ROLE OF ADAPTIVE SEDIMENT MANAGEMENT IN ELWHA DAM REMOVAL

INTRODUCTION

Adaptive management is a structured, iterