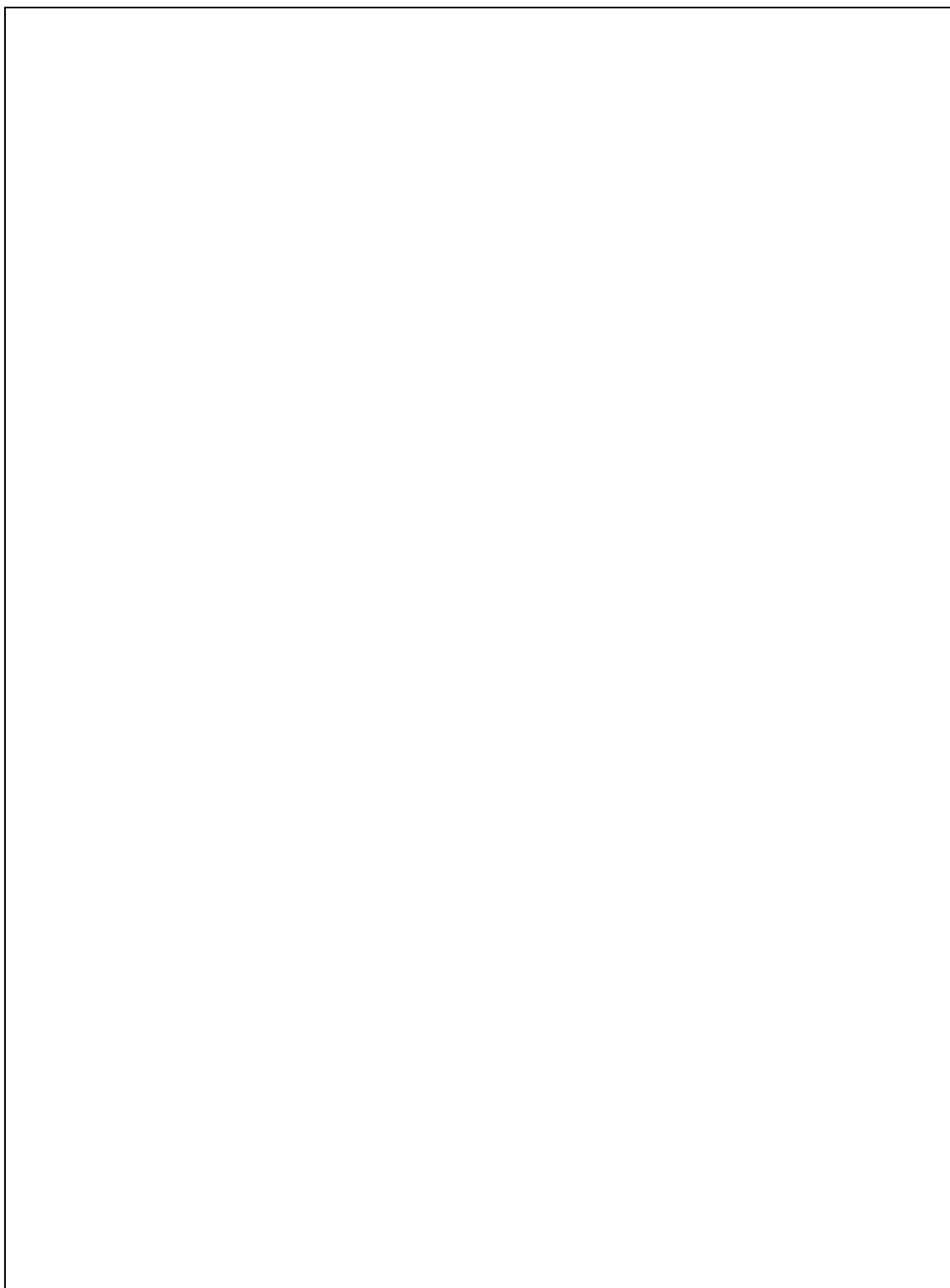


Figure 26. Elwha Reservoir Model Results for Hydrologic Scenario 3.
(Reservoir sediment terraces remaining in Lake Mills after removal of
Glines Canyon Dam.)

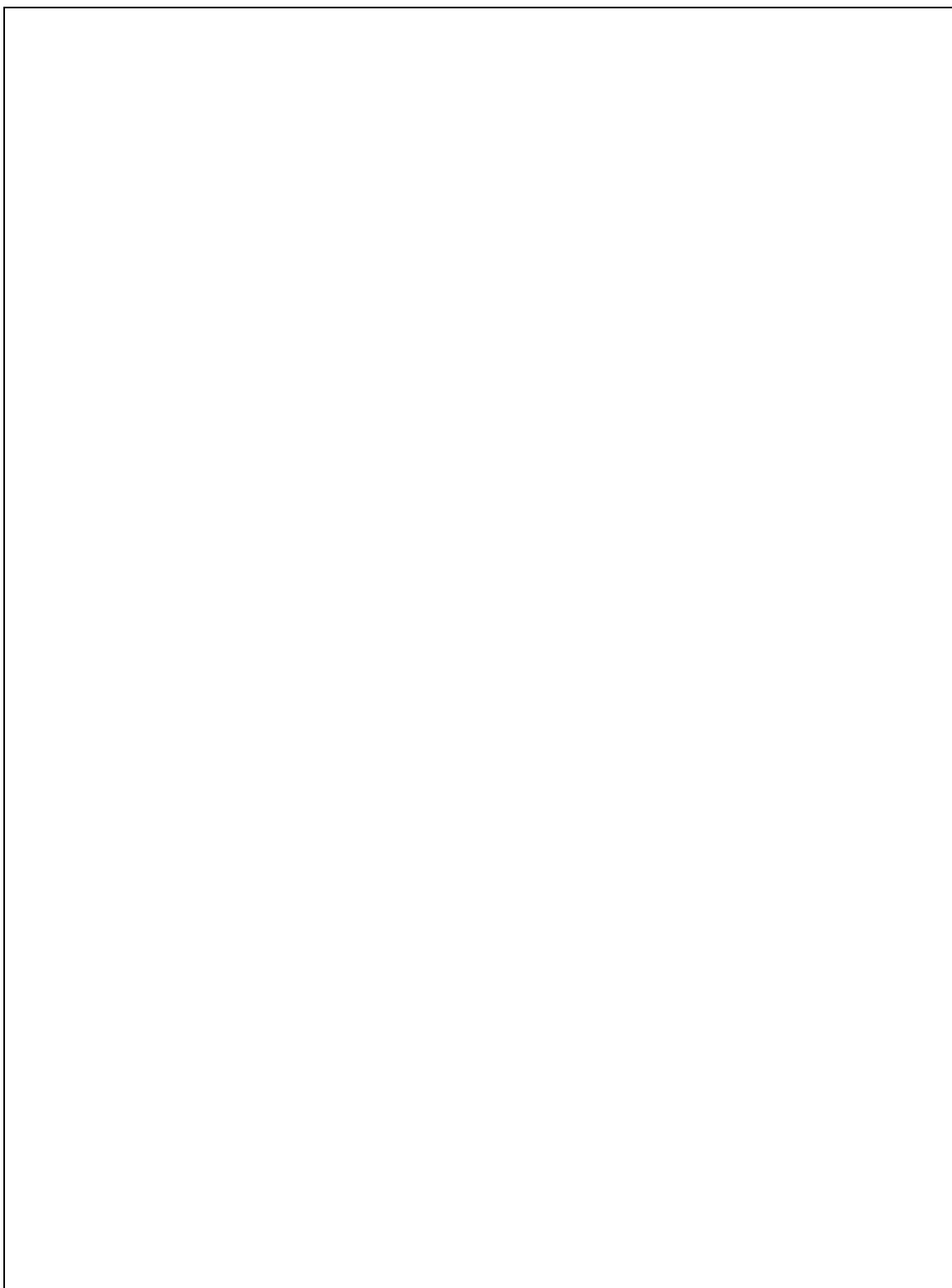
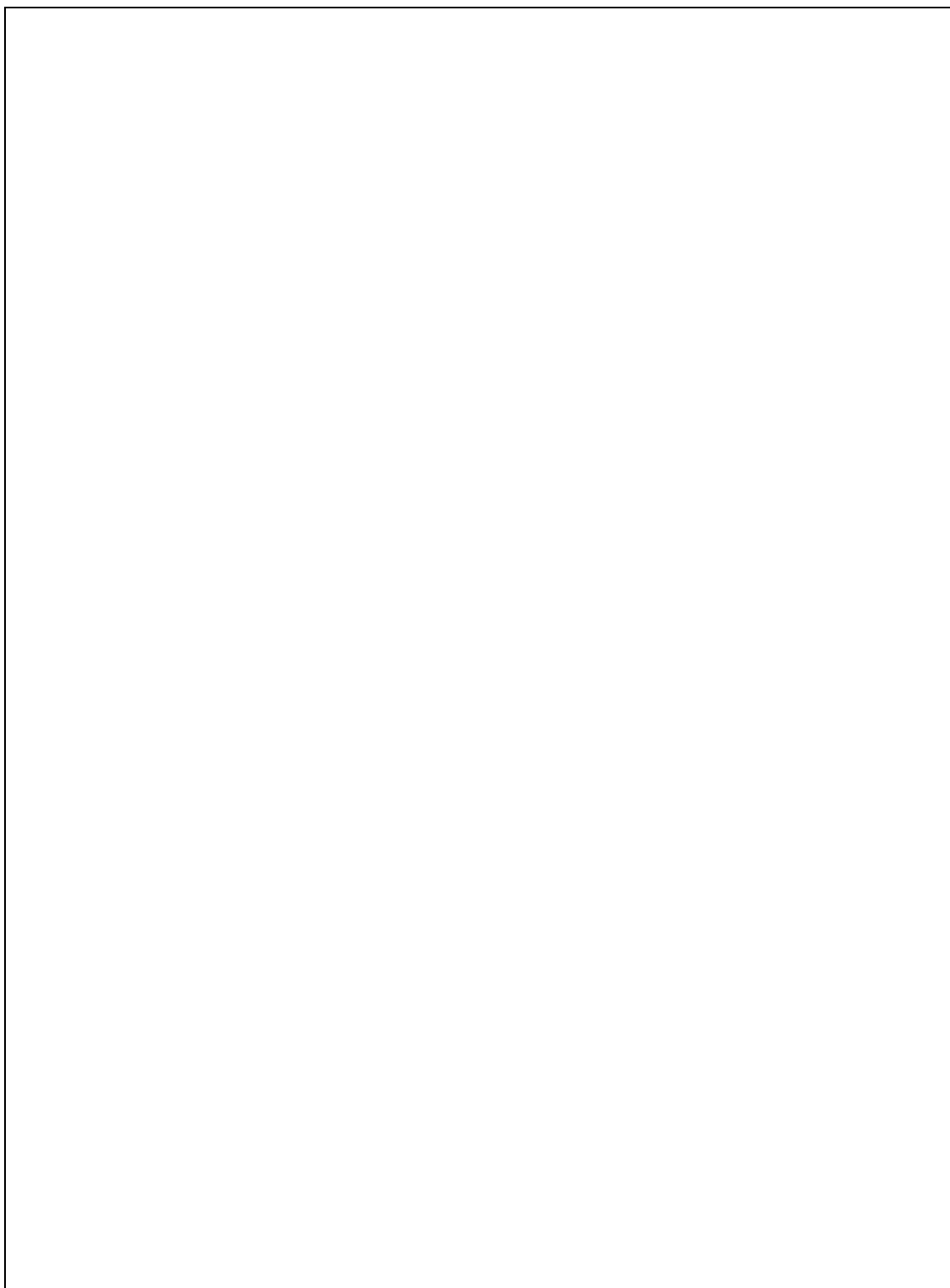


Figure 27. Elwha Reservoir Model Results for Hydrologic Scenario 4.
(Reservoir sediment terraces remaining in Lake Mills after removal of
Glines Canyon Dam.)



D. LAKE ALDWELL SEDIMENT MODELING DURING REMOVAL OF ELWHA DAM

The predicted release of water and sediment from Lake Mills was used as input for the Elwha Reservoir model when applied to Lake Aldwell. Attenuation or storage of the released water and sediment within the river channel between the two lakes was ignored.

1. Lake Aldwell Model Input — Current topography data for Lake Aldwell were obtained from the 1994 bathymetric survey. Because there is no record of a predam survey, predam topography was estimated by Reclamation (August 1995) using current topography and drill hole information. Fourteen cross sections were established on the 1994 topographic map from just upstream of the damsite to the Highway 101 bridge. The locations of these cross sections are shown on figure 28. A table of predam (1913) and current (1994) thalwegs was constructed from the current cross section data and drill hole information. Some 1994 thalweg elevations were adjusted because the model could not handle adverse slopes (e.g. upward slope of the riverbed in the downstream direction). In addition, the table includes cross-sectional area versus lake elevation for each cross section (table 13).

A current table of reservoir capacity versus lake elevation for Lake Aldwell was computed from the 1994 cross section data.

Reclamation (August 1995) provided sediment volume and size gradation data for the reservoir sediments of Lake Aldwell. However, data were not available to describe how size gradations varied with elevation. The reservoir sediments can be classified in two different ways: by size (coarse and fine) and by location (delta and lakebed). Of the 3.88 myd³ of sediment, 1.29 myd³ are coarse (sand, gravel, and cobbles) and 2.59 myd³ are fine (silt- and clay-size). Classifying by location, 1.78 myd³ are in the delta area and 2.10 myd³ are in the lakebed and pro-delta areas.

The entire lakebed was assumed to consist of fine sediment. The entire delta was assumed to contain 72.7 percent coarse sediment ($0.727 = 1.293 \text{ myd}^3 \text{ coarse} / 1.778 \text{ myd}^3 \text{ delta}$) and 27.3 percent fine sediment.

Table 13. Lake Aldwell Cross Section Tables.

(Predam [1931] and post-dam [1994] cross-section thalwegs and reservoir cross-sectional areas [see figure 28 for map].)

Location (feet)	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Station	0	1000	2000	3000	4000	5000	6000	7780	8180	8380	8720	9200	9960	10680
1913 thalweg elevation (feet)	97	113	114	119	119.5	126	138	495	500	503	508	511	515	518
1994 thalweg elevation (feet)	110	119.5	120	128	129	130	142	530	540	580	580	580	590	590
Elevation (feet)	1989 Cross-sectional Area (ft²)													
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
100	0	0	0	0	0	0	0	0	0	0	0	0	0	0
110	0	0	0	0	0	0	0	0	0	0	0	0	0	0
120	1475	0	0	0	0	0	0	0	0	0	0	0	0	0
130	3500	4250	2125	0	750	0	0	0	0	0	0	0	0	0
140	6100	10450	6175	4850	2100	950	0	0	0	0	0	0	0	0
150	9350	17250	11150	12500	3725	2350	1515	0	0	0	0	0	0	0
160	13301	24573	16725	21000	5600	3950	4990	2675	0	0	0	0	0	0
170	18004	32367	22826	30250	7750	5725	9416	10116	3680	0	0	0	0	0
180	23358	40556	29380	40050	10150	7650	14193	19044	17415	7115	214	0	0	0
190	29210	49088	36387	50250	12800	9750	19321	29459	32000	22102	5669	427	0	0
200	35538	57993	43933	60975	15795	12048	24785	41295	47353	38278	22545	9203	7570	3847

Figure 28. Lake Aldwell, Location of River Cross Sections.

