ELWHA RIVER RESTORATION: SEDIMENT ADAPTIVE MANAGEMENT

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Abstract The U.S. Department of the Interior plans to remove Elwha and Glines Canyon Dams on the Elwha River near Port Angeles, Washington to restore anadromous fish and the natural ecosystem. Elwha Dam was completed in 1913 and forms Lake Aldwell. Glines Canyon Dam was completed in 1927 and forms Lake Mills. These dams will be removed in controlled increments over a two to three-year period, beginning in 2011. During the middle of dam removal, reservoir sedimentation is projected to be 21 million yd^3. The sediment release impact period associated with dam removal is anticipated to last 3 to 5 years.

The sediment effects of dam removal have been predicted based on the 1994 Lake Mills Drawdown Experiment, numerical modeling, and physical laboratory modeling. These predictions have been used to help design mitigation measures for water quality and flood protection, including water treatment plants, new wells, a new surface water intake, raising the height of existing levees, and the construction of new levees.

These two dams will be the largest removed in North America. Although there is convergence in the predictions from field tests, numerical modeling, and physical modeling there is still uncertainty. An adaptive management plan for sediment has been developed to reduce uncertainty of the predicted results and ensure that the planned mitigations work properly.

The adaptive management plan relies on real-time monitoring to verify if actual results agree with predictions within a certain tolerance. If necessary, additional actions would be taken to ensure that sediment impacts remain at an acceptable level. Localized impacts would be identified and treated locally where necessary. System wide impacts would be addressed by slowing or temporarily halting dam removal until impacts have reduced to tolerable levels.

Monitoring would initially focus on the sediment erosion within the two reservoirs and on turbidity downstream from the two dams. Measures would be taken to ensure that the reservoir deltas are not incised by a single erosion channel along the reservoir margin. If necessary, delta erosion channels would be encouraged to erode and redistribute the delta sediments within each reservoir at the pace of dam removal. This will help ensure that sediments still in the reservoir after dam removal will be left in a stable condition. Monitoring of downstream riverbed aggradation would begin once sand and gravel-sized sediment have eroded from the reservoirs.

INTRODUCTION

The Elwha River is located in northwest Washington State, on the Olympic Peninsula and west of Port Angeles. The Elwha River Restoration Project calls for the removal of Elwha and Glines Canyon Dams (Figure 1) to restore the Elwha River ecosystem and native anadromous fisheries in a safe, environmentally sound, and cost-effective manner. The river erosion alternative was selected by the Secretary of the Interior to manage the nearly 18 million yds^3 of reservoir sediment

that were be trapped behind the two dams in 1994 (Gilbert and Link, 1995; Olympic National Park (ONP), 1996; and U.S. Department of the Interior (DOI), 1997). The total reservoir sedimentation volume is expected to increase to 21 million yds^3 by the middle of dam removal in 2012. Under the river erosion alternative, it is predicted that, depending on river flows, about one-quarter to one-third of the coarse sediment (sand and gravel) and about one-half to two-thirds of the fine sediment (silt and clay) will be eroded by the river during dam removal (Randle et al., 1996 and Randle, 2002). The eroded sediment would be subsequently transported downstream from the two reservoirs by the Elwha River to the sea with some deposition along the way. The sediment release impact period associated with dam removal is anticipated to last 3 to 5 years.

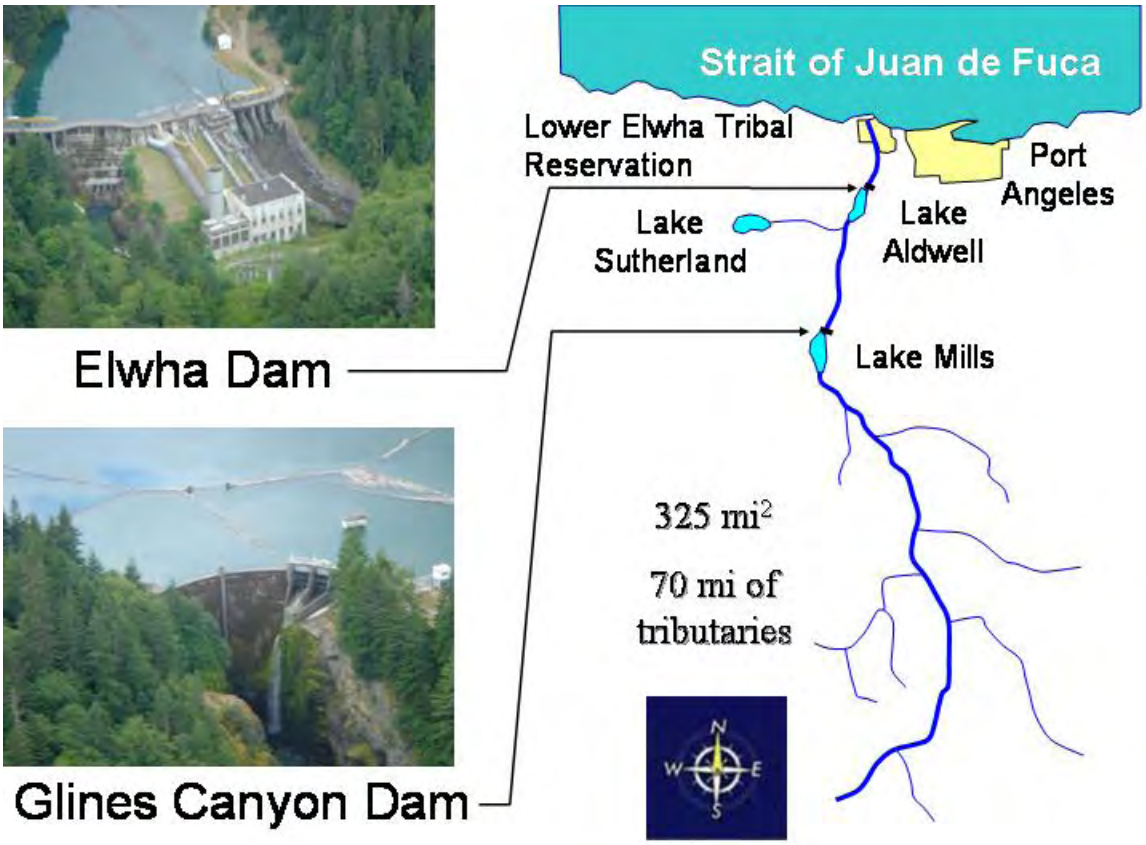

Figure 1 Elwha and Glines Canyon Dams are located on the Elwha River near Port Angeles, Washington, U.S.A.

The river erosion alternative required the construction of mitigation measures, prior to dam removal, to address predicted impacts to downstream water users from the release of fine sediment carried in suspension. Mitigation was also required to address potential impacts to downstream flood stages from the deposition of coarse sediment on the river bed (aggradation). Additionally, planned reservoir hold periods (1½ to 2 months) were incorporated into the dam removal plan to limit the release of reservoir sediments into the downstream river during critical fish usage periods. These reservoir hold periods are referred to as fish windows.

An adaptive management program is planned to ensure that Elwha River Restoration Project (Project) management objectives are met and that sediment impacts are contained by mitigation

measures. This implementation plan describes the critical components needed to accomplish the adaptive management program.

PROGRAM OVERVIEW

The fundamental motivation for using adaptive management is to reduce uncertainty. This occurs by promoting flexible decision making that can be adjusted as outcomes from previous management actions and other events become better understood (Williams et al, 2007). Monitoring data are a necessary component to measure river responses and whether management actions are working and meeting objectives. If objectives are not being met, then the focus would shift on determining why not and how existing actions should be modified or new actions implemented to achieve those objectives. For the Elwha River Restoration Project (Project), monitoring tasks were developed that can be conducted in a "real-time" operational mode for rapid decision making during the dam-removal process. There may be a need to modify the decision criteria, or add new criteria, as more information becomes available. These decision criteria are based on the best available information prior to dam removal, which includes the following key technical evaluations:

- 1994 Lake Mills Drawdown Experiment in Lake Mills (Childers et al, 2000),
- sediment transport modeling conducted for the EIS (Randle et al, 1996 and Randle, 2002),
- hydraulic modeling conducted to evaluate potential flood impacts (Corum, 2003), and
- physical modeling of Lake Mills drawdown and delta erosion (Bromley, 2006).