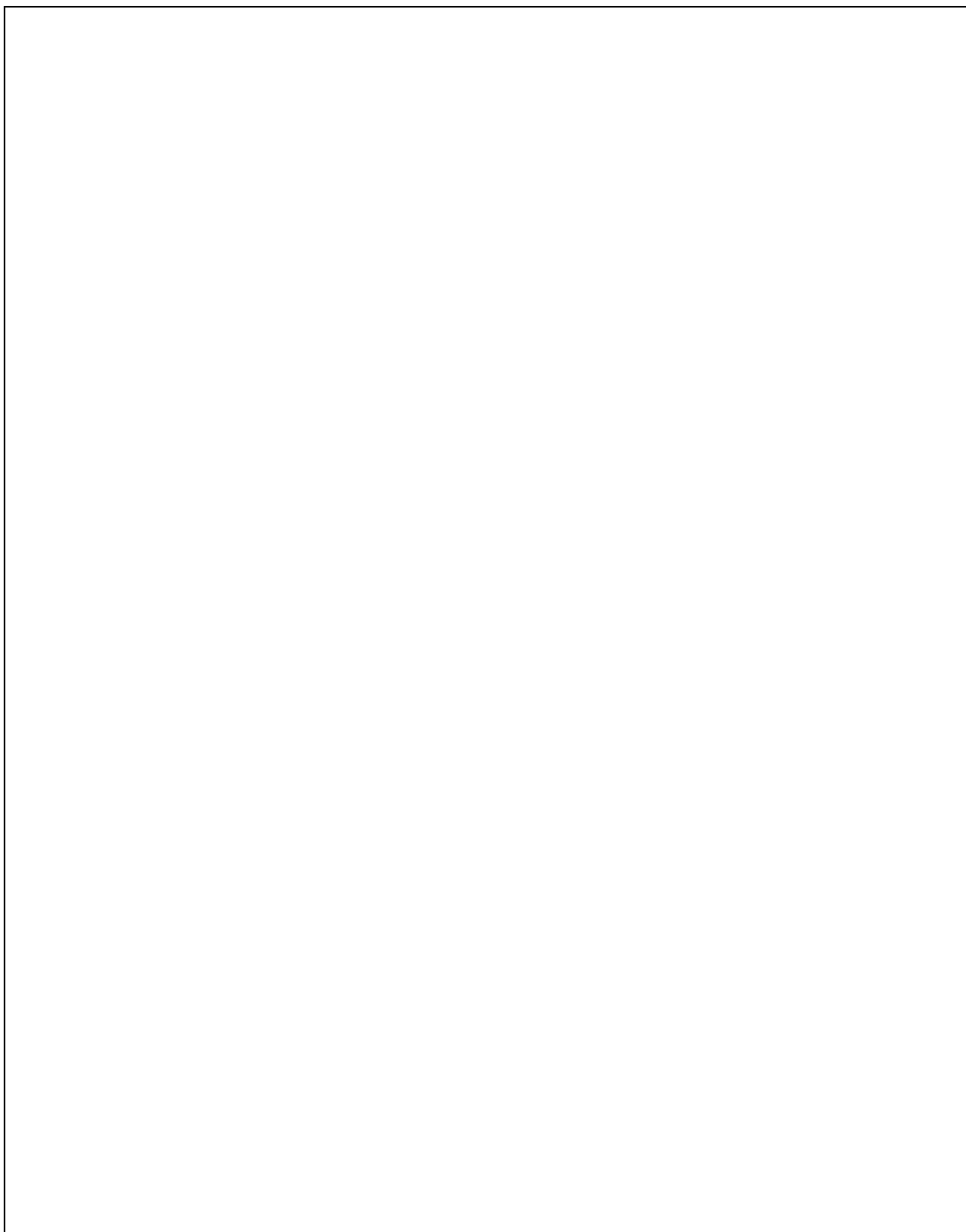
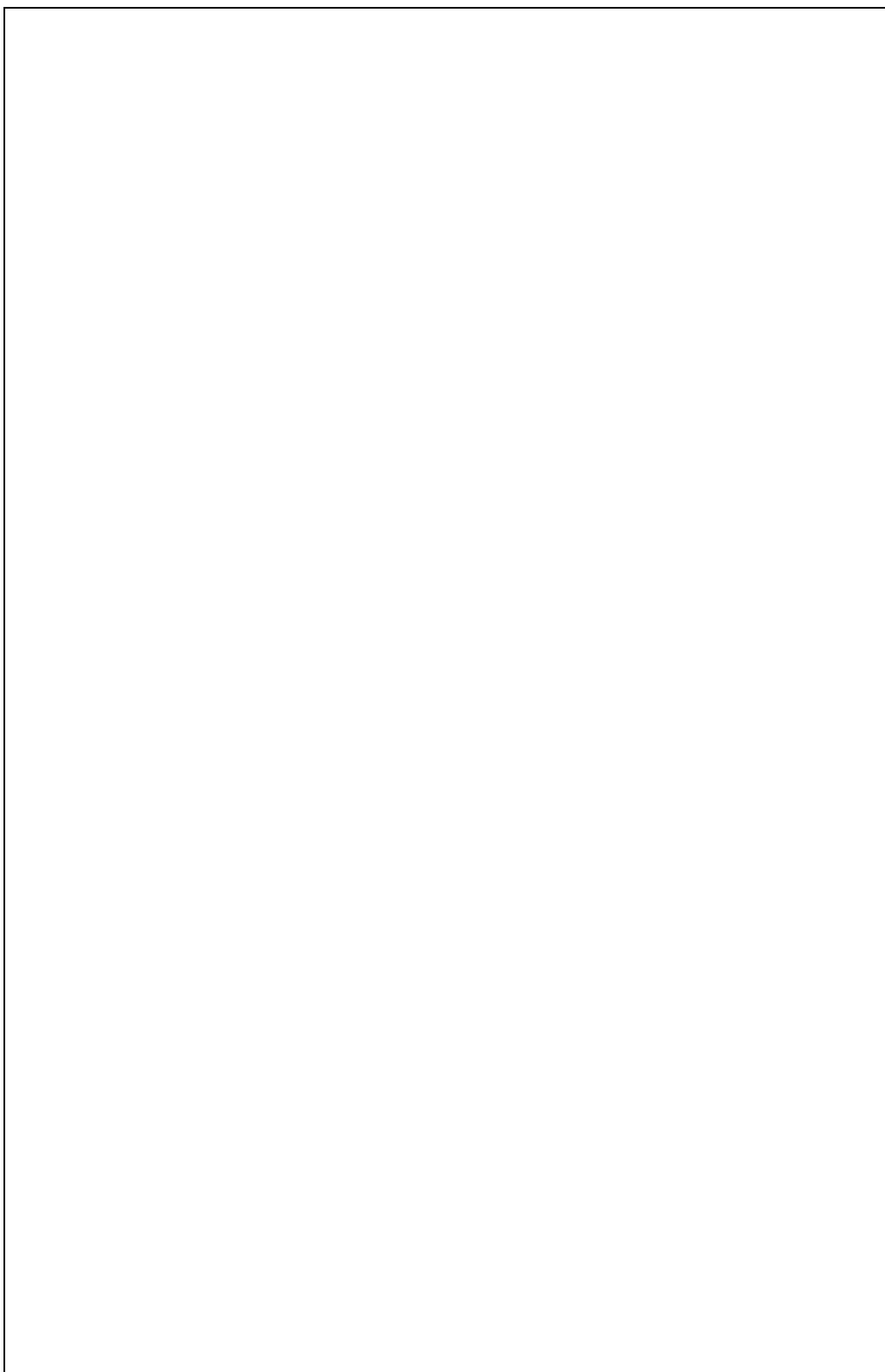


Figure 29. Elwha Reservoir Model Results for a Constant Inflow of 1,000 cfs.
(Lake Aldwell drawdown and the release of water, fine sediment concentration, and coarse sediment load versus time, in days, during the removal of Elwha Dam.)



The coefficients and exponents used in the model for Lake Mills were also used in the model for Lake Aldwell:

- The erosion width exponent “b” of equation 1 was set equal to 2
- The longitudinal erosion slopes for coarse and fine sediment were set equal to the computed equilibrium slope of 0.00052
- Daily erosion coefficients during initial and subsequent phases of dam removal were based on figure 16.

Reservoir drawdown simulations were performed using both constant and variable lake inflow hydrographs.

2. Lake Aldwell Model Results

- **Constant Lake Inflow** — A simulation was performed using a constant lake inflow of 1,000 cfs and ignoring any release of water or sediment from Lake Mills upstream. This simulation is helpful for understanding how the schedule of lake drawdown affects sediment release. Simulation results of fine and coarse sediment released downstream are shown in figure 29.

The fine sediment concentration pattern released downstream follows the pattern of lake drawdown. No fine or coarse sediment is released for the 1-year period while the lake remains at a constant elevation (day 120 to day 435). After the delta front reaches the dam, the pattern of coarse sediment release follows the pattern of notch openings in the dam. Like the simulations of Lake Mills, release rates of fine and coarse sediment tend to be highest immediately after each increment of dam removal and then decrease with time until the next dam removal increment. In general, fine sediment release concentrations are initially low, then tend to increase with time as more sediment is eroded and lake water volumes decrease. Predicted sediment terraces within the delta are shown for cross section K on figure 30 (figure 28 for the location of this cross section).

- **Variable Lake Inflow** — The same four hydrologic scenarios used in the simulation of Lake Mills were also used in the simulation of Lake Aldwell:
 - Hydrologic scenario 1. June 1, 1968 to September 30, 1971
 - Hydrologic scenario 2. June 1, 1950 to September 30, 1953
 - Hydrologic scenario 3. June 1, 1971 to September 30, 1974
 - Hydrologic scenario 4. June 1, 1989 to September 30, 1992

Hydrologic scenario 1 includes the lowest peak discharge for any three consecutive water years of record. Scenario 4 includes the highest peak discharge for any three consecutive years of record. Scenarios 2 and 3 were arbitrarily chosen to represent the range between the extremes of scenarios 1 and 4. Scenario 2 includes a year of relatively high annual peak discharge followed by a year of relatively low and then moderate annual peak discharge. Each year of scenario 3 has a progressively higher annual discharge. A hydrograph plot of each scenario for the inflow to Lake Mills is presented in figure 19. The computed outflow hydrographs from Lake Mills for these scenarios (figures 20 through 23) were used as input to the Elwha Reservoir model applied to Lake Aldwell.

Simulation results of water, fine sediment concentration, and coarse sediment load released from Lake Mills and Lake Aldwell, during concurrent removal of both dams, are presented for each hydrologic scenario in figures 31 through 34. The predicted sediment surface elevation when the eroding delta

first reaches Elwha Dam ranges from 130 to 140 feet. The volumes of fine and coarse sediment eroded downstream from both lakes are listed in table 14.

Table 14. Summary of Model Results for Fine and Coarse Sediment Release from Lake Mills and Lake Aldwell.

FINE SEDIMENT RESULTS				
	Hydrologic Scenario			
Lake Mills	1	2	3	4
Peak mean daily discharge (cfs)	5,490	11,800	18,100	21,400
Sediment inflow (yd ³)	156,000	158,000	352,000	571,000
Sediment outflow (yd ³)	3,861,000	3,723,000	4,366,000	4,712,000
Net Erosion (yd ³)	3,706,000	3,565,000	4,014,000	4,140,000
Percent of 6,620,000 yd ³	56	53	60	63
Lake Aldwell	1	2	3	4
Sediment inflow (yd ³)	3,861,000	3,723,000	4,366,000	4,712,000
Sediment outflow (yd ³)	5,064,000	5,050,000	5,761,000	6,212,000
Net erosion (yd ³)	1,203,000	1,327,000	1,395,000	1,500,000
Percent of 2,590,000 yd ³	46	51	54	58
Total Erosion (yd ³)	4,908,000	4,893,000	5,409,000	5,640,000
Percent of 9,210,000 yd ³	53	53	58	61
COARSE SEDIMENT RESULTS				
	Hydrologic Scenario			
Lake Mills	1	2	3	4
Peak mean daily discharge (cfs)	5,490	11,800	18,100	21,400
Sediment inflow (yd ³)	156,000	158,000	352,000	571,000
Sediment outflow (yd ³)	1,161,000	977,000	1,760,000	2,334,000
Net erosion (yd ³)	1,005,000	819,000	1,408,000	1,763,000
Percent of 7,210,000 yd ³	14	11	20	25
Lake Aldwell	1	2	3	4
Sediment inflow (yd ³)	1,161,000	977,000	1,760,000	2,334,000
Sediment outflow (yd ³)	1,401,000	1,622,000	3,049,000	3,110,000
Net erosion (yd ³)	240,000	645,000	1,290,000	776,000
Percent of 1,290,000 yd ³	19	50	100	60
Total Erosion (yd ³)	1,245,000	1,464,000	2,698,000	2,539,000
Percent of 8,500,000 yd ³	15	17	32	30

Figure 30. Elwha Reservoir Model Results for a Constant Inflow of 1,000 cfs.
(Reservoir sediment terraces remaining in Lake Aldwell after removal of Elwha Dam.)



Figure 31. Elwha Reservoir Model Results for Hydrologic Scenario 1.
(Lake Aldwell drawdown and the release of water, fine sediment concentration, and coarse sediment load from Lake Mills and Lake Aldwell versus time during concurrent dam removal.)

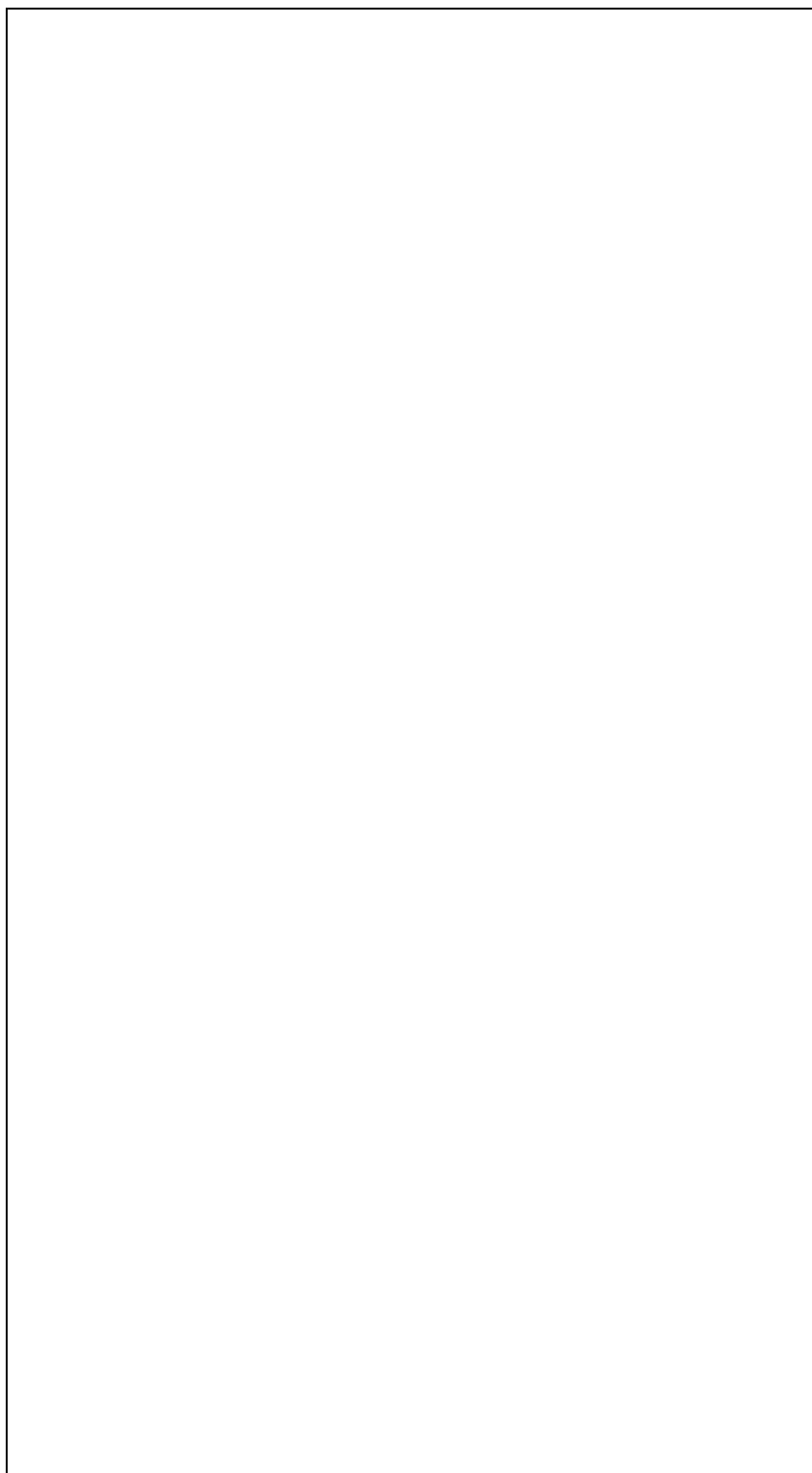


Figure 32. Elwha Reservoir Model Results for Hydrologic Scenario 2.
(Lake Aldwell drawdown and the release of water, fine sediment concentration, and coarse sediment load from Lake Mills and Lake Aldwell versus time during concurrent dam removal.)

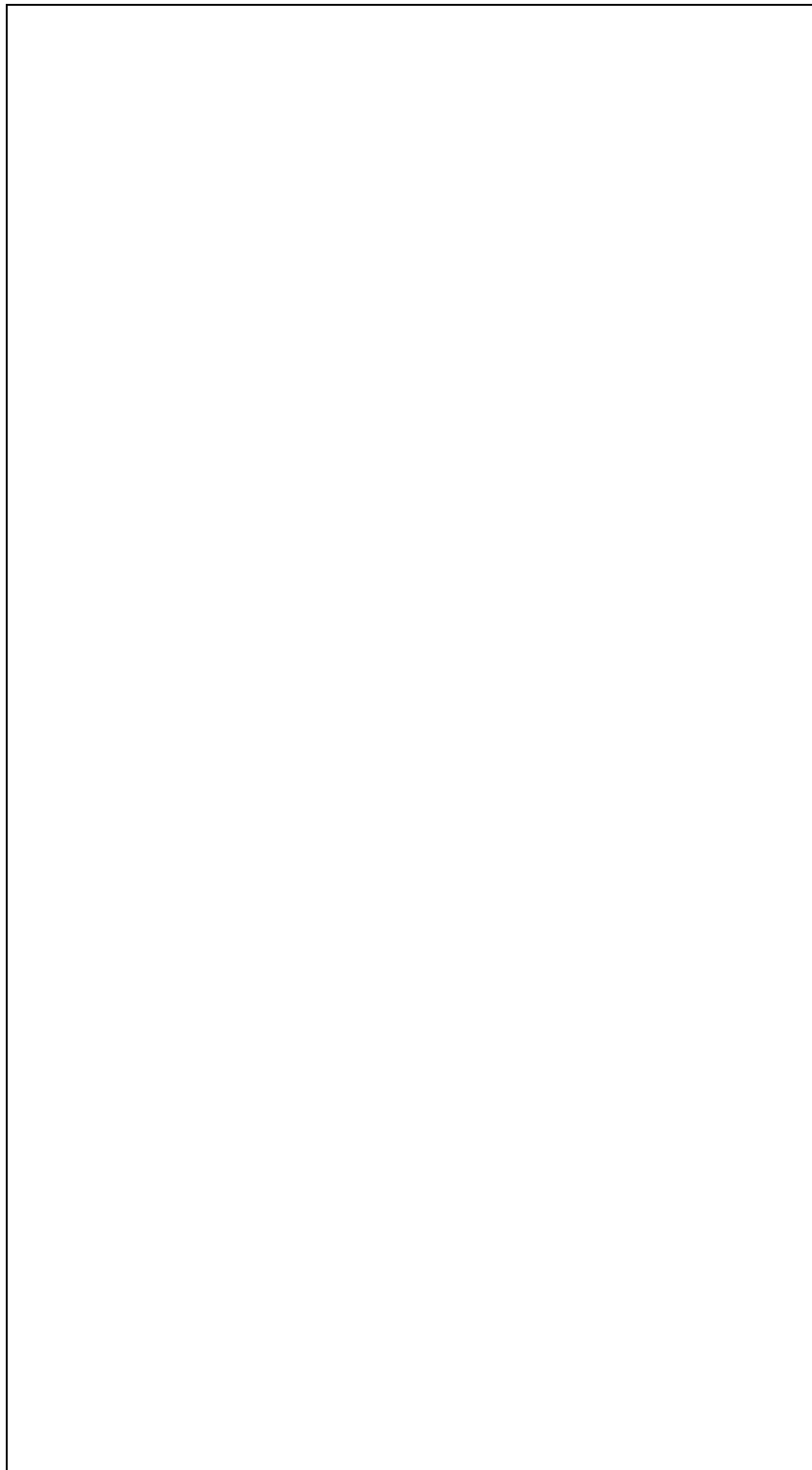


Figure 33. Elwha Reservoir Model Results for Hydrologic Scenario 3.
(Lake Aldwell drawdown and the release of water, fine sediment concentration, and coarse sediment load from Lake Mills and Lake Aldwell versus time during concurrent dam removal.)