Management Objectives Once the removal of Elwha and Glines Canyon Dams begin, the monitoring program will be used to help ensure that sediment management objectives established by the National Park Service are being achieved (ONP, 1996 and U.S. DOI, 1997). Key sediment management objectives for adaptive management are listed below:

1. Dam removal should occur fast enough to minimize the duration of sediment impacts to the aquatic environment, but slow enough so that impacts to downstream water users and property owners are not substantial or they can be mitigated.

2. Reservoir delta sediments should be eroded and redistributed so that the resulting topography is stable and consistent with natural landscapes. In addition, reservoir sediment erosion and redistribution should keep pace with the rate of reservoir drawdown so that sediments are not left behind in an unstable condition following dam removal which could cause large and uncontrolled releases of sediment to the river.

3. High suspended sediment concentrations should be mitigated for water users by the efficient operation of downstream water treatment facilities.

4. Sediment deposition along the river channel should not increase the 100-year flood stage beyond 2.5 feet for the lower river (downstream from Elwha Dam) and 1.5 feet for the middle river reach (between the two reservoirs).

5. Sediment concentrations can be treated at the Elwha Water Treatment Plant to meet water quality standards.

6. Adequate water clarity should be maintained in the Elwha River and estuary for fish migration during critical migration periods.

7. Large landslides along the reservoirs or the release of flood waves are avoided by limiting the rates of reservoir drawdown.

Adaptive Management Decision Trees Data from each monitoring activity has a critical link to determining if management objectives are being met, if not, why not, and what contingency measures will be needed. Localized flooding problems that might occur during dam removal will be identified, but the dam-removal schedule would not be affected. National Park Service Managers will determine if the Project needs to take any local corrective actions. System-wide aggradation problems would be addressed by temporarily halting reservoir drawdown for a period of days or weeks until river discharge has reduced the aggradation to acceptable levels.

Adaptive Management is primarily focused on the three-year period during dam removal. In addition, post dam removal monitoring activities are included to identify when sediment conditions downstream from the former dams are at near normal conditions. A monitoring and adaptive management decision tree is presented in Figure 2.

RESERVOIR SEDIMENT MANAGEMENT

The first and most critical stage of adaptive management of sediment begins by controlling the increment and duration of reservoir drawdowns in Lake Mills and Lake Aldwell. An important objective of the sediment management program is to erode and redistribute delta sediments downstream and along the reservoir valley so that the resulting reservoir topography is stable and consistent with natural landscapes. In addition, the redistribution of coarse sediments will cover the finer lakebed sediments and provide more suitable substrate for new woody vegetation to grow. The erosion and redistribution of reservoir delta sediment needs to keep pace with reservoir drawdown so that reservoir sediments are not left behind in an unstable condition after dam removal that could cause large and uncontrolled sediment releases to the downstream river.

Most of the coarse reservoir sediment (88 percent) is presently in the upstream reservoir, Lake Mills (Figure 3). The thickest delta deposit, measured from drill holes, was 70.5 feet in Lake Mills and 42.6 feet in Lake Aldwell (Gilbert and Link, 1995). Therefore, the primary adaptive management focus will be on the Lake Mills delta during the first 50 to 70 feet of reservoir drawdown. Additional monitoring will be conducted at Lake Aldwell to monitor the potential movement of landslides, manage the reservoir sediment in that reservoir, and sediment being transported through Lake Aldwell from Lake Mills.