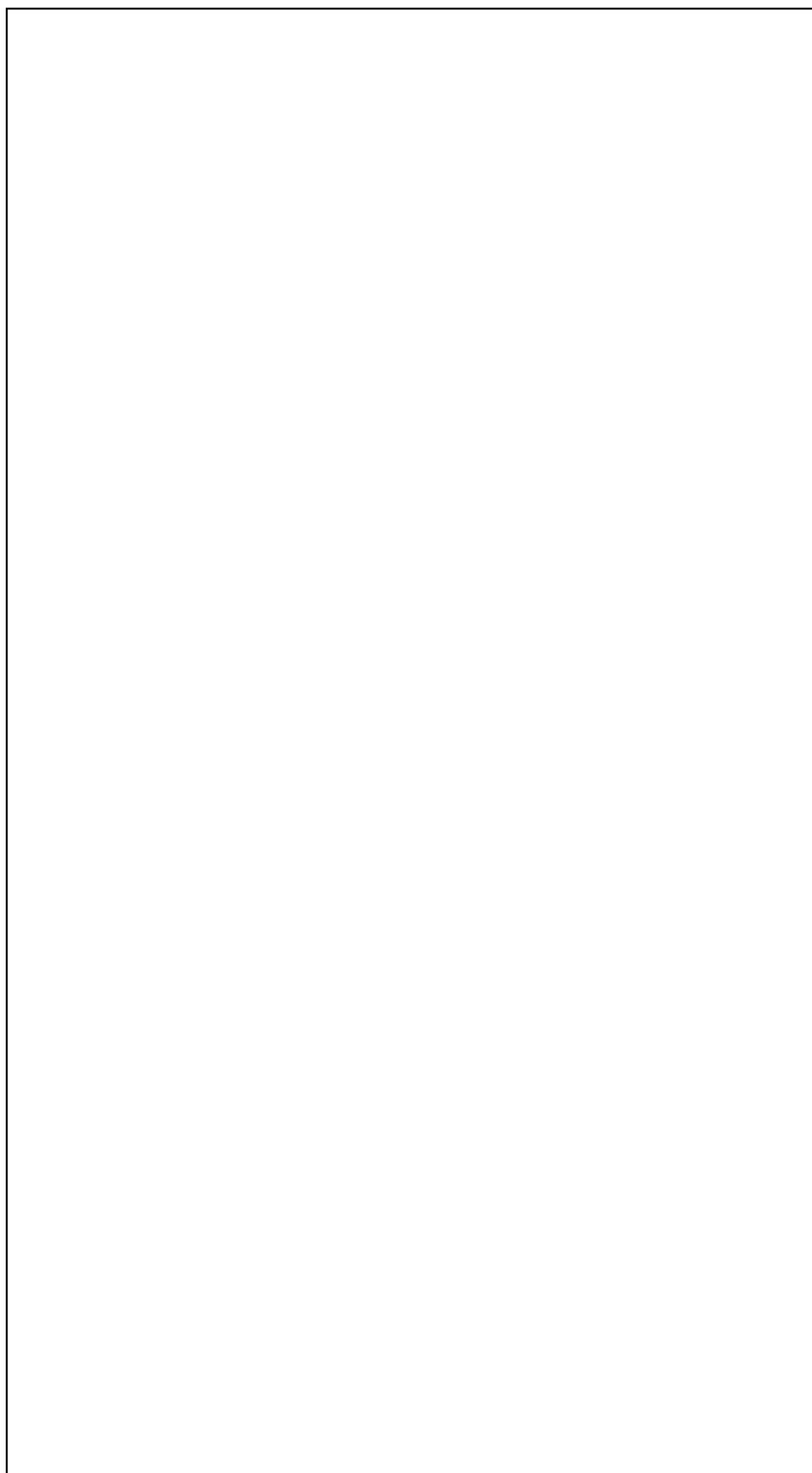
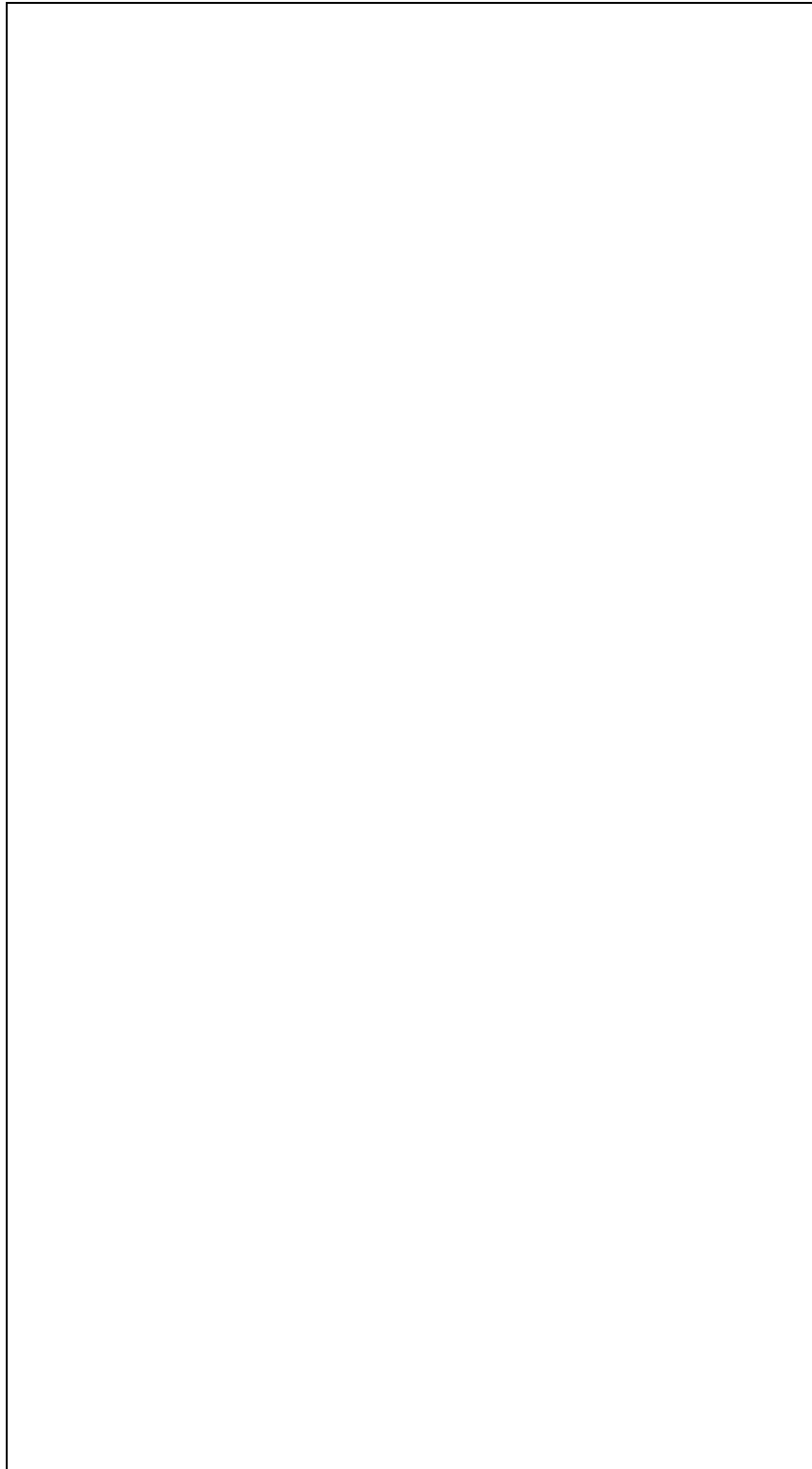


Figure 34. Elwha Reservoir Model Results for Hydrologic Scenario 4.
(Lake Aldwell drawdown and the release of water, fine sediment concentration, and coarse sediment load from Lake Mills and Lake Aldwell versus time during concurrent dam removal.)



The release of fine and coarse sediment from Lake Aldwell, during concurrent removal of both dams, has many similarities to the previous simulations of Lake Mills. Five distinct periods at Lake Aldwell are evident for each of these four hydrologic scenarios (table 15 and appendix D):

- **Begin lake drawdown for dam removal (phase 1)** — This period would be from June through October of the first year. Fine sediment concentrations released downstream would be initially low and then increase as drawdown continues. Concentrations would be 500–5,000 ppm most days with maximum concentrations of 6,700–43,000 ppm (lasting 1–3 days). Coarse sediment from the delta would erode and redeposit in the lower lake but no coarse sediment would be released downstream.
- **Stop lake drawdown and dam removal during winter high flows (phase 1)** — This period would probably be from November through January of the second year. Exposed delta sediment would continue to erode but none would be released downstream. The remaining lake would be flushed by the high lake inflows and fine sediment concentrations released downstream would be low and close to natural conditions.
- **Continue dam removal and lake drawdown after winter high flows (phase 1)** — This period would likely be from February through April of the second year. Fine sediment concentrations released downstream would be 1,000–10,000 ppm most days with maximum concentrations of 5,600–11,000 ppm (lasting 1–3 days). Coarse sediment from the delta would be approaching the dam but no coarse sediment would be released downstream.
- **Stop dam removal and lake drawdown during spring high flows (phase 1)** — This period would be from May through June of the second year. Coarse delta sediment would almost reach the dam but none would yet be released downstream. The remaining lake would be small and flushed by the high lake inflows. Fine sediment concentrations released downstream would be similar to natural conditions.
- **Finish dam removal after spring high flows (phases 2 and 3)** — This period would likely be from July through September or October of the second year. Coarse sediment from the delta would reach the dam and be released downstream. Coarse sediment release rates would be initially high but decrease rapidly with time. Fine sediment concentrations released downstream would be 1,000–5,000 ppm most days with maximum concentrations of 15,000–51,000 ppm (lasting 1–3 days).
- **Reservoir sediment erosion and release following dam removal (phase 4)** — This period would likely begin during October of the second year and continue for about two more years (model simulations continued through September of the fourth year). The erosion and release of coarse and fine sediment would be low and close to natural conditions most of the time. However, floodflows of progressively higher magnitude (such as in scenario 3) would continue to widen erosion channels through the reservoir and produce high rates of both coarse and fine sediment release downstream. Peak concentrations of fine sediment would be 21,000–38,000 ppm. Peak concentrations typically would be of short duration (1–3 days) and the magnitudes of these events would tend to decrease with time.

Table 15. Summary of Fine Sediment Release Concentrations Downstream from Elwha Dam During Concurrent Dam Removal.

(Presently, sediment concentrations below the dam are typically low [less than 50 ppm], except during floodflows when peak concentrations can exceed 1,000 ppm. PPM is parts per million by weight.)

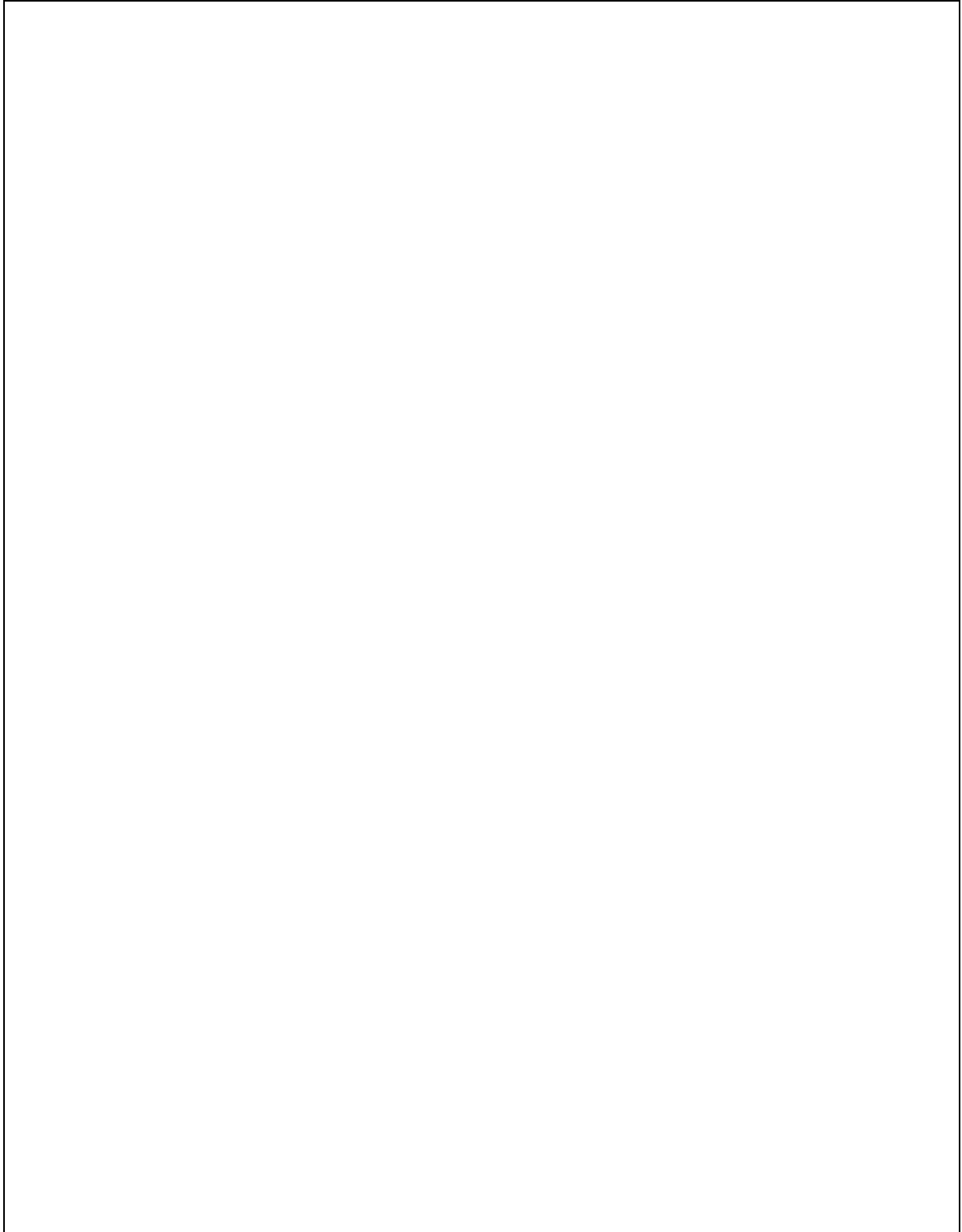
Dam removal period	Time of year	Fine sediment concentration Duration downstream from Elwha Dam
Begin final lake drawdown for dam removal	Typically from June through October, year 1	· 31 to 43 days < 200 ppm · 123 to 217 days > 200 ppm · 107 to 209 days > 500 ppm · 52 to 170 days > 1,000 ppm · 1 to 68 days > 5,000 ppm · 0 to 26 days >10,000 ppm · Peak concentration — 6,700 to 43,000 ppm
Stop lake drawdown and dam removal during winter high flows	Typically during November and December year 1, through January, year 2	· 20 to 85 days < 200 ppm
Continue dam removal and lake drawdown after winter high flows	Typically during January through April or May, year 2	· 0 to 3 days < 200 ppm · 20 to 126 days > 200 ppm · 20 to 99 days > 500 ppm · 20 to 83 days > 1,000 ppm · 9 to 33 days > 5,000 ppm · 0 to 2 days >10,000 ppm · Peak concentration — 5,600 to 11,000 ppm
Stop dam removal during high spring flows	Typically from April or May through July, year 2	· 80 to 100 days < 200 ppm
Finish dam removal after high spring flows	Typically from July through October, year 2	· 0 days < 200 ppm · 90 to 111 days > 200 ppm · 89 to 109 days > 500 ppm · 87 to 108 days > 1,000 ppm · 13 to 53 days > 5,000 ppm · 3 to 25 days >10,000 ppm · Peak concentration — 15,000 to 51,000 ppm
Flood-induced erosion following dam removal	Typically from October, year 1, through September, year 4	· 606 to 698 days < 200 ppm · 9 to 103 days > 200 ppm · 7 to 86 days > 500 ppm · 5 to 79 days > 1,000 ppm · 3 to 9 days > 5,000 ppm · 2 to 6 days >10,000 ppm · Peak concentration — 21,000 to 38,000 ppm

The Elwha Reservoir model predicts the initial development of sediment terraces within the lakebed and delta areas of Lake Aldwell. However, many of the lower elevation terraces are lost to channel widening during floodflows. Channel erosion widths at the predam thalweg of Lake Aldwell are listed in table 16 for each hydrologic scenario. The final reservoir topography for cross section K of the delta (for each hydrologic scenario) is presented in figure 35. The location of this reservoir cross section is shown in figure 28. In general, model results predict that lower elevations terraces would be lost to bank erosion during floodflows and channel bank heights would be greater.

Table 16. Maximum Channel Erosion Widths at the Predam Thalweg in Lake Aldwell for Each Hydrologic Scenario.

Hydrologic scenario	Highest peak discharge (cfs)	Maximum erosion width (feet)
1	5,490	410
2	11,800	510
3	18,100	610
4	21,400	650

Figure 35. Elwha Reservoir Model Results for Hydrologic Scenarios 1, 2, 3, and 4. (Reservoir sediment terraces at cross section K in Lake Aldwell after removal of Elwha and Glines Canyon Dams. The wide active channel widths predicted by the model are shown in the figures. Although not predicted by the model, a narrower low-flow channel would likely exist.)