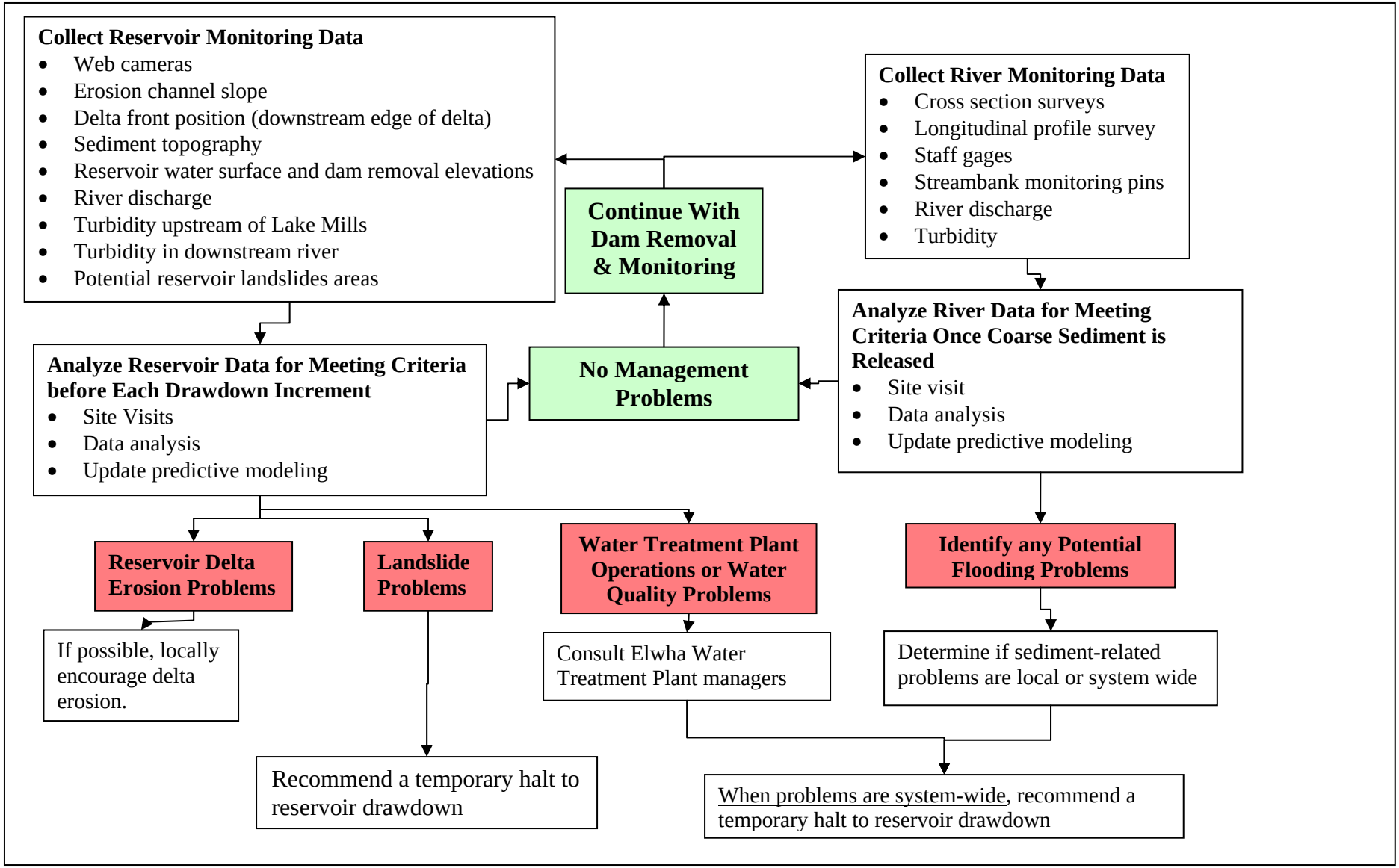

Figure 2 Adaptive management decision tree during dam removal to determine if management objectives are being met, and if not, what contingency actions are required.

Figure 3 2009 aerial photograph of Lake Mills delta (left) and Lake Aldwell delta (right).