E. DISCUSSION

The Elwha Reservoir model is a useful tool to predict how much coarse and fine sediment would erode from the reservoir and the pattern and magnitude of the sediment released downstream. Development of the Elwha Reservoir model was based in part on results from the 1994 Lake Mills drawdown experiment and on a mixing cell model developed by Smillie and Jackson (1995). Model results agreed well with field measurements and observations. Key points observed from the drawdown experiment and replicated in the model include:

- The erosion width at the delta front was equal to the reservoir width (delta erosion widths upstream were much less).
- The eroded delta sediment redeposited immediately downstream from the initial delta front, completely filling across the lake and almost up to the drawn-down lake elevation.
- Not all of the exposed delta sediment was eroded during the drawdown experiment. The remaining sediment was left behind as terraces on the reservoir margins and as an island. The Elwha Reservoir model predicts that most of the delta sediment in Lake Mills would be left behind along the reservoir in the form of terraces.
- Sediment particles up to 128 mm were eroded during the drawdown experiment. The Elwha Reservoir model computed volumes based on reservoir geometry and assumed that all particle sizes within that volume would erode (only 1 percent of the coarse sediment in Lake Mills is larger than 125 mm).
- Lake water immediately downstream from the delta was very turbid but dam releases were very clear. Elwha Reservoir model results show that fine sediment concentrations released downstream from the dams were very low during the first few increments of dam removal.

Erosion slopes during the drawdown experiment were steep (0.0067) and produced rapid rates of erosion. For a given lake elevation, erosion rates would decrease with time as the slope of the channel decreased. In the Elwha Reservoir model, the more mild the erosion slope the greater the erosion volume. Therefore, a relatively mild slope of 0.00052 was used in the final model simulations for both lakes to produce a conservative estimate of erosion volumes.

In the Elwha Reservoir model, the eroded fine sediment is assumed to be re-suspended in the lake and remain suspended until transported past the dam. This assumption means that the fine sediment never settles out on the margins of the reservoir and, consequently, may overestimate the concentrations of fine sediment released downstream from the dams.

CHAPTER IX. COARSE SEDIMENT TRANSPORT CAPACITY

A large release of coarse sediment from Lake Mills and Lake Aldwell could result in short-term riverbed aggradation which could increase local flood stage for a given discharge. The amount of riverbed aggradation depends on the river's sediment transport capacity, the rate sediment is eroded and transported from the two lakes, and the natural sediment supply upstream from Lake Mills. Restoring the natural supply of coarse sediment would likely result in some localized, long-term riverbed aggradation relative to existing conditions. The coarse sediment transport capacities (bed-material load) of the Elwha River below Glines Canyon and Elwha Dams are discussed in this section.

If Glines Canyon and Elwha Dams are removed, some portion of the coarse delta sediment would be eroded from both lakes and would be transported downstream toward the Strait. This eroded coarse sediment would be in addition to the natural coarse sediment supply from upstream. The rate at which sediment is transported downstream could be physically limited by the river's transport capacity — especially in the 3-mile-long reach near the mouth.

The Elwha River is generally steep — composed of pools and riffles — especially upstream from Lake Mills and in the middle reach between the two lakes. The lower three miles of river near the mouth are less steep and more susceptible to general aggradation. As a riverbed aggrades, the energy slope of the river tends to increase, resulting in a corresponding increase in velocity and sediment transport rate. Therefore, rates of aggradation tend to decrease with time even when sediment supply rates remain high. This is often accompanied by a reduced resistance to flow and increased velocities and sediment transport capacity.

Aggradation in pools, rather than the high-velocity riffles, may not significantly increase river stage for a given flow. A certain amount of riverbed aggradation could occur that results in only a nominal increase in river stage. For this study, the nominal amount of riverbed aggradation is defined to be that which would not cause the river stage to increase by more than 0.5 feet at any location for a riverflow of 5,000 cfs. A river stage increase of 0.5 feet or less is thought to be nominal or insignificant because of the steep topography of the riverbanks and valley side slopes. A riverflow of 5,000 cfs was chosen because it has a relatively high transport capacity and approximates the annual peak discharge (Reclamation, March 1995).

A procedure was developed to estimate the limiting reach-transport capacity for a given riverflow, assuming that riverbed aggradation would occur but not increase river stage beyond a certain assumed increment (either 0.5, 2.0, or 5.0 feet). If the resulting transport capacity of the reach is less than the upstream coarse sediment supply, then the resulting riverbed aggradation would increase river stage beyond the assumed increment. This procedure provided early results for development of sediment management plans and for a comparison with subsequent model results using HEC-6, which are described in chapter X. Coarse sediment transport capacity can be computed using this procedure without first knowing the supply rate from upstream — which is required input for the HEC-6 model.

A. PROCEDURE

1. Summary — The limiting reach-transport capacity (for a given riverflow) was computed assuming that riverbed aggradation would result in an increase in river stage up to an assumed increment. The elevation of riverbed aggradation was computed at each cross section of the reach by trial-and-error iterations. By increasing the low elevations of certain cross sections up to a constant elevation (because of assumed aggradation), both the computed transport rate and river stage tend to increase. Thus, the low elevations of each cross section were increased to maximize the limiting reach transport capacity, subject to the assumed increment of increased river stage.

The aggraded cross sections were then used to compute the limiting reach-transport capacity for a range of discharges and a sediment-discharge relationship was developed. Annual transport for the reach was computed using this sediment-discharge relationship and a flow-duration analysis of mean daily flow.

2. Details — A special version of the STARS model was used to compute river hydraulics and coarse sediment transport capacity. Model input includes riverflow, channel topography (defined by cross sections), an estimate of the channel roughness, and the bed-material size gradation at each cross section. This special version of the STARS model computes the water surface profile and coarse sediment transport capacity, but does not compute any changes in riverbed topography or bed-material size gradation. An aggradation elevation can be given for each cross section. When this is done, the model adjusts the cross section data so that no riverbed elevations are lower than the specified aggradation elevation. The location of these cross sections is shown in figure 36.

The river cross sections described in chapter V, section G were used in the STARS model. The roughness coefficients were calibrated by trial and error such that the computed water surface elevations matched the elevations measured during the cross section surveys.

The current capacity of the river to move its riverbed is very low because the sizes of the existing bed material are large — 3 to 18 inches (80 to 460 mm). However, the capacity of the river to transport coarse sediment from the lake deltas is much larger. Therefore, a very thin layer of coarse sediment from the Lake Mills delta was assumed to cover the entire riverbed in the STARS model. The size gradation of this layer was set equal to the composite size gradation for the coarse delta sediment of Lake Mills (figure 37). Computed sediment transport capacity at 5,000 cfs was therefore much larger at high-velocity cross sections (such as riffles) than at low-velocity cross sections (such as pools).

An iterative procedure used to maximize computed sediment transport of a reach. The river channel was manually aggraded at certain cross-sections in order to maximize the sediment transport capacity of the reach. The cross-section with the lowest sediment transport capacity (the limiting or controlling cross-section) was aggraded so as not to increase the river stage elevation more than the assumed increment (0.5, 2.0, or 5.0 ft) above the baseline river surface elevation for a flow of 5,000 cfs.

The baseline elevations for each cross section and the computed water surface profile represents existing conditions for a flow of 5,000 cfs. This baseline water surface profile was computed using the STARS model, assuming a flow of 5,000 cfs and no aggradation of the riverbed. The baseline water surface profile includes the existing rock diversion dam at RM 3.48 (cross section 17).

Figure 36. Elwha River, Locations of River Cross Sections

11" by 17" fold-in. Source: Appendix figure 1, drawing 1440-100-14; from Elwha 95-5 (Reclamation, March 1996). TR and JH agreed to insert on fonecons of 7/25 and 7/29.

[backside of Figure 36]

Figure 37. Composite (Average) Size Gradation of Coarse Sediment from the Lake Mills Delta.



However, for the aggradation analysis, it was assumed that this rock diversion dam would be removed and replaced by an infiltration gallery.

Aggrading a cross-section usually increased the sediment transport capacity at that cross section, but sometimes decreased the transport capacity at another section. Each cross-section was aggraded so that it was no longer the reach-limiting cross section (having the lowest sediment transport capacity of the reach) or until the computed water surface had increased by the assumed increment over the baseline water surface elevation.

The special version of the STARS model was then run for flows up to 19,000 cfs using the aggraded cross sections from the previous step. The reach-limiting transport capacity for coarse sediment was then plotted with discharge to develop a sediment-discharge rating curve.

The annual reach-limiting transport capacity was then estimated from the sediment-discharge rating curve and the flow-duration analysis of mean daily flows. The flow-duration analysis for the Elwha River at McDonald Bridge was obtained from the USGS WATSTOR database for the period 1927–94. The sediment transport capacity, corresponding to a certain discharge, was multiplied by the percent of days in which that flow has historically occurred. These products of sediment transport capacity and percent days were totaled for a range of flows from 12 cfs to 19,000 cfs to yield the annual reach-limiting transport capacity for coarse sediment.

Table 17. Comparison of Elwha River Cross Section Nomenclature.

River mile	Cross section		Description
	This report† (figure 36)	Corps of Engineers #†	
0.00	0		Strait
0.38	1	1+00	
0.78	2	2+00	
1.03	4	4+00	
1.28	5	5+00	
1.44	6	6+00	
1.68	7	7+00	Near upstream end of Federal levee
1.92	8	7+50	
2.20	9	8+00	
2.50	10	9+00	
2.79	11	10+00	
2.90	12	11+00	
3.10	13	12+00	Near middle of fish-rearing channel
3.24	14	13+00‡	Near upstream end of fish-rearing channel
3.29	15	16+00	Above one-lane bridge
3.40	15A*		Same shape as cross section 15
3.45	16A*		Interpolated
3.47	16		
3.48	not used	17+00	Diversion dam
3.49	18		Pool behind diversion dam
3.58	19	19+00	Upstream end of pool behind diversion dam
3.68	20A*		Interpolated
3.69	20B*		Same shape as cross section 20
3.83	20	20+00	Transmission line
4.04	20C*		Same shape as cross section 20
4.23	20D*		Same shape as cross section 20
4.46	20E*		Same shape as cross section 20
4.84	21A*		Interpolated
4.86	21	21+00	Pool below spillway
4.92	22	22+00	Elwha Dam, end of left spillway
# U.S. Army Corps of Engineers. 1996. James L. Lencioni, "Flooding Impacts Associated with Removal of the Elwha and Glines Canyon Dams." Appendix 4 of <i>Elwha River Ecosystem Restoration Implementation — Draft Environmental Impact Statement I</i>. (National Park Service, April 1996.) † These Corps cross section locations are <i>not</i> survey stations. * These sections do not appear in figure 36. ‡ Replaced by section 14 Note: Cross sections 23 to 34 match the Corps designations 23+00 to 34+00			

B. RESULTS

The Elwha River from Lake Mills to the Strait was divided into two reaches: the middle reach between the two lakes and the lower reach below Elwha Dam. A separate analysis of the transport capacity of coarse sediment was done for each reach.

For the lower reach, sufficient cross section data were available to compute water surface profiles from the mouth to Elwha Dam (chapter V, section G). Cross section data were also available for the middle reach but their spacing was not sufficiently close to compute accurate water surface profiles for the entire reach. However, cross section and hydraulic data collected by Hosey (1990) were available to compute water surface profiles in three separate short sub-reaches of the middle reach. These three short reaches were used to represent conditions of the middle reach.

1. Lower reach (below Elwha Dam) — The reach-limiting transport capacity for coarse sediment was computed by assuming that riverbed aggradation would cause river stage (for a riverflow of 5,000 cfs) to increase over the baseline river stage by up to three limits: 0.5, 2.0, and 5.0 feet. Any assumptions that riverbed aggradation would cause river stages to increase by more than 5.0 feet would be overly conservative.

In modeling the lower reach, the cross sections through the main river channel and side channels through the wooded floodplain were treated separately. In some cases, the cross section data indicate that the elevations of the side channels were as low, or lower, than the elevations of the main river channel. The conveyance of water through the wooded floodplain and its side channels is quite low and water would likely pond during flood stage. Therefore, the side channels of the floodplain were assumed to be ineffective flow areas and ground elevations were raised up to the level corresponding to the 5,000 cfs river stage. Fine sediment could deposit in the floodplains during floodflows but coarse sediment could not significantly aggrade in the floodplain without migration of the main channel.

In the case where riverbed aggradation would result in nominal increases in river stage (up to 0.5 feet), the annual reach-limiting transport capacity for coarse sediment was estimated to be 490,000 tons per year (330,000 yd³ per year; tables 19 and 20).

The transport capacity at the river mouth (cross section 0) was ignored because of the strong currents of the Strait and its large capacity for deposition. The initial transport capacity upstream was low (less than 50,000 tons/day) at several low-velocity cross sections, many of which are pools (table 18). In order to increase the reach-limiting transport capacity, riverbed aggradation was assumed to occur at 13 cross sections.[†] At nine of these cross sections,^{††} the assumed aggradation significantly increased the computed sediment transport capacity. At all other cross sections, the sediment transport capacity either decreased or increased slightly, but the reach-limiting transport capacity increased from the initial conditions. At a discharge of 5,000 cfs, the reach-limiting transport capacity is at cross section 20C and is 13,800 tons/day. The computed water surface elevation increased by 0.5 feet at cross sections 20C and 20D.

[†] Cross sections 1, 4, 6, 10, 15, 15A, 18, 19, 20, 20C, 20E, 21, and 22.

^{††} Cross sections 6, 15, 15A, 18, 19, 20 20C, 21, and 22.

The aggradation amounts presented in table 18 were used in the STARS model to compute the reach-limiting transport capacity for a range of discharges (figure 38). These transport capacities were then multiplied by the corresponding percent days of occurrence to compute the annual transport capacity for the reach (table 19).

In the case where riverbed aggradation would result in increases in river stage up to 2.0 feet, the annual reach-limiting transport capacity for coarse sediment was estimated to be 1,300,000 tons per year (900,000 yd³ per year; tables 20 and 21).

In order to increase the reach-limiting transport capacity, riverbed aggradation was assumed to occur at 13 cross sections[†] (table 20). The assumed aggradation significantly increased the computed sediment transport capacity at all of these cross sections. At all other cross sections, the sediment transport capacity either decreased or increased slightly, but the reach-limiting transport capacity increased from the initial conditions. At a discharge of 5,000 cfs, the reach-limiting transport capacity is at cross section 20E and is 25,900 tons/day. However, the transport capacity was very close to this value at cross sections 20, 20C, and 20D. The computed water surface elevation increased by 2.0 feet at cross sections 20C and 1.9 feet at cross section 20D. Although the increase in water surface elevation is less at cross section 20E, the transport capacity at this cross section is very close to the capacity at the three cross sections downstream.

In the case where riverbed aggradation would result in increases in river stage of 5.0 feet, the annual reach-limiting transport capacity for coarse sediment was estimated to be 1,400,000 tons per year (950,000 yd³ per year; tables 22 and 23).

In order to increase the reach-limiting transport capacity, riverbed aggradation was assumed to occur at 17 cross sections^{††} (table 22). The assumed aggradation significantly increased the computed sediment transport capacity at 12 cross sections.^{†††} At all other cross sections, the sediment transport capacity either decreased or increased slightly, but the reach-limiting transport capacity increased from the initial conditions. At a discharge of 5,000 cfs, the reach-limiting transport capacity is at cross section 4 and is 33,700 tons/day. However, the transport capacity was very close to this value at cross sections 5, 6, 20C, 20D, and 20E. The computed water surface elevation increased by 4.6 feet at cross sections 20E and 4.5 feet at cross section 20D. Although the increase in water surface elevation is less at cross section 4, the transport capacity at this cross section is very close to the capacity at cross sections 20D and 20E.

The aggradation amounts presented in table 22 were used in the STARS model to compute the reach-limiting transport capacity for a range of discharges (table 23). These transport capacities were then multiplied by the corresponding percent days of occurrence to compute the annual transport capacity for the reach.

[†] Cross sections 1, 4, 6, 10, 15, 15A, 18, 19, 20, 20C, 20E, 21, and 22.

^{††} Cross sections 1, 4, 5, 6, 7, 8, 10, 15, 15A, 18, 19, 20, 20C, 20D, 20E, 21, and 22.

^{†††} Cross sections 1, 4, 10, 15, 15A, 18, 19, 20, 20C, 20E, 21, and 22.

The volume of sediment that could aggrade in the main channel without increasing river stage beyond the assumed limits was also computed for the reference discharge of 5,000 cfs. The total volume was estimated from the computed aggradation areas at each cross section. For the case where river stage elevation would not increase by more than 0.5 ft above the baseline river elevation, 100,000 yd³ of sediment could be aggraded in the main channel.

For the case where river stage elevation would not increase by more than 2.0 ft above the baseline river elevation, 300,000 yd³ of sediment could be aggraded in the main channel.

If river stage elevation did not increase by more than 5.0 ft above the baseline river elevation, 470,000 yd³ of sediment could be aggraded in the main channel.

For the lower reach, there was a large increase (45 percent; from 17,700 to 25,000 tons/day) in the reach-limiting sediment transport capacity when riverbed aggradation was allowed to increase baseline river stages by up to 2.0 feet. However, the rate of increase in sediment transport capacity was less (30 percent; from 25,900 to 33,700 tons/day) when riverbed aggradation was allowed to increase baseline river stages by up to 5.0 feet when compared to the case of a 2.0-foot limit. For base cases, cross section 20E (RM 4.46) was at or near the reach-limiting transport capacity. This cross section is in about the middle of a 1-mile-long reach that is bounded by hydraulic controls (riffles) at both ends. It was assumed that riverbed aggradation would not occur at these high-velocity riffles and that the river stage would not increase for a given discharge. With the water surface elevations fixed at both ends of this 1-mile-long reach, there was a limit as to how much the transport capacity could be increased. When riverbed aggradation was allowed to increase baseline river stages at cross section 20E from 2.0 to 5.0 feet, the energy slope at this cross section increased from 0.00211 to 0.00311, but the velocity decreased from 4.56 feet per second (ft/s) to 3.97 ft/s, and the unit stream power (slope times velocity) only increased from 0.00962 to 0.0123 (28 percent).