Reservoir Sediment Erosion Processes Initially, reservoir drawdown associated with dam removal will result in the erosion of the exposed delta surface. As long as a reservoir pool remains between the delta and the dam, eroded coarse delta sediments (sand and gravel) will re-deposit across the width of the receded reservoir (Figures 4 and 5). Fine sediment (silt and clay) that is eroded will go into suspension and some may be released from the reservoir. Initially, the mass of fine sediment eroded from the delta surface will be small and the eroded fine sediment will mix with a large reservoir, so the sediment concentration released downstream would be initially small. As reservoir drawdown progresses, larger quantities of fine sediment will be exposed and eroded. Over time, larger volumes of eroded fine sediment will mix with a smaller reservoir. Therefore, concentrations of fine suspended sediment released from the reservoir will increase substantially over time and will vary with river discharge.

Figure 4 During the early part of the 1994 Lake Mills drawdown experiment, two lobes of eroded delta sediment had re-deposited at the downstream end of each erosion channel.

Figure 5 By the end of the 1994 drawdown experiment, the volume of eroded sediments was enough to deposit a new delta across the entire width of the receded reservoir.

Reservoir Sediment Monitoring and Adaptive Management During the initial reservoir drawdown, monitoring activities will focus on river erosion through the upstream deltas and the downstream advancement of the delta front (Figure 6). Monitoring tasks will include reservoir surveys, site investigations of the extent, slope, and erosion areas of the eroding delta, reservoir

elevation levels, turbidity, and river discharge. Web cameras will be used that can relay real-time photographs to a website at intervals between 15 minutes and 2 hours. The plan is to install web cameras overlooking each reservoir to continuously monitor the sediment erosion and redistribution during dam removal and the reservoir drawdown. Web cameras would also be installed to monitor the removal of each dam.

Figure 6 The eroding banks of the delta remained steep during the 1994 Lake Mills drawdown experiment.

As of 2009, the total flow entering Lake Mills is largely being captured by one channel along the right margin of the delta (Figure 3). This right channel has become perched and is currently higher than the delta surface to the left (west). Large woody debris has also formed a log revetment along the forest edge and left bank of this perched, right delta channel (Figure 7). Physical model experiments (Bromley, 2006) suggest that if one channel incises along the reservoir margin and captures the entire river flow, there is a risk that a large portion of the delta will be left in place during reservoir drawdown (Figure 8). In addition, a large log jam is present at the upstream end of the delta, which limits the amount of river flow that can enter the left delta channel. In recent years, a dense alder forest has also grown on the delta that may limit the erosion of the delta surface (Figure 3). Without intervention on the Lake Mills delta, the dominant conveyance of the right delta channel, the dense and extensive alder forest, and log revetment along the right channel will likely inhibit lateral erosion of the delta. A large portion of the delta left in place after dam removal would result in either a very unnatural landscape in the former reservoir or the potential for uncontrolled reservoir sediment erosion after dam removal. Therefore, work to breach the log revetment and clear trees along the alignment of a pilot erosion channel began during February 2010. Additional monitoring is needed to determine if mechanized equipment will be needed to fully establish the pilot erosion channel.

After the top half to two-thirds of each dam has been removed, the volume of eroding delta sediments may be sufficient to reach the dam and the reservoir pool will become completely filled in with sediment (Randle et al., 1996). The top elevation of sediment deposits against the dam depends on the volume of reservoir sediment that is eroded and the longitudinal slope of the erosion channels through the reservoir sediment. A critical reservoir elevation is reached when the remaining reservoir water storage volume would just contain all of the exposed reservoir sediments above the critical elevation. As long as the reservoir water surface remains above the critical elevation, no coarse sediments could be eroded from the reservoir, even if all the exposed

reservoir sediments were to erode and enter the receded reservoir. The critical reservoir elevation is conservative and overestimates the actual reservoir elevation where coarse sediments could be released past the dam. This is because not all the exposed reservoir sediments would erode and the exposed sediments would not erode to a level elevation. Continued dam removal and reservoir drawdown below the critical elevation will eventually result in the downstream release of coarse sediment past the dam.

Figure 7 Large woody debris has formed a log revetment on the Lake Mills delta along the forest edge and left bank of the right channel.

Figure 8 Photographs of the Lake Mills laboratory model (Bromley, 2006) show extensive delta erosion when river erosion occurred down the middle of the delta (left photograph). However, a large portion of the delta sediments were left un-eroded (and in an unstable condition) when one erosion channel was allowed to capture all the flow and erode along the reservoir margin.

When reservoir drawdown reaches the critical elevation, topographic and bathymetric surveys will be conducted at each reservoir. These surveys will measure the volume of reservoir sediments that have eroded and assess the stability of the exposed sediments in the reservoir area. The survey results will help determine if reservoir sediment erosion is keeping pace with dam removal and reservoir drawdown. If the rate of dam removal is too fast, an uncontrolled sediment release from the reservoir could occur, especially after dam removal. Dam removal below the critical elevation will trigger an important stage of monitoring to ensure that uncontrolled sediment releases do not occur that could cause excessive aggradation of the river bed and a resulting large increase in flood stage.

RIVER AGGRADATION AND FLOOD STAGE

Once coarse sediments are released from the dams, monitoring activities would be initiated that track the downstream progression of first coarse sediment wave. The frequency of these tasks will depend on the speed of the coarse sediment wave once it is released from the reservoir.

Of the 11 million yd^3 of silt and clay-sized sediment in the two reservoirs, one-half to two-thirds is expected to erode and be transported into the downstream river channel. Significant aggradation of the downstream river channel is not expected to occur from these fine sediments. Of the 10 million yd^3 of coarse sediments in the reservoir deltas (sand, gravel, and cobble), about one-quarter to one-third is expected to erode and be transported into the downstream river channel. Sand alone is not expected to aggrade the downstream river channel and significantly increase flood stage. However, gravel and cobble-sized sediments, with some sand, do have the potential to deposit along the river channel and increase flood stage, if they are released at too fast a rate from the upstream reservoirs. Deposition is expected to largely occur in river pools, side channels, eddies (recirculation zones), and floodplain edges along the river channel.

Monitoring of riverbed aggradation and the potential increase in flood stage would begin once coarse sediments are released from the either reservoir. Monitoring will be conducted using a combination of stage recorders, channel cross-section surveys, and longitudinal profile surveys. In the downstream two to three miles of the Elwha River, the channel has historically migrated across the floodplain. In addition, the channel has become more sinuous due to the decreased sediment supply. As coarse sediment is introduced from the eroding deltas, the river is expected to become straighter along this downstream reach. A one-dimensional hydraulic model (HEC-RAS) was applied to the Elwha River for flood impact analysis by the U.S. Army Corps of Engineers (Corum, 2003). This model will be updated annually, using the latest available river channel survey data, to identify any effects on flood stage. Use of the latest survey data in the HEC-RAS model will account for changes in river channel alignment, longitudinal slope, width, and bed elevation.

WATER QUALITY

The suspended sediment concentrations and turbidity resulting from dam removal are, at times, expected to exceed 10,000 ppm. Short term impacts from high suspended sediment concentrations are thought to be outweighed by the long-term benefits of habitat restoration. Fish windows are designed to reduce suspended sediment concentrations during critical periods for fish. Therefore, the focus of water quality monitoring and adaptive management is on protecting the municipal and industrial water supply.

A new Elwha Water Treatment Plant, at river mile (RM) 3.3, has been constructed to supplement new and upgraded municipal and industrial water treatment facilities. The new Elwha Water Treatment Plant will treat raw river water with high suspended sediment concentrations (up to 40,000 ppm) during the sediment impact release period. Based on predictive modeling, peak suspended sediment concentrations may occasionally exceed 10,000 ppm for a few days; the highest numerical model prediction was 40,000 ppm (Randle et al, 1996 and Randle, 2002). The

treatment plant must be able to provide adequate water for existing municipal and industrial users during the dam removal period.