Table 18. Summary Results of Riverbed Aggradation, Water Surface Elevations, and Coarse Sediment Transport Capacity for the Elwha River, Lower Reach Cross Sections.

(The assumption is made that river stages would not increase by more than the nominal amount of 0.5 feet at any cross section.)

Cross section	River mile	Initial thalweg elevation (feet)	Aggradation (feet)	Initial water surface elevation (feet)	Increase in water surface elevation (feet)	Initial coarse sediment transport capacity (tons/day)	Aggraded coarse sediment transport capacity (tons/day)
0	0.00	-4.5	0.0	0.0	0.0	1,950†	2,200†
1	0.38	-2.9	3.1	3.8	0.4	26,800‡	28,300
2	0.78	5.7	0.0	12.3	0.2	82,000	73,700
4	1.03	9.5	4.5	16.6	0.4	23,000‡	23,400
5	1.28	18.0	0.0	22.2	0.2	72,600	61,000
6	1.44	17.7	3.3	26.1	-0.1	46,400‡	65,200
7	1.68	23.1	0.0	28.6	0.3	60,000	52,200
8	1.92	28.0	0.0	32.8	-0.2	45,600	45,800
9	2.20	31.4	0.0	37.0	0.1	87,600	88,500
10	2.50	33.1	2.6	41.8	0.1	27,600‡	31,200

11	2.79	38.8	0.0	44.9	0.1	51,000	47,500
12	2.90	39.5	0.0	47.9	0.0	149,000	146,000
13	3.10	47.7	0.0	55.3	0.0	91,700	91,600
14	3.24	55.7	0.0	59.2	0.0	76,900	76,900
15	3.29	50.8	2.0	60.1	0.0	46,000‡	59,600
15A	3.40	50.8	3.7	60.8	0.4	9,440‡	23,800
16A	3.45	59.1	0.0	63.3	0.0	509,000	445,000
16	3.47	57.1	0.0	66.1	0.0	67,300	67,300
18	3.49	53.4	9.6	70.5	-3.8	10,400‡	103,000
19	3.58	52.7	10.3	70.5	-1.7	55,400‡	122,000
20A	3.68	69.0	0.0	72.4	-0.1	363,000	179,000
20B	3.69	66.3	0.0	73.2	0.0	139,000	101,000
20	3.83	66.3	1.5	74.4	0.0	12,200‡	15,300
20C	4.04	66.3	4.6	75.3	0.5	4,360‡	13,800@
20D	4.23	71.8	0.0	77.4	0.5	62,300	43,700
20	4.46	71.8	2.3	81.2	-0.4	17,700‡	16,900
21A	4.84	90.2	0.0	94.8	0.0	255,000	261,000
21	4.86	81.3	8.7	96.8	-0.2	65,900‡	115,000
22	4.92	63.2	28.8	97.2	0.1	364‡	22,700
† Sediment transport capacity at the river mouth was ignored. ‡ The riverbed was aggraded at these low-velocity cross sections because of the low initial coarse sediment transport capacity. @ Cross section 20C had the reach-limiting transport capacity for a discharge of 5,000 cfs.							

Figure 38. STARS Model Results: Coarse Sediment Transport Capacity Versus Discharge.
(Assuming riverbed aggradation resulting in various increases in river stage, for
the lower and middle reaches of the Elwha River.)

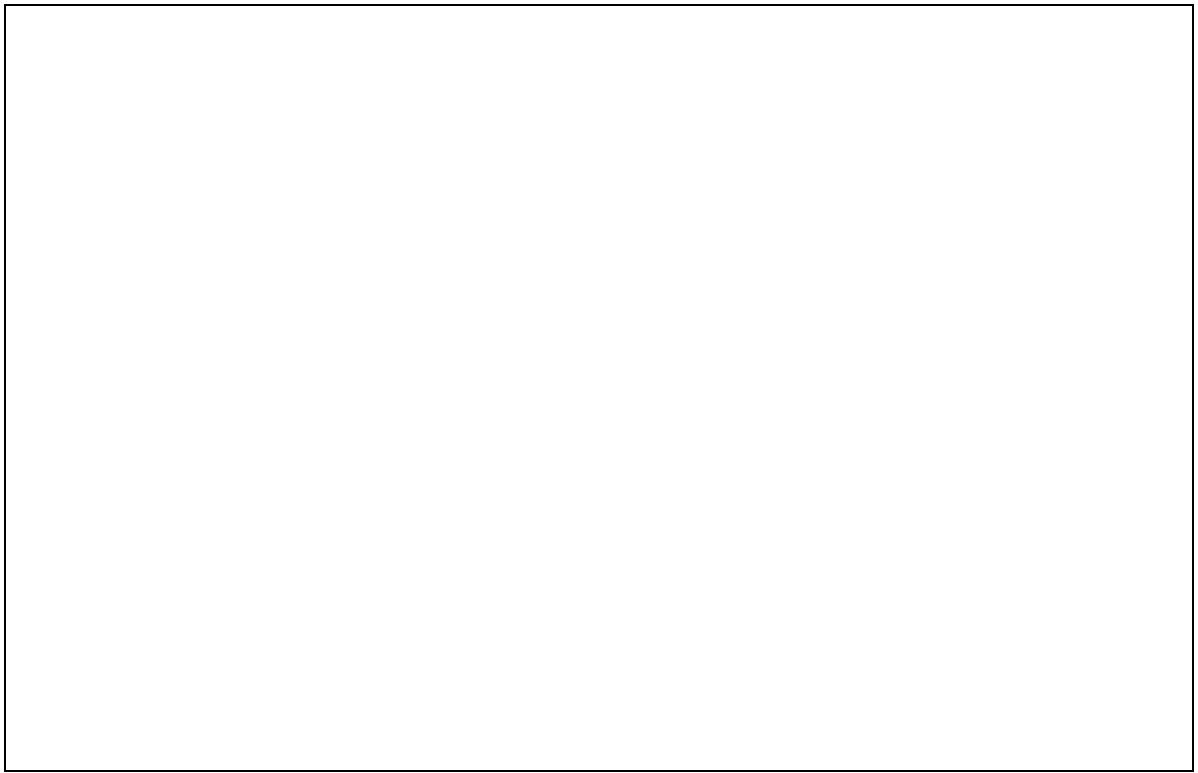


Table 19. Annual Coarse Sediment Transport Capacity Computations for the Elwha River, Lower Reach.

(Assumption is made that river stages would not increase by more than the nominal amount of 0.5 feet at any cross section. The annual sediment transport capacity is 487,000 tons (1,333 tons/day x 365 days) or 328,000 yd³ assuming a density of 110 lbs/ft³.)

Frequency range (percent-days)		Interval (percent-days)	Frequency midpoint (percent-days)	Mean daily discharge (cfs)	Coarse sediment transport capacity (tons/day)	Discharge- frequency product (cfs)	Sediment frequency product (cfs)
0.00	0.02	0.02	0.01	19,000	55,800	3.80	11.16
0.02	0.10	0.08	0.06	14,500	42,700	11.60	34.17
0.10	0.50	0.40	0.30	9,300	26,200	37.26	104.78
0.50	1.50	1.00	1.00	5,974	16,300	59.74	163.16
1.50	5.00	3.50	3.25	4,073	10,300	142.56	361.69
5.00	15.00	10.00	10.00	2,810	4,140	281.00	414.10
15.00	25.00	10.00	20.00	2,090	1,360	209.00	135.60
25.00	35.00	10.00	30.00	1,710	594	171.00	59.40
35.00	45.00	10.00	40.00	1,440	280	144.00	28.00
45.00	55.00	10.00	50.00	1,220	130	122.00	13.00
55.00	65.00	10.00	60.00	1,040	59	104.00	5.90
65.00	75.00	10.00	70.00	855	20	85.50	2.00
75.00	85.00	10.00	80.00	676	5	67.60	0.50
85.00	95.00	10.00	90.00	499	1	49.90	0.10
95.00	98.50	3.50	96.75	359	1	12.57	0.04
98.50	99.50	1.00	99.00	237	0	2.37	0.00
99.50	99.90	0.40	99.70	78	0	0.31	0.00
99.90	99.98	0.08	99.94	22	0	0.02	0.00
99.98	100.00	0.02	99.99	12	0	0.00	0.00
Totals (rounded)						1,504 cfs	1,333 cfs

Table 20. Summary Results of Riverbed Aggradation, Water Surface Elevations, and Coarse Sediment Transport Capacity for the Elwha River, Lower Reach Cross Sections.

(Assumption is made that river stages would not increase by more than 2.0 feet at any cross section.)

Cross section	Channel distance	Initial thalweg elevation	Aggra-dation	Initial water surface	Increase in water surface	Initial coarse sediment	Aggraded coarse sediment
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	(miles)	(feet)	(feet)	elevation (feet)	elevation (feet)	transport capacity (tons/day)	transport capacity (tons/day)
0	0.00	-4.5	0.0	0.0	0.0	1,950†	2,710†
1	0.38	-2.9	4.9	3.8	1.3	26,800‡	32,500
2	0.78	5.7	0.0	12.3	0.6	82,000	48,400
4	1.03	9.5	7.2	16.6	1.6	23,000‡	31,000
5	1.28	18.0	0.0	22.2	1.0	72,600	36,200
6	1.44	17.7	3.3	26.1	-0.6	46,400‡	62,400
7	1.68	23.1	0.0	28.6	0.6	60,000	53,900
8	1.92	28.0	0.0	32.8	-0.3	45,600	44,800
9	2.20	31.4	0.0	37.0	0.1	87,600	88,500
10	2.50	33.1	5.7	41.8	0.5	27,600‡	37,600
11	2.79	38.8	0.0	44.9	0.5	51,000	39,300
12	2.90	39.5	0.0	47.9	0.0	149,000	135,000
13	3.10	47.7	0.0	55.3	0.0	91,700	92,600
14	3.24	55.7	0.0	59.2	0.0	76,900	76,800
15	3.29	50.8	2.0	60.1	0.0	46,000‡	59,300
15A	3.40	50.8	6.2	60.8	1.0	9,440‡	58,800
16A	3.45	59.1	0.0	63.3	0.3	509,000	318,000
16	3.47	57.1	0.0	66.1	-0.2	67,300	56,000
18	3.49	53.4	9.6	70.5	-3.9	10,400‡	155,000
19	3.58	52.7	10.3	70.5	-1.6	55,400‡	124,000
20A	3.68	69.0	0.0	72.4	-0.1	363,000	178,000
20B	3.69	66.3	0.0	73.2	0.0	139,000	101,000
20	3.83	66.3	3.2	74.4	0.3	12,200‡	26,000
20C	4.04	66.3	7.3	75.3	2.0	4,360‡	26,700
20D	4.23	71.8	1.4	77.4	1.9	62,300	27,000
20-E	4.46	71.8	6.2	81.2	0.8	17,700‡	25,900@
21A	4.84	90.2	0.0	94.8	0.0	255,000	238,000
21	4.86	81.3	8.7	96.8	-0.2	65,900‡	115,000
22	4.92	63.2	29.8	97.2	0.1	364‡	41,600
† Sediment transport capacity at the river mouth was ignored. ‡ The riverbed was aggraded at these low-velocity cross sections because of the low initial coarse sediment transport capacity. @ Cross section 20E had the reach-limiting transport capacity for a discharge of 5,000 cfs.							

Table 21. Annual Coarse Sediment Transport Capacity Computations for the Elwha River, Lower Reach.

(Assumption is made that river stages would not increase by more than of 2.0 feet at any cross section. The annual sediment transport capacity is 1,340,000 tons [3,679 tons/day x 365 days] or 904,000 yd³ assuming a density of 110 lbs/ft³.)

Frequency range (percent-days)		Interval (percent-days)	Frequency midpoint (percent-days)	Mean daily discharge (cfs)	Coarse sediment transport capacity (tons/day)	Discharge- frequency product (cfs)	Sediment-fr equency product (cfs)
0.00	0.02	0.02	0.01	19,000	90,800	3.80	18.16
0.02	0.10	0.08	0.06	14,500	73,300	11.60	58.65
0.10	0.50	0.40	0.30	9,300	49,000	37.26	195.98
0.50	1.50	1.00	1.00	5,974	31,800	59.74	317.70
1.50	5.00	3.50	3.25	4,073	19,000	142.56	665.70
5.00	15.00	10.00	10.00	2,810	9,720	281.00	971.60
15.00	25.00	10.00	20.00	2,090	5,610	209.00	561.10
25.00	35.00	10.00	30.00	1,710	3,620	171.00	362.30
35.00	45.00	10.00	40.00	1,440	2,340	144.00	233.50
45.00	55.00	10.00	50.00	1,220	1,500	122.00	150.20
55.00	65.00	10.00	60.00	1,040	899	104.00	89.90
65.00	75.00	10.00	70.00	855	393	85.50	39.30
75.00	85.00	10.00	80.00	676	125	67.60	12.50
85.00	95.00	10.00	90.00	499	20	49.90	2.00
95.00	98.50	3.50	96.75	359	1	12.57	0.04
98.50	99.50	1.00	99.00	237	0	2.37	0.00
99.50	99.90	0.40	99.70	78	0	0.31	0.00
99.90	99.98	0.08	99.94	22	0	0.02	0.00
99.98	100.00	0.02	99.99	12	0	0.00	0.00
Totals (rounded)						1,504 cfs	3,679 cfs

Table 22. Summary Results of Riverbed Aggradation, Water Surface Elevations, and Coarse Sediment Transport Capacity for the Elwha River, Lower Reach Cross Sections.
(Assumption is made that river stages would not increase by more than 5.0 feet at any cross section.)

Cross section	Channel distance (miles)	Initial thalweg elevation (feet)	Aggra-dation (feet)	Initial water surface elevation (feet)	Increase in water surface elevation (feet)	Initial coarse sediment transport capacity (tons/day)	Aggraded coarse sediment transport capacity (tons/day)
0	0.00	-4.5	0.0	0.0	0.0	1,950†	2,730†
1	0.38	-2.9	4.9	3.8	1.3	26,800‡	35,000
2	0.78	5.7	0.3	12.3	0.7	82,000	46,500
4	1.03	9.5	8.5	16.6	2.7	23,000‡	33,700@
5	1.28	18.0	3.7	22.2	2.8	72,600‡	35,400
6	1.44	17.7	6.3	26.1	1.3	46,400‡	34,900
7	1.68	23.1	3.4	28.6	2.0	60,000‡	37,700
8	1.92	28.0	3.0	32.8	1.1	45,600‡	40,300
9	2.20	31.4	0.0	37.0	0.6	87,600	54,700
10	2.50	33.1	5.7	41.8	0.2	27,600‡	40,400
11	2.79	38.8	0.0	44.9	0.7	51,000	41,300
12	2.90	39.5	0.0	47.9	0.1	149,000	127,000
13	3.10	47.7	0.0	55.3	0.0	91,700	93,800
14	3.24	55.7	0.0	59.2	0.0	76,900	76,800
15	3.29	50.8	2.0	60.1	0.0	46,000‡	58,900
15A	3.40	50.8	6.2	60.8	1.0	9,440‡	58,900
16A	3.45	59.1	0.0	63.3	0.3	509,000	318,000
16	3.47	57.1	0.0	66.1	-0.2	67,300	56,000
18	3.49	53.4	9.6	70.5	-3.9	10,400‡	115,000
19	3.58	52.7	10.3	70.5	-1.6	55,400‡	124,000
20A	3.68	69.0	0.0	72.4	-0.1	363,000	178,000
20B	3.69	66.3	0.0	73.2	0.0	139,000	101,000
20	3.83	66.3	5.3	74.4	0.9	12,200‡	56,500
20C	4.04	66.3	9.7	75.3	4.1	4,360‡	35,300
20D	4.23	71.8	6.3	77.4	4.5	62,300‡	35,800
20-E	4.46	71.8	11.1	81.2	4.6	17,700‡	35,100
21A	4.84	90.2	0.0	94.8	0.4	255,000	151,000
21	4.86	81.3	8.7	96.8	-0.3	65,900‡	94,200
22	4.92	63.2	29.8	97.2	0.1	364‡	46,900
† Sediment transport capacity at the river mouth was ignored. ‡ The riverbed was aggraded at these low-velocity cross sections because of the low initial coarse sediment transport capacity.							

@ Cross section 20E had the reach-limiting transport capacity for a discharge of 5,000 cfs.

Table 23. Annual Coarse Sediment Transport Capacity Computations for the Elwha River, Lower Reach.

(Assumption is made that river stages would not increase by more than 5.0 feet at any cross section. The annual sediment transport capacity is 1,400,000 tons [3,848 tons/day x 365 days] or 946,000 yd³ assuming a density of 110 lbs/ft³.)