Monitoring will include the continuous measurement of turbidity near the new surface water diversion structure to (RM 3.2) and upstream from Lake Mills (RM 15). River stage and discharge will be continuously measured at the long-term USGS gaging station at McDonald Bridge (RM 8.7). A predictive model will be periodically updated as new reservoir and water quality monitoring data is collected. The continuous measurement of turbidity downstream from Elwha Dam and predictive model results can be used to anticipate operational needs at the Elwha Water Treatment Plant. The measurement of turbidity, rather than suspended sediment concentration, is planned because of lower anticipated cost, greater expected feasibility, and permit requirements.

ADAPTIVE MANAGEMENT DECISION CRITERIA

The following questions would be answered before each 15-foot increment of reservoir drawdown is initiated (see Figure 2). The questions would be answered using results from the reservoir, river aggradation and flood stage, and water quality monitoring activities. If no concerns are identified by answers to any of the questions, then the Project would proceed with the next increment of dam removal and reservoir drawdown. If concerns are identified, then a recommendation on sediment issues would be made prior to the next reservoir drawdown:

(1) Is there any evidence of landslide movement along and above the reservoir shoreline?
- If yes, then recommend a temporary halt to reservoir drawdown while investigating the cause and extent of landside movement.

(2) Are there at least two alluvial (erodible) banks along the entire length of the one or more delta erosion channels?
- If no, then recommend a strategy for flow diversion measures at the upstream end of the delta so that there are at least two erodible banks or two active erosion channels.

(3) Before the eroding delta front has reached the dam, have delta sediments deposited across at least 80 percent of the receded reservoir width during the last reservoir drawdown increment?
- If no, then determine if erosion of the delta has reduced to a negligible rate.
  - If vertical or lateral delta erosion is continuing at a significant rate (feet per day vertically or tens of feet per day laterally), then recommend holding the reservoir water surface constant until the eroding delta sediments have deposited across the width of the receded reservoir.
  - If erosion of the delta has stopped, then determine why.
    - If delta erosion has stopped because of low river discharge and channel bed armoring, then proceed with another increment of reservoir drawdown.
    - If delta erosion has stopped and there is only one erosion channel or the banks have become armored by cobbles, trees, or large woody debris, then divert flow at the upstream end of the delta to activate another erosion channel.

(4) Is the longitudinal slope, of the primary delta erosion channel, remaining relatively constant over time and have headcuts reached the upstream end of the delta within Rica Canyon?
- If the longitudinal erosion slope has become significantly steeper over two consecutive reservoir drawdowns, then determine by inspection if the vertical incision of the delta has stopped and, if so, recommend one of following actions:
  - If vertical incision is continuing, then recommend holding the reservoir water surface constant until the longitudinal erosion slope has reached equilibrium.
  - If vertical incision has stopped, then recommend trying to break up the channel-bed armor layer with pumps, hoses, and nozzles. If the bed is heavily armored with multiple layers of coarse material, then proceed with reservoir drawdown and continue monitoring.

(5) Are all islands of exposed reservoir delta less than 30 feet higher than the surrounding channel incision?
- If no, determine if the islands greater than 30 ft high are actively eroding.
  - If high delta islands are actively eroding, then recommend holding the reservoir constant while monitoring the continued island erosion.
  - If high delta islands are not actively eroding and they are not likely to erode during the next month, then recommend holding the reservoir water surface while eroding the high islands with high pressure hoses.

(6) Are forecasted suspended sediment concentrations beginning to approach the capabilities of the downstream water treatment plant?
- Before sediment concentrations could ever be allowed to approach the limits of the Elwha Water Treatment Plant, the Project would have to temporarily halt drawdown of both Lake Mills and Lake Aldwell to ensure that sediment concentrations can be treated to an acceptable level.

(7) Is downstream river-bed aggradation beginning to cause a potential increase in the 100-year flood stage that would exceed the limits of flood control protection measures?
- If yes, then increase the monitoring frequency of the downstream channel and consider slowing the rate of dam removal.