Frequency range (percent-days)		Interval (percent-days)	Frequency midpoint (percent-days)	Mean daily discharge (cfs)	Coarse sediment transport capacity (tons/day)	Discharge- frequency product (cfs)	Sediment- frequency product (cfs)
0.00	0.02	0.02	0.01	19,000	170,000	3.80	33.95
0.02	0.10	0.08	0.06	14,500	120,000	11.60	95.73
0.10	0.50	0.40	0.30	9,300	67,000	37.26	268.08
0.50	1.50	1.00	1.00	5,974	38,700	59.74	386.66
1.50	5.00	3.50	3.25	4,073	22,200	142.56	777.35
5.00	15.00	10.00	10.00	2,810	10,400	281.00	1,043.90
15.00	25.00	10.00	20.00	2,090	5,120	209.00	511.50
25.00	35.00	10.00	30.00	1,710	3,010	171.00	301.00
35.00	45.00	10.00	40.00	1,440	1,840	144.00	183.50
45.00	55.00	10.00	50.00	1,220	1,150	122.00	115.30
55.00	65.00	10.00	60.00	1,040	712	104.00	71.20
65.00	75.00	10.00	70.00	855	378	85.50	37.80
75.00	85.00	10.00	80.00	676	171	67.60	17.10
85.00	95.00	10.00	90.00	499	44	49.90	4.40
95.00	98.50	3.50	96.75	359	1	12.57	0.04
98.50	99.50	1.00	99.00	237	0	2.37	0.00
99.50	99.90	0.40	99.70	78	0	0.31	0.00
99.90	99.98	0.08	99.94	22	0	0.02	0.00
99.98	100.00	0.02	99.99	12	0	0.00	0.00
Totals (rounded)						1,504 cfs	3,848 cfs

2. Middle reach (between the two lakes) — The reach-limiting transport capacity for coarse sediment of the middle reach was computed assuming that only nominal aggradation would occur (i.e., aggradation would not cause the river stage to increase by more than 0.5 ft at a discharge of 5,000 cfs). Three separate, short reaches were analyzed — each having only three cross sections. Computations for this reach are shown in table 24.

Assuming nominal aggradation, the annual reach-limiting transport capacity for coarse sediment was estimated to be 2,480,000 tons per year (1,670,000 yd³ per year).

- **Lake Aldwell aggradation at Highway 101 bridge** — Concern was expressed about the effects of possible riverbed aggradation at the Highway 101 bridge (which crosses the Elwha River just upstream of Lake Aldwell) after the removal of Elwha Dam. An analysis was performed using the STARS computer program to compute the water surface elevation and sediment transport capacity at the Highway 101 bridge cross section.

Post-dam and predam cross sections were developed for Lake Aldwell from 1989 and 1994 topography and subsurface data. Two surveyed cross sections, 23 (Highway 101 bridge cross section) and 24 (the cross section immediately upstream of the bridge) were also used in the analysis.

The post-dam (1994) cross sections of Lake Aldwell were used to compute the water surface elevation at cross section 23 for a flow of 45,000 cfs (the 100-year flood) with no riverbed aggradation. A lake elevation of 197.0 feet was assumed as the initial condition. An analysis using the predam cross sections resulted in the same computed water surface elevation at the bridge site. This computed water surface elevation was established as the baseline river elevation at cross section 23 for use in the sediment transport analysis.

The sediment transport capacity of the reach was analyzed using the predam cross sections and the composite gradation of the Lake Aldwell delta sediments. The riverbed channel was aggraded at cross section 23 while not allowing the lake elevation to rise more than 0.5 foot above the baseline river elevation. Cross section 23 was aggraded 7.9 feet and the transport capacity at the cross section was calculated to be 15,000,000 tons/day.

The expected sediment load was computed using the sediment rating curve developed from bedload samples taken at the USGS gauge on the Elwha River above Lake Mills. The calculated sediment load is 800,000 tons/day for a flow of 45,000 cfs. Because the estimated sediment load is much less than the limiting sediment transport capacity for the upstream reach, aggradation at the bridge cross section is not expected to be a problem.

C. DISCUSSION

The computational method described in this chapter provides rough quantitative results regarding the reach-limiting transport capacity. The method is reliable to determine the relative transport capacities of the lower and middle reaches.

The reach-limiting transport capacity for the lower reach (below Elwha Dam) is less than that of the middle reach (between the two reservoirs). Therefore, the lower reach is controlling from a sediment management perspective. The reach-limiting transport capacity of the middle reach, assuming only nominal aggradation, is greater than that of the lower reach even assuming that aggradation would increase river stages up to 5.0 feet in the lower reach. Thus, aggradation of the middle reach would be less than aggradation of the lower reach.

Table 24. Computations of Aggradation and Coarse Sediment Transport Capacity for the Middle Reach of the Elwha River.
(Cross section 4D — in a pool reach — had the reach-limiting transport capacity.)

Cross section	Cumulative channel distance (feet)	Thalweg elevation (feet)			Water surface elevation (feet)			Coarse sediment transport capacity (tons/day) at a discharge of 5,000 cfs	
		Initial	Aggraded	Difference	Initial	Aggraded	Difference	Initial	Aggraded
4U	0	309.5	312.2	2.7	317.39	317.84	0.45	24,100	54,700
4	376	310.3	312.9	2.6	316.86	316.86	0	34,200	55,000
4D	557	311.8	312.4	.6	316.26	316.26	0	41,300	54,500
6U2	0	267.6	267.6	0	272.36	272.77	0.41	171,000	121,000
6U1	614	260.3	263.1	2.8	268.81	269.51	0.5	66,200	119,000
6	923	262	264.1	2.1	267.96	267.96	0	57,700	116,000
9U	0	218	221	3	227.3	227.35	0.05	50,800	72,100
9	143	220.8	221	.2	226.75	226.95	0.2	77,200	71,400
9D	363	220.2	221.6	1.4	226.2	226.2	0	61,000	70,500

CHAPTER X. HEC-6 SEDIMENT TRANSPORT MODELING

An analysis of the river's capacity to transport coarse sediment was described in chapter IX. Use of a standard numerical model to predict the amount, location, and timing of riverbed aggradation, and the corresponding increases in flood stage, is described in this chapter.

Riverbed aggradation and increases in flood stage were predicted using the modeling program HEC-6 (Corps, 1993). This is a one-dimensional, movable-boundary, open-channel flow model designed to simulate and predict changes in river profiles resulting from scour and/or deposition over a period of years. Results from this model are limited to strictly vertical bed changes; width changes can not be simulated. Additionally, the model assumes that channel bed and bank roughness coefficients remain constant with time.

The impacts on flood stage from riverbed aggradation were of most interest. After each HEC-6 simulation, the predicted cross section data were again used by HEC-6 to compute the water surface profile for a single discharge (and time step) corresponding to the 100-year flood. The predicted thalweg and water surface elevations were then compared to the existing (initial) thalweg and water surface elevations, before aggradation.

The short- and long-term impacts of coarse sediment release, resulting from the removal of Glines Canyon and Elwha Dams, were modeled for the lower reach — downstream from Elwha Dam. The middle reach between the two lakes was not modeled with HEC-6 because the spacing of the river cross-section survey data was not sufficiently close to compute accurate river hydraulics and sediment transport through the entire reach. However, the middle reach is steeper and therefore less susceptible to riverbed aggradation than the lower reach. Also, the results of the analysis described in chapter IX indicate that the lower reach is of greatest importance in terms of riverbed aggradation.

The short-term model simulations were for about a 3-year period during, and immediately following, dam removal (chapter X, section B below). Long-term simulations were a continuation of certain short-term simulations (chapter X, section C below). All of the long-term simulations were for 50-year periods and used historic mean daily flows as the upstream discharge. These long-term simulations assumed that coarse sediment was no longer eroded from either reservoir area and that the upstream supply of coarse sediment was equal to the natural supply, upstream from Lake Mills (chapter VII, section A).

Short-term model simulations used a variety of assumptions related to the upstream water discharge and coarse sediment supply. Simulations of both constant and variable discharge were performed. For the three short-term simulations assuming a constant discharge, the first one assumed that the upstream supply rate of coarse sediment was equal to the average erosion rate measured during the 1994 Lake Mills drawdown test. The other two simulations assumed that the upstream supply rate of coarse sediment was equal to the transport rates past Glines Canyon Dam that were previously predicted by HEC-6 (chapter VII, section C). These three short-term simulations (assuming a constant discharge) were not used in the conclusions (chapter XI), but were helpful in gaining experience with the application of the HEC-6 model to the Elwha River.

For all of the short-term simulations with variable discharge (chapter X, section B–2), outputs of water and sediment from the Elwha Reservoir model (chapter VIII) were used as the upstream boundary conditions in the HEC-6 model.

A. MODEL INPUT DATA

1. Cross-section data — The cross section data used in the transport capacity analysis of the lower reach (chapter IX), described in chapter V, section G, were used as initial conditions in the HEC-6 model. Delineation of the main river channel and overbank areas and corresponding Manning's n roughness coefficients were determined for each cross section based on interpretation of cross section plots and aerial photographs. A contraction-loss coefficient of 0.1 and an expansion-loss coefficient of 0.5 were assumed for transitions between wide and narrow cross sections. The model applies these coefficients to the differences in velocity heads between any two cross sections.

The active channel width (the portion of the cross section where the model is allowed to compute changes in the bed elevations) was set equal to the wetted river width (a function of discharge and cross section shape).

2. Sediment data — The Yang transport equations for sand and gravel were selected for the majority of the simulations because of their proven applicability to many rivers and to both sand- and gravel-size sediment. The Meyer-Peter and Müller formulas were used in other simulations. In an independent model study of the lower Elwha River, the Corps (at the Waterway Experiment Station, Vicksburg, MS; November 24, 1995) tested the following sediment transport equations:

- Toffaleti and Schoklitsch combined;
- Meyer-Peter and Müller;
- Laursen and Copeland combined;
- Parker;
- Yang.

Overall, the Yang equations for sand and gravel performed the best and were used in their final model simulation (R. Copeland and B. Hall, Corps, Waterways Experiment Station, Vicksburg, MS, written communication, 1995).

Exner equation (continuity equation for sediment material) computations in HEC-6 were limited to 50 iterations for each time step for bed-material composition calculations. Based on measurements from the 1994 Lake Mills drawdown experiment, the value of 2.7 was used as the specific gravity of sand particles and 110 lbs/ft³ was used as the dry unit weight of sediment (USGS, 1995). The model default values were assumed for all of the remaining variables.

Various bed-material size gradations were tried in the HEC-6 modeling of the lower reach. Existing bed-material size gradations were used as the initial conditions in the first short-term model simulations that assumed a constant discharge and an upstream sediment supply rate equal to the average measured during the 1994 Lake Mills drawdown test. The existing riverbed consists primarily of cobbles, boulders, and bedrock (chapter I, section C–1; also Reclamation, March 1996). For modeling purposes, the thickness of this bed material was assumed to be 3 feet. In this simulation, the coarse upstream sediment supply was finer than the initial bed material and was not transported past the cross sections furthest upstream — apparently because of mixing with the very coarse streambed gradations.

Finer bed-material size gradations (for the initial conditions of the lower reach) were used with greater success in modeling the other two short-term cases of constant discharge. Therefore, in subsequent short- and long-term simulations, the entire riverbed was assumed to be covered with a thin layer of coarse sediment from the Lake Mills delta. Various composite size gradations of sediment from the Lake Mills delta were used as the initial bed-material size gradation at each cross section of the lower reach and assigned a thickness of 0.1 foot. This relatively thin layer of bed material was incorporated to assist the model in predicting sediment transport of the upstream supply without mixing with the existing coarse bed material. The 0.1-foot thickness prevented the model from predicting any significant riverbed erosion at high velocity cross sections.

Because silts and clays would not be part of the bed-material load, modeling of this fine material would not significantly affect results; therefore, the composite size gradations from the Lake Mills delta were developed without silts and clays. These composite gradations were also used to define the gradation of the upstream sediment supply. Sensitivity testing of these composite size gradations was performed to verify the limitations of the Yang sediment transport equations for the coarser size ranges (chapter X, section C).

3. Hydrologic data — Hydrologic data for the long-term simulations consisted of mean daily discharges from USGS Elwha River gauging station at McDonald Bridge (No. 12045500). Mean daily discharges from 1919–68 (the first 50 years of continuous record) were input to the model as the upstream boundary flow conditions immediately below Elwha Dam.

The downstream boundary of the modeled reach was the river mouth at the Strait. For each model simulation, sea level was assumed to be constant with time. Three different sea elevations were assumed at the downstream boundary for sensitivity testing of combined short- and long-term simulations:

- An elevation of 6.6 feet, which is the mean higher high tide elevation (mean of the highest daily tides) plus 1.0 foot (J. Lencioni, Corps, Seattle District, Seattle, WA, oral communication, 1995);
- An elevation of 3.6 feet, which is the mean daily high-tide elevation plus 1.0 foot; and
- An elevation of 0.0 feet, which assumes no tide.

A mean sea level of 6.6 feet was used in initial short- and long-term simulations, and water surface profile computations of the 100-year flood. A mean sea level of 0.0 feet was rationalized as being most representative of the average daily sea level for the final short- and long-term simulations. The sensitivity testing revealed that the sea level impacted the computed water surface profiles up to about RM 1.8. Examples of the differences in thalweg elevations between long-term simulations with sea levels of 3.6 and 6.6 feet and the final 0.0-foot sea level simulation are shown in Table 25.

Table 25. Comparison of Resultant Thalweg Elevations from Various Sea Level Assumptions.

Additional aggradation for simulations using sea level elevations greater than zero		
River mile	Sea level = 3.6 feet	Sea level = 6.6 feet
0.0	+3.8	+6.7

0.2	+4.0	+5.8
0.4	-1.6	-1.9
1.05	-1.4	+0.2
1.95	.0	.0

4. Temperature data — Water temperatures for all model simulations were varied four times a year: 30 °F (January 1), 45 °F (April 1 and October 1), and 60 °F (July 1). Additional temperature data incorporated in the model were linearly interpolated between these values to the nearest 5 °F. Water temperature affects the fluid viscosity, sediment particle fall velocity, and the sediment transport rate. The lower the water temperature, the greater the viscosity, the slower the sediment particle fall velocity, and the greater the sediment transport rate. Fine-grained sediments such as clays, silts, and fine sands are much more sensitive to temperature than coarse-grained sediments such as coarse sands, gravels, and cobbles.

B. SHORT-TERM MODEL RESULTS

1. Constant discharge simulations — Three different constant discharge simulations of the lower river reach were performed to test the HEC-6 model with the basic data set. None of these model simulations were used in the final conclusions but were helpful in gaining experience with the application of HEC-6 to the Elwha River.

- **Lake Mills Drawdown Experiment Data** — HEC-6 was used to simulate riverbed aggradation for a 30-day period in the lower reach, assuming a constant discharge of 1,400 cfs and a constant supply of coarse sediment for the upstream boundary. The upstream supply rate was set equal to 44,000 tons/day, which is equal to the average erosion rate measured during the 1994 Lake Mills drawdown experiment. The size gradation of the upstream sediment supply was set equal to the average-size gradation of bed-load samples collected during the drawdown experiment. Initial size gradations of the riverbed were based on measurements of existing conditions.

Neither the Yang nor the Meyer-Peter and Müller transport equations predicted sediment transport beyond the two cross sections furthest upstream. Unrealistic aggradation in excess of 100 feet was predicted at the cross section furthest upstream in these 30-day simulations. Reducing the upstream sediment load to 4,000 tons/day for the 1,400 cfs riverflow resulted in aggradation in excess of 30 feet at the section furthest upstream and from about +4.5 feet to –2.5 feet along the remainder of the reach after 100 days.

The average size gradation of bed-load samples from the drawdown experiment is coarse — median size of 4 mm — and is only representative of the delta surface. Also, the movement of gravel and cobbles was due to head-cut erosion induced by the lowering of Lake Mills. It is doubtful that these coarse sediments could erode past the dam site and through the middle river reach at the same rate as measured during the drawdown experiment. Therefore, size gradations more representative of the entire delta were used to represent the upstream sediment supply in subsequent model simulations.

- **HEC-6 computed sediment supply** — The lower river reach was also modeled with predicted sediment release rates from Lake Mills (during complete dam removal) computed by HEC-6. Results obtained from HEC-6 modeling of the Glines Canyon Dam removal (chapter VII, section C; also

figure 12) were used as the upstream sediment supply to the lower reach. In both the 1,500 cfs and 5,000 cfs constant-flow simulations, the total sediment transported past Glines Canyon Dam for the two weeks following each increment of dam removal was averaged over 15 days and input to the HEC-6 model for the lower reach as the upstream sediment supply for that period. Sediment supply was not modified to account for the differing lag times each size fraction would experience as transported through the middle reach.

The cutting of six notches in succession over 90 days has been modeled with HEC-6 using a steady flow of 1,500 cfs (chapter VII, section C). The average 15-day sediment release rates varied as follows: 10,717; 14,421; 15,224; 18,875; 16,601; and 18,957 tons/day. The total sediment inflow to the lower reach was 955,000 yd³. Of this total, HEC-6 predicted the deposition of 863,000 yd³, resulting in aggradation of about 3.5 feet at the mouth and up to 4.3 feet in upstream pools.

The cutting of four notches in succession over 60 days has also been modeled with HEC-6 assuming a steady flow of 5,000 cfs (chapter VII, section C). The average 15-day sediment release rates increased with each successive dam-removal increment: 3,280; 19,720; 30,270; and 30,825 tons/day, respectively. The total sediment inflow to the lower reach was 847,000 yd³. Of this total, HEC-6 predicted the deposition of 472,000 yd³, mostly at the cross sections furthest upstream and furthest downstream. Aggradation at the river mouth was about 2.5 feet.

2. Variable discharge simulations — The HEC-6 model was used to compute short-term riverbed aggradation of the lower reach, resulting from dam removal and variable lake inflow. The results from the Elwha Reservoir model (chapter VIII, section D) were used as the upstream boundary conditions in the HEC-6 simulations of the lower reach.

Hydrologic scenarios 1 and 4 (chapter VIII, section C–1), representing the historic 3-year extremes, were both used in the short-term model simulations. For these two scenarios, Lake Aldwell was ignored and only coarse sediment released from Lake Mills was considered (chapter VIII, section C–2). Hydrologic scenario 4 (June 1989–September 1992) had the largest volume of reservoir sediment erosion but had relatively high sediment transport rates from the larger discharges. Hydrologic scenario 1 (June 1968–September 1971) had relatively low volume of reservoir sediment erosion but also a relatively low capacity to transport it. Simulation of hydrologic scenario 3 (June 1971–September 1974), with progressively higher annual-peak discharges, produced the greatest amount of riverbed aggradation. This scenario was used to model the concurrent removal of both dams and the combined coarse sediment release from both reservoirs without regard to lag effects of the middle reach. Scenario 2 (June 1950–September 1953) did not expand the range of impacts and was not used in the HEC-6 modeling.

The downstream boundary of the modeled reach was at the river's mouth. The water surface elevation at this boundary was conservatively set equal to 6.6 feet, the mean higher high tide plus 1.0 foot, for the entire simulation in hydrologic scenarios 1 and 4. For hydrologic scenario 3, the downstream water surface elevation was set equal to a constant elevation of 0.0 feet.

The HEC-6 model requires that the upstream sediment supply be specified as a function of riverflow (sediment-discharge rating table). In modeling the highly variable sediment loads associated with dam removal, the simulation had to be stopped and restarted several times (“hot starts”) to match the sediment-discharge rating table to the changing sediment transport rates computed by the Elwha Reservoir model. The HEC-6 model simulations were temporarily stopped, the cross section data were saved, the sediment-discharge rating table was manually adjusted, and the simulations were

resumed with a hot start. Because the bed-material size gradations at each cross section were not automatically saved, these data were reset to the initial conditions at the beginning of each hot start. However, this made little difference because the initial bed-material size gradations were very similar to the size gradation of the upstream sediment supply.

The sediment loads predicted by the Elwha Reservoir model were averaged over each 2-week period of dam removal and provided as input to the HEC-6 model. Following dam removal, the sediment-discharge rating tables for the natural supply of coarse sediment (chapter VII, section A) were used for periods of low flow. Another rating table was used for periods of progressively higher floodflows. This sediment-discharge rating table represented the transport capacity through Lake Mills under predam conditions and was computed using the predam (1921) reservoir topography upstream from Glines Canyon Dam.

Computational time steps for the HEC-6 model were set as long as one day, although 1-hour or ½-hour time steps were used during periods of high sediment inflow (e.g., dam notching sequences and floodflows). The size gradation of the initial bed material and upstream sediment supply were both set equal to the composite size gradation of the Lake Mills delta but the fraction of material greater than 8 mm was lumped into the fine gravel range (4–8 mm).

In the simulation of hydrologic scenario 1 (low peak discharges), riverbed aggradation (excluding the upstream 0.1 mile of river) ranged from almost zero at several cross sections to 7.3 feet at RM 4.4 and was 2.8 feet near the mouth (RM 0.2). This resulted in an increase in 100-year-flood stage of up to 2.6 feet (RM 0.2) and an average stage increase of 0.3 feet. High riverbed aggradation near the mouth was due to the assumed 6.6-foot tide elevation during the entire simulation. Sediment was transported further down the reach in the simulation of hydrologic scenario 4 (high peak discharges), compared with hydrologic scenario 1. The computed water surface profiles of these two extreme hydrologic scenarios were about the same (most differences were less than one foot).

Excessive aggradation in the bedrock canyon below Elwha Dam was temporarily computed by HEC-6 during these simulations. This is because the upstream sediment supply rates computed by the Elwha Reservoir model were excessively high during some short periods. The HEC-6 model responded to these high supply rates by temporarily storing sediment at the upstream two or three cross sections and subsequently transporting it downstream. Actual deposition in this reach (except for the scour pool below the spillway) is unlikely because the sediment transport capacity is greater than through the more mild slope reach of Lake Aldwell. Therefore, either less sediment would be eroded from Lake Aldwell or the transport rates through the lake would be less (with a longer duration) than computed by the Elwha Reservoir Model.

3. Final Short-Term Model Results — The HEC-6 model predictions for the simulation of hydrologic scenario 3 were considered the final short-term results and were used as the initial conditions for the final long-term model simulation. After the simulation of hydrologic scenario 3, the predicted thalweg profile and the computed water surface profile for the 100-year flood were compared with the profiles of the initial conditions (figure 39). Riverbed aggradation (excluding the upstream mile of river) ranged from almost zero at several cross sections to 8.8 feet at RM 3.6 and 1.7 feet near the mouth (RM 1.05). This resulted in an increase in 100-year-flood stage of up to 2.7 feet (RM 3.6) with an average stage increase of 0.7 feet.

Compared to the simulations of coarse sediment release from only Lake Mills (using hydrologic scenarios 1 and 4), this final simulation of sediment release from both lakes predicted slightly greater

aggradation levels in the lower half of the reach and progressively greater aggradation from mid-reach to the cross section furthest upstream. The Elwha Reservoir model predicted greater coarse sediment erosion from Lake Aldwell than the river's transport capacity as is evident by the severe short-term aggradation depicted in the upstream one mile of the reach. Differences between the 100-year-flood elevations and thalweg profiles for the initial, short-term (using hydrologic scenario 3), and long-term simulations are shown in Table 26.

Figure 39. HEC-6 Short-term Model Results.
(Comparison of Existing Channel Thalweg and Water Surface Profiles. Corresponding to the 100-year flood, with conditions after 3 years of hydrologic scenario 3.)

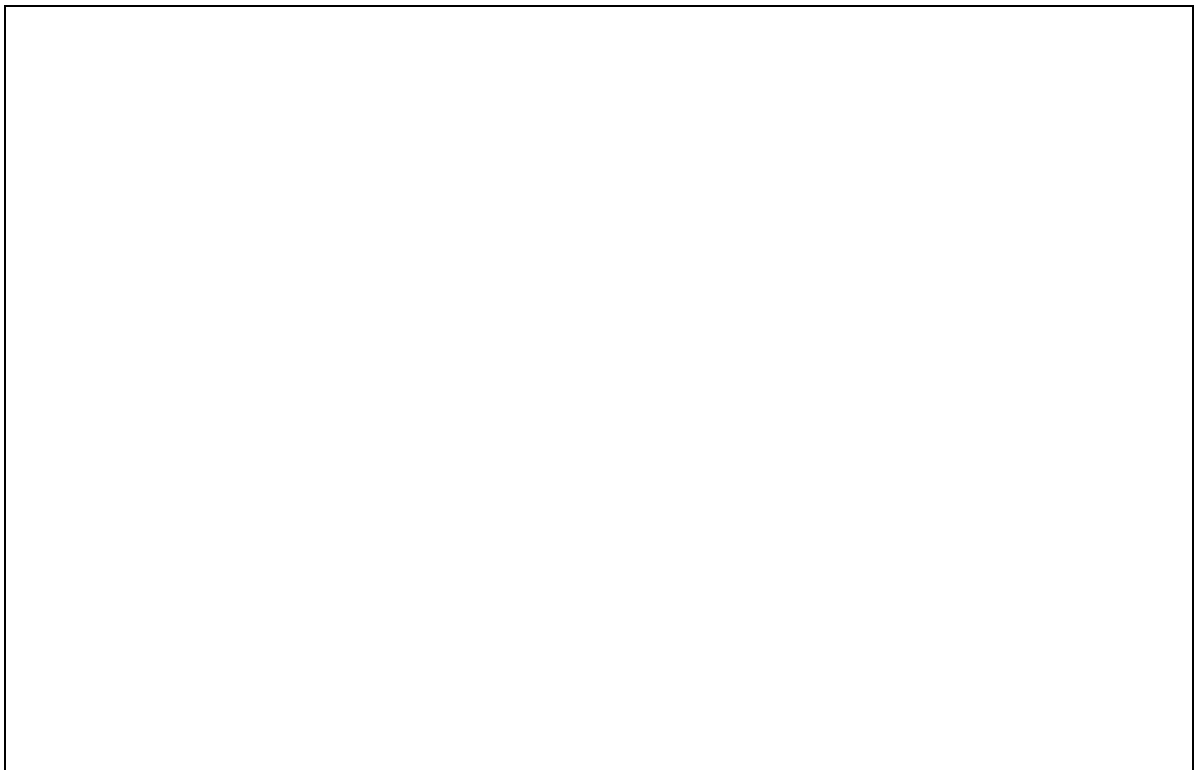


**Table 26. HEC-6 Short-term and Long-term Model Results:
Differences from Initial Conditions.**

Elwha Dam to Strait of Juan de Fuca		100-year-flood water surface elevation: difference from initial conditions			Thalweg		
Cross section	River mile	Initial elevation	1971–74 short term	1919–70 Long term	Initial thalweg elevation	Aggradation (+) Degradation (–)	
						Short-ter m	Long-ter m
0	0.00	6.6	0.0	0.0	–4.5	3.7	2.8
1	0.38	8.6	2.0	2.0	–2.9	0.0	–0.1
2	0.78	15.9	0.5	3.4	5.7	1.4	5.7
4	1.03	21.3	0.4	4.2	9.5	0.9	7.8
5	1.28	27.8	1.0	5.5	18.0	1.7	6.7
6	1.44	30.7	0.4	4.6	17.7	1.5	8.3
7	1.68	35.6	–0.1	3.7	23.1	–0.1	6.0
8	1.92	39.1	0.1	2.1	28.0	–0.1	4.2
9	2.20	44.0	–0.2	3.2	31.4	–0.1	3.4
10	2.50	48.7	0.1	0.8	33.1	–0.1	3.9
11	2.79	52.5	0.5	3.1	38.8	–0.1	3.6
12	2.90	58.1	0.1	1.1	39.5	–0.1	4.6
13	3.10	63.8	0.8	3.1	47.7	3.2	4.6
14	3.24	64.9	1.2	4.9	55.7	1.2	2.2
15	3.29	67.1	1.8	3.9	50.8	6.2	7.5
15A	3.40	72.0	2.0	3.3	50.8	8.5	9.6
16A	3.45	72.7	1.4	3.0	59.0	2.5	3.4
16	3.47	76.9	0.8	1.7	57.1	4.2	4.5
18	3.49	76.3	0.6	1.8	53.4	5.9	5.7
19	3.58	77.3	2.7	3.4	52.7	8.8	6.5
20A	3.68	81.3	–0.1	0.1	68.9	0.0	0.0
20B	3.69	86.7	–0.2	–0.3	66.3	1.4	1.2
20	3.83	87.4	0.0	–0.1	66.3	5.0	2.3
20C	4.04	88.3	1.0	0.8	66.3	10.1	5.2
20D	4.23	88.9	3.1	2.3	71.8	9.2	2.0
20	4.46	91.5	7.3	5.8	71.8	12.2	2.9
21A	4.84	104.9	12.7	12.6	90.2	–0.1	–0.1
21	4.86	108.8	19.8	19.6	81.3	6.1	7.9
22	4.92	111.4	16.0	16.2	63.3	26.5	25.5

C. LONG-TERM MODEL RESULTS

Short-term model simulations of 3 years were continued for another 50 years using measured historic flows and the natural coarse sediment supply (chapter VII, section A). It was assumed that no additional reservoir-sediment erosion would occur. The hydrology for all long-term simulations was based on the first 50 years of continuous record (mean daily discharges from the period 1919–70). These discharges were measured by the USGS at the Elwha River gauging station at McDonald Bridge. Final cross section data from the short-term simulations were used as initial conditions in the long-term simulations. Size gradations of the riverbed and upstream sediment supply were both set equal to the size gradation of coarse delta sediment in Lake Mills.

The HEC-6 modeling results for the lower river reach predicted that riverbed aggradation would result from the removal of both dams and that the river stage for a given discharge would increase. Contrary to what had been expected, long-term simulations predicted more riverbed aggradation than the short-term simulations. Most of the riverbed aggradation would be from gravel-size and coarser particles. In general, the model predicted that sand-size particles (finer than 2.0 mm) would tend to pass through the lower reach but that gravel-size particles would tend to accumulate. About 1 myd³ of gravel were input in the short-term simulation of hydrologic scenario 3 but an additional 1.5 myd³ of gravel were input over the 50 years of the long-term simulation. Tables 27 and 28 show volumes of riverbed aggradation relative to total coarse sediment inflow. The total short-term coarse sediment inflow volume for hydrologic scenario 1 was only about 15 percent of the long-term aggradation volume; whereas the short-term sediment inflow volume for hydrologic scenario 4 was 55 percent of the long-term volume. A higher percentage of the sediment inflow volume was deposited in the short-term simulation of hydrologic scenario 1, compared with other simulations, because of the low discharge and sediment transport capacity of this scenario.

Table 27. Comparison of Sediment Inflow and HEC-6 Model Results of Aggradation Volumes for Short-term Simulations.

Simulation	Sediment		Percent (aggradation/inflow)
	Inflow (myd ³)	Aggradation (myd ³)	
Hydrologic scenario 1 (Lake Mills only)	0.790	0.586	74
Hydrologic scenario 4 (Lake Mills only)	1.42	0.754	53
Hydrologic scenario 3 (Lake Mills and Lake Aldwell)	2.78	1.33	48

1. Sensitivity testing of sediment size gradation — HEC-6 model results for the long-term simulations (using the Yang sediment transport equations) indicate that sediment particles coarser than 8 mm cannot be transported through the river reach at the rate supplied from upstream. Consequently, coarse gravels aggrade the riverbed in the upper portion of the modeled reach. For sensitivity testing, the size gradations of the upstream sediment supply (and the initial bed material at each cross section) were set equal to the composite size gradation of coarse sediment within the Lake Mills delta. In this simulation, large volumes of material deposited in the upstream one-mile of the reach. Table 28 shows the volumes of sediment supply and aggradation. Three additional finer

supply gradations were modeled to verify this imbalance between the computed sediment transport capacity and supply.

In the next two cases, the thin layer of initial bed-material size gradation remained equal to the original composite gradation. In the first modified size gradation, sediment particles larger than medium gravel (16 mm) were grouped into the medium-gravel size range. This gradation is referred to as the medium-gravel limit gradation. In the second gradation, the almost 25 percent of material coarser than 8 mm was eliminated and the percent retained values for the remaining size fractions were re-proportioned. This gradation is referred to as the fine-gravel gradation limit. As shown in table 28, use of the fine-gravel limit gradation reduced the volume of material deposited in the lower reach by over 500,000 yd³. The gradation was modified a third time for the final short- and long-term runs. In this final gradation (similar to the medium-gradation limit), sediment particles larger than fine gravel (8 mm) were grouped into the fine gravel size fraction (32 percent in this size range).

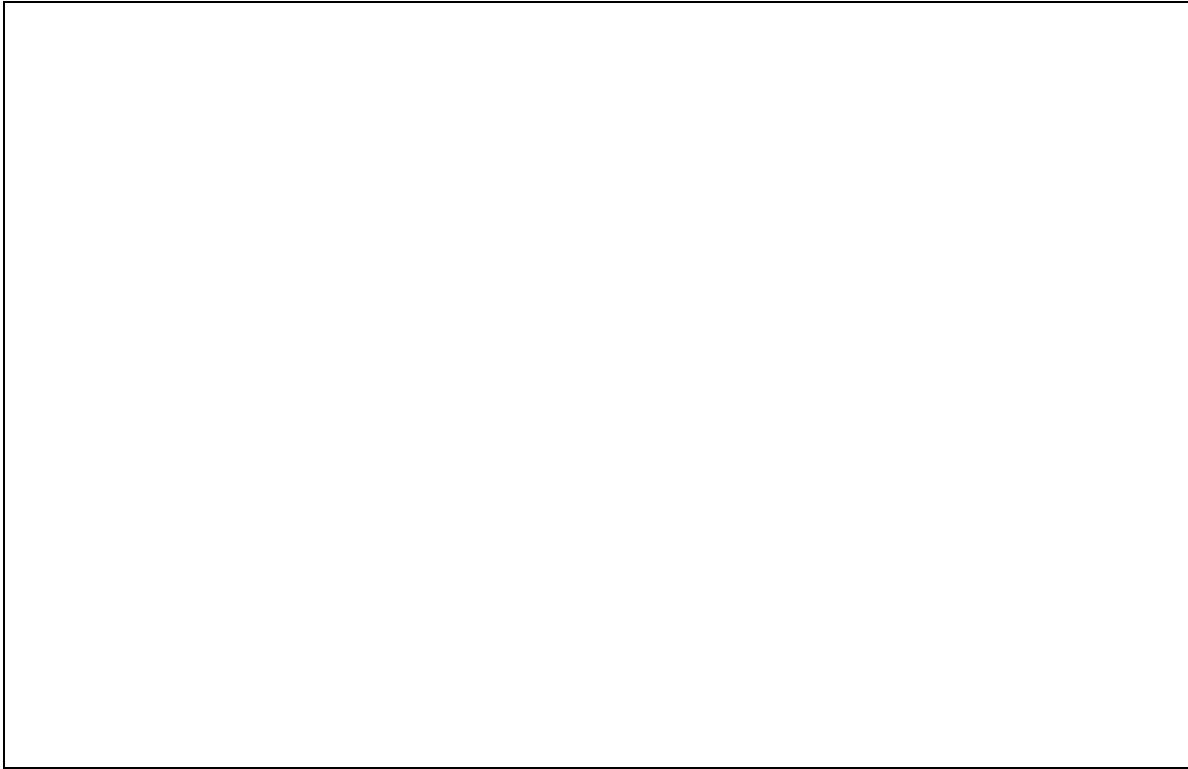
Table 28. Comparison of Sediment Inflow and HEC-6 Model Results of Aggradation Volumes for Long-term Simulations Using Different Size Gradations for the Upstream Sediment Supply.

Size gradation	Sediment		Percent (aggradation/ inflow)
	inflow (myd ³)	aggradation (myd ³)	
Composite size gradation	5.04	2.89	57
Medium gravel limit (< 16 mm)	5.04	2.89	57
Fine gravel limit (< 8 mm)	5.04	2.30	46
Final simulation, fine gravel limit (< 8 mm)	5.04	2.74	54

Figure 40 is a comparison of the thalweg profiles for the coarse, medium, and fine gradations resulting from 50-year simulations. In general, the amount of aggradation in the upstream one-mile of the lower reach (RM 4 to 5) decreased with the elimination of coarse and medium gravels. Essentially no sediment was deposited in the middle one-third of the lower reach in the simulation using the fine-gravel limit gradation. However, in the simulation using the medium-gravel limit gradation, a majority of sediment that was transported from the upstream one-mile of the lower reach was deposited in the middle portion of the reach. This resulted in even greater aggradation than predicted by the composite (coarse) gradation simulation. Aggradation in the downstream one-third of the lower reach was about equal for each of the gradations. Resultant 100-year-flood water surface elevations were usually within one foot at the downstream one-third of the lower reach. Further upstream, water surface elevation predictions varied by more than 7 feet in some cases.