(8) Are there bank erosion or flooding problems?
- If bank erosion or flooding problems are observed, then determine if the problems are a local problem or part of a larger system-wide problem. Localized problems would only be treated locally. System-wide problems would be addressed by slowing or temporarily halting the rate reservoir drawdown.

CONCLUSIONS

The sediment impacts resulting from the removal of Glines Canyon and Elwha Dams have been predicted from field experiments, physical modeling, and numerical modeling. Based on these predictions, the magnitude of downstream sediment impacts can be accommodated by controlling the rate of dam removal and reservoir drawdown and by constructing or upgrading

water treatment facilities and flood-control levees. However, there is still uncertainty in these predictions. Therefore, a monitoring and adaptive management plan has been designed to reduce this uncertainty and take corrective actions when and where necessary during the project implementation. An adaptive management goal is to insure that the reservoir sediment erosion keeps pace with the rate of reservoir drawdown so that large volumes of unstable reservoir sediment do not erode from the former reservoirs after dam removal.

Adaptive management monitoring will be implemented in a tiered fashion where monitoring activities, locations, and frequencies will change with time as conditions change. Monitoring data will be used to routinely update predictive models of the reservoir sediment erosion and downstream release. These updated models will provide short-term forecasts of sediment impacts throughout the project implementation. Before suspended sediment concentrations could ever be allowed to approach the limits of the water treatment plant, drawdown of both reservoirs would be temporarily halted to ensure that sediment concentrations would be treated to an acceptable level. Monitoring data would also be used to insure that any riverbed aggradation does not exceed flood mitigation measures.

REFERENCES

Bromley, C. (2006). *Draft Sediment Processes Associated with the Removal of the Glines Canyon Dam*, Project Report No. 475, University of Minnesota, St. Anthony Falls Laboratory, Minneapolis, Minnesota

Childers, D., Kresch, D.L., Gustafson, A.S., Randle, T.J., Melena, J.T., and Cluer, B. (2000). "Hydrologic Data Collected During the 1994 Lake Mills Drawdown Experiment, Elwha River, Washington," *Water-Resources Investigations Report 99-4215*, U.S. Geological Survey, Tacoma, Washington, 115 pages.

Corum, Z. (2003). *Elwha River Restoration Study: Flooding Impacts Associated With Removal of Elwha and Glines Canyon Dams—Revised, Prepared for Olympic National Park Elwha Restoration Project Office*, U.S. Army Corps of Engineers, Seattle, Washington.

Olympic National Park. (1996). *Elwha River Ecosystem Restoration Implementation, Draft Environmental Impact Statement*, National Park Service, Port Angeles, WA.

Randle, T.J. (2002). Memorandum to Brian Winter, Olympic Elwha Project Team Leader, Elwha River Restoration Project, Olympic National Park, National Park Service. Application of the report entitled: "Sediment Analysis and Modeling of the River Erosion Alternative", Elwha Technical Series PN-95-9, Randle, Young, Melena, and Ouellette, U.S. Bureau of Reclamation, October 1996.

Randle, T.J.; Young, C.A.; Melena, J.T.; Ouellette, E.M. (1996). "Sediment Analysis and Modeling of the River Erosion Alternative," *Elwha Technical Series PN-95-9*, U.S. Department of the Interior, Bureau of Reclamation, Boise, Idaho, 138 pages.

Gilbert, J. and Link, R. (1995). "Alluvium Distribution in Lake Mills, Glines Canyon Project and Lake Aldwell, Elwha Project, Washington," *Elwha Technical Series PN-95-4*, U.S. Bureau of Reclamation, Pacific Northwest Region, Boise, ID, 60 pages.

Williams, B. K., R. C. Szaro, and C. D. Shapiro. (2007). *Adaptive Management: The U.S. Department of the Interior Technical Guide*. Adaptive Management Working Group, U.S. Department of the Interior, Washington, DC