Figure 40. HEC-6 Model Results: Sensitivity of Sediment Size Gradation on Predicted Thalweg Profiles of the Lower River.

(The size gradations listed in the legend are for the upstream sediment supply and the initial bed materials.)



2. Final long-term model results — Figure 41 shows the predicted long-term coarse sediment impacts resulting from concurrent removal of both Glines Canyon and Elwha Dams. The thalweg and 100-year-flood water surface profiles for both the initial (existing) conditions and the after 53 years of simulation are shown in this figure. This simulation was performed using the 3 years of hydrologic scenario 3 (during sediment erosion from both reservoirs), followed by 50 years of historic flow and natural sediment supply with sizes limited to fine gravel. The amount of riverbed aggradation in the upstream end of the modeled reach (RM 4 to 5) was greater after the short term (3 years) than after the long term (53 years). Downstream from RM 4, the amount of riverbed aggradation is greater over the long term than the short term. The amount of riverbed aggradation (excluding the 0.1 mile below Elwha Dam) ranged from almost zero at some cross sections to 9.6 feet near RM 3.4. This resulted in increases in 100-year-flood elevations from zero at some cross sections to 5.5 feet at RM 1.05 — with an average increase of 2.7 feet. Long-term model results indicate that without mitigation the existing Federal levee would be overtopped by nearly 2 feet at RM 0.8 but not all locations upstream. Long-term aggradation values for the entire lower reach and impacts to the 100-year-flood water surface elevations are presented in table 26.

Figure 41. HEC-6 Long-term Model Results.
(Comparison of existing channel thalweg and water surface profiles, corresponding to the 100-year flood, with conditions after 53 years.)



D. DISCUSSION

The HEC-6 modeling results for the lower reach provide useful information on the effects of dam removal and sediment release on riverbed aggradation and corresponding increases in river stages. Model results presented in this report agree well with those reported by the Corps (R. Copeland and B. Hall, Corps, Waterways Experiment Station, Vicksburg, MS, written communication, 1995).

In both model studies, the assumption was made that all of the coarse sediment released from Lake Mills would immediately be transported to Lake Aldwell. Sediment deposition and storage in the middle reach were ignored. However, this assumption has some validity as a comparison of channel transport capacity through the middle reach suggest that minimal deposition may occur (chapter IX). HEC-6 model simulations included factors that tend to under-predict the amount of coarse sediment transport and over-predict the amount of riverbed aggradation and corresponding increases in flood stage.

1. Aggradation — During riverbed aggradation, channel characteristics (such as slope, shape, and roughness) would change so that the river's sediment transport capacity is increased. Although, the HEC-6 model can simulate aggradation and degradation by vertical changes in channel elevation, it cannot simulate channel migration or changes in channel width. The model assumes that channel roughness and length are constant throughout the simulation. In reality, channel roughness and length (slope) would increase or decrease so that the sediment transport capacity of the channel would more closely match the sediment supply rate from upstream. HEC-6 does account for slope changes resulting from aggradation or degradation through a reach, but does not account for changes (increases or decreases) in roughness or slope caused by channel migration, bank erosion, or width changes.

2. Sediment — Fine sediment was not modeled because it would not be representative of the bed material. However, high sediment concentrations (greater than 10,000 ppm) that would occur periodically during dam removal would tend to increase coarse sediment transport capacity because of the increased density and viscosity of the water-sediment mixture.

Most of the predicted aggradation was from gravel-size sediment. This was the case when using either the combined Meyer-Peter and Müller or Yang sediment transport equations. The Yang transport equations are applicable for both sand and gravel and are thought to have more general application to a variety of rivers than the combined Meyer-Peter and Müller equations. However, the Yang gravel-transport equation is only calibrated for particle sizes up to 10 mm, which includes only very-fine and fine gravel. The present ability to accurately predict the transport of coarser gravels and cobbles is very limited. When coarse gravel and cobbles were simulated, model results predicted large amounts of deposition in the first mile of river downstream from Elwha Dam — which includes a steep bedrock canyon reach. When coarse sediment sizes were limited to fine gravel (8 mm), model results predicted about the same amount of total aggradation, but more uniform deposition throughout the lower reach. Therefore, the decision was made to lump the fraction of sediment coarser than fine gravel into the fine gravel range (4 to 8 mm) for the final short- and long-term simulations.

The model simulations described in this report, as well as those performed by the Corps, predicted short-term aggradation of the lower Elwha River as a result of reservoir sediment release and continued aggradation over the long term as a result of restoring the river's natural sediment supply. Long-term aggradation would occur if the lower river channel and floodplains functioned as an aggrading alluvial fan prior to construction of the dams. In this case, aggradation would occur over the short term because of sediment release from the reservoirs and continue over the long term with

restoration of the natural sediment supply. Growth of the river delta below sea level would be controlled by the currents in the Strait. Although, the water surface elevation and tides of the Strait would hydraulically control aggradation at the mouth, the river would be free to aggrade upstream to the high-velocity, bedrock canyon reach below Elwha Dam.

As aggradation occurs over the long term, channel migration would be more frequent than under existing conditions. The main river channel would migrate across the one-mile-wide floodplain near the mouth. However, long-term aggradation could not continue indefinitely under present hydrologic and sediment yield conditions. This is because river slope and sediment transport capacity would increase with continued aggradation until equilibrium conditions were established. Long-term aggradation would occur until the channel configuration establishes an equilibrium condition in keeping with the increased (natural) sediment supply. HEC-6 model results do indicate a trend of decreasing aggradation rates with time, which suggest that the river channel would eventually reach an equilibrium condition. The time required to reach equilibrium is not known but could be estimated from future monitoring data after dam removal.

PART IV

CONCLUSIONS

CHAPTER XI. CONCLUSIONS

With monitoring and mitigation, the River Erosion Alternative constitutes a viable sediment management plan for the removal of Glines Canyon and Elwha Dams. Computer model results indicate that the proposed rate of dam removal (chapter III) would not lead to excessive aggradation of the riverbed downstream (chapters IX and X). However, mitigation would be needed for increases in river stage and fine sediment concentration. Extensive monitoring and control of the dam removal rate is needed to avoid unforeseen problems with riverbed aggradation, flooding, and water quality.

Specific conclusions for the erosion, redistribution, and downstream release of reservoir sediment are presented first followed by conclusions regarding the downstream river channel.

A. RESERVOIR SEDIMENT

Conclusions regarding reservoir sediment are organized by project phase: initial and final stages of dam removal and lake drawdown, and the post dam removal phase. During the initial stages of dam removal and lake drawdown, coarse sediment of the lake deltas would progressively erode and redeposit toward the dam while fine sediment would be re-suspended and mixed with the lake water. During the final stages of dam removal, the remaining lake volume would be completely filled with sediment and coarse sediment would be released downstream. In the post dam removal phase, the river would have eroded channels through the reservoir sediment down to the predam alluvium but these erosion channels would continue to erode laterally during floods over the short term.

Because both reservoirs are about 10 times wider than the Elwha River channel, most of the reservoir sediment would remain in the area of the former reservoirs and would be stable over the long term. Currently, fine (clay- and silt-sized) sediments are primarily stored along the lakebed of each reservoir while coarse sediments (sand, gravel, and cobbles) are primarily stored as delta deposits at the upstream ends of each lake. Elwha Reservoir model results (chapter VIII) indicate that about half of the fine sediment (5 myd³) would be eroded from the reservoirs and transported in suspension to the Strait of Juan de Fuca. Maximum concentrations of fine sediment would be tens of thousands of ppm (10,000–50,000 ppm). From 15 to 35 percent (1.2–3.0 myd³) of the total coarse sediment in both reservoirs is expected to be eroded and transported downstream as bed load. The remaining sediment would be left behind as terraces along the reservoir margins and would be stable over the long term. Some regrading of these terraces may be desirable.

Extensive monitoring of sediment erosion, redeposition, and transport through the reservoirs and sediment transport and deposition through the river channels downstream is critical to the success of the sediment management plan. Sediment monitoring activities should consist of stream gauging, repeat cross section surveys, and repeat photography (both ground and aerial).

The rate of sediment release can be controlled by controlling the rate of dam removal and lake drawdown. However, sediment release downstream would not immediately stop after temporarily halting dam removal. In order to control downstream impacts, the rate of dam removal should take into account the erosion channel slope and width, coarse and fine sediment release rates, and lake inflow. Depending on monitoring results and additional analysis, the rate of dam removal (or lake

drawdown) may need to be reduced during periods of low riverflow to avoid or reduce channel aggradation downstream (based on modeling and judgement).

1. Initial dam removal and lake drawdown (Phase 1) — As the dams are removed in controlled increments, coarse delta sediment would be progressively eroded and redeposited downstream over the fine lakebed sediment. During each new increment of dam removal, the river would incise channels through the deltas. The river would widen these channels while the reservoirs are held at a constant elevation in preparation for the next increment of dam removal. Additional channel incision and widening would occur during periods of high lake inflow when dam removal increments are temporarily halted. Before being transported downstream, delta sediment would fill in behind the partially removed dams (60–70 feet thick behind Glines Canyon Dam and 30–40 feet thick behind Elwha Dam). Peak rates of sediment release from the reservoirs would coincide with each new dam removal increment.

Drawing the lakes down a certain increment and holding them at a constant elevation would result in both vertical and lateral erosion of the reservoir sediment (based on results from the Lake Mills drawdown experiments). Erosion channels would form that would erode and redeposit coarse sediment (sand size and coarser) immediately downstream from the delta front. Vertical erosion (caused by head cutting) would result from the lower lake level. Eroded coarse sediment would deposit at the mouths of the erosion channels. The channels would then erode laterally to reach the deeper areas of the lake. The lateral erosion would increase (at a parabolic rate) with distance downstream to a maximum width where the erosion channels enter the receded lake. The total erosion width would equal the reservoir width at the delta front if the lake elevation is held constant for a long enough period. The entire delta front would be extended downstream and erosion rates would rapidly reduce.

The eroded coarse sediment would deposit on top of the existing lakebed sediment (based on professional judgement and the experience gained from the 1994 Lake Mills drawdown test). Although some mixing of the delta and lakebed sediment would occur, a layer of predominately coarse sediment would cover a layer of predominately fine sediment.

Only a portion of the coarse reservoir sediment would be eroded during each drawdown increment and only a portion of the eroded sediment would reach the dam and be transported downstream (based on computer model results from chapter VIII). Because of head cutting, armor layers would not initially prevent erosion of underlying sediment during lake drawdown. However, as the erosion process continues, armor layers may slow coarse sediment erosion rates. Large woody debris would not be expected to prevent or slow sediment erosion rates, redistribution within the reservoir, or release downstream (based on observations during the 1994 Lake Mills drawdown test).

The eroded fine sediment would be suspended in the lake. Concentrations of suspended sediment would increase with depth due to settling of the particles. Suspended sediment of a lower concentration near the lake surface would be released with lake outflow (based on results from the 1994 Lake Mills drawdown experiment). Concentrations of suspended sediment in the lake would increase with time as the lake volume decreased and the volume of fine-sediment erosion increased (based on computer model results described in chapter VIII). After the first few increments of dam removal, fine sediment concentrations released from the reservoirs would be high during periods of dam removal — typically 200–1,000 ppm, but occasionally as high as 30,000–50,000 ppm (1–3 days). Release concentrations would be relatively low — less than 200 ppm — during periods of high lake inflow during which dam removal activities would stop.

2. Final dam removal (Phases 2 and 3) — Both coarse and fine sediment would be released downstream with continued increments of dam removal. With each increment of dam removal, a head cut of some initial width would rapidly migrate upstream followed by lateral erosion (channel widening). Sediment release rates past the dam site would be high after each notch opening in the dam and then decrease exponentially with time (based on HEC-6 model results; see chapter VII, section C). Coarse-sediment release rates would be high until the river channels had cut through the overlying layers of coarse sediment. Armor layers may develop which could temporarily stop or slow vertical erosion and may cause some additional lateral erosion (based on judgement).

The coarse-sediment-release rate from the dam (based on modeling results and judgement) would be a function of:

- Dam-removal increment or height of notch opening;
- Time between notch openings;
- Lake inflow;
- Channel erosion slope and velocity;
- Sediment particle size; and
- Upstream sediment supply rate.

Fine-sediment release rates would be high until the river channels had cut through the fine sediment layers down to the predam alluvium (based on Elwha Reservoir model results; see chapter VII).

3. Post dam removal (Phase 4) —The river would erode down to predam alluvium following the last phase of dam removal. The natural sediment load, originating upstream from Lake Mills, would be added to the reservoir sediment, eroded from Lake Mills and Lake Aldwell, and released into the downstream river channel. Relatively little reservoir sediment would be released during low flow periods and the amount of coarse and fine sediment released downstream would approximately equal the upstream sediment supply. Additional release of reservoir sediment would occur due to channel widening during floodflows. After the first floodflow, significant channel widening would only occur during subsequently higher floodflows. Terraces of the remaining reservoir sediment would resemble the predam landscape.

Erosion and transport of reservoir sediment downstream from the damsite are highly dependent on the magnitude and sequence of floodflows. In general, the amount of reservoir sediment eroded during floodflows would be expected to decrease exponentially with time (based on Toutle River measurements {Smillie and Jackson, 1995} and Elwha Reservoir model results, see chapter VIII). Reservoir sediment erosion rates would be initially high with the first floodflow following dam removal. Subsequent floodflows of progressively greater magnitude would be expected to cause additional channel widening but the volume of sediment erosion would tend to decrease with each floodflow. Beyond about five years after dam removal, sediment rates transported past the former dam sites would revert back to the natural, predam conditions.

B. DOWNSTREAM RIVER CHANNEL

Fine sediment concentrations in the middle and lower reaches would be essentially the same as the concentrations released from the reservoirs. Fine sediment deposition would only occur in very-slow-velocity areas such as channel floodplains, islands, pools, and in the Strait of Juan de Fuca.

In general, coarse-sediment transport capacity of the middle reach would be higher than the expected sediment erosion rates from the Lake Mills. Riverbed aggradation is not expected to increase water surface elevation by more than 0.5 feet (chapter IX). However, greater amounts of riverbed aggradation are possible. The HEC-6 model was not applied to the middle reach. However, the Corps (1996) estimated, as an upper limit, that 100-year flood water surface elevations may increase an average of about 1.5 feet and by as much as 2.5 feet in some areas over the long term after the dams are removed.

Coarse sediment transport capacity of the lower reach is less than the middle reach and localized riverbed aggradation would be expected to occur during and immediately following dam removal. Sand-size and finer sediment would readily be transported through the reach but gravel-size and coarser sediment would move much more slowly and locally aggrade the riverbed in low-velocity areas. General aggradation could continue in the lower reach over the long term. This could result in an increase in the river stage (over 50 years) between 0–5 feet during the 100-year flood, with an average increase of about 2.5 feet. Short-term riverbed aggradation would vary between almost zero at some locations to 9 feet in the pool at RM 3.6. This would increase river stages of the 100-year flood from almost zero at some locations to 2–3 feet at RM 3.6, with an average increase of less than 1 foot (chapter X).

The maximum rate of coarse sediment transport to the Strait of Juan de Fuca would equal the limiting transport capacity of the lower reach (figure 38).

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PEER REVIEW SHEET

Elwha River Ecosystem and Fisheries Restoration Project, Washington

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Document ID Number: U.S. Bureau of Reclamation ETS-PN-95-9

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Study Manager: Robert J. Hamilton, Pacific Northwest Regional Office, Boise, Idaho (PN-6306)

The study documented by this report was performed by hydraulic engineers of the Sedimentation and River Hydraulics Group (D-8540), Technical Service Center, Denver, Colorado, under the direction of Timothy J. Randle. The principal authors of each chapter are presented in the table below:

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1. Introduction	Timothy J. Randle
2. Sediment Management Issues	Timothy J. Randle
3. River Erosion Alternative	Timothy J. Randle
4. Qualitative Assessment	Timothy J. Randle
5. Data Collection	Timothy J. Randle and James T. Melena
6. Initial Sediment Analysis and Modeling for Lake Mills	Elizabeth M. Ouellette and Christi A. Young
7. Elwha Reservoir Sediment Model	Timothy J. Randle
8. Coarse Sediment Transport Capacity	James T. Melena
9. HEC-6 Sediment Transport Modeling	Christi A. Young
10. Conclusions	Timothy J. Randle
Appendix A. Hydrographic Survey Equipment and Method	James T. Melena
Appendix B. Elwha River Mean Daily Peak Discharge at McDonald Bridge	Timothy J. Randle
Appendix C. Sediment Concentrations Released from Lake Mills During Removal of Glines Canyon Dam	Timothy J. Randle
Appendix D. Sediment Concentrations Released from Lake Mills and Lake Aldwell During Concurrent Dam Removal	Timothy J. Randle

Peer Review

The draft document, dated November, 14, 1995, was sent to several technical specialists for peer review. Comments were received from most of these individuals. Many very helpful and constructive comments were provided and nearly all of these were incorporated into the final draft submitted to the Regional Office. Technical peer review comments were received from the following individuals:

Mr. Joseph Lyons, U.S. Bureau of Reclamation, Technical Service Center, Denver, Colorado
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Reclamation Peer Reviewer: I have reviewed the assigned Sections/Chapters noted for the above document and believe them to be in accordance with the project requirements, standards of the profession, and Reclamation policy.

Reviewer: _____ Date: _____
(Joseph K. Lyons)

Authors: I have discussed the above document and review requirements with the Peer Reviewer(s) and believe that this review is completed, and that the document will meet the requirements of the project.

Team Member: _____ Date: _____
(Timothy J. Randle)

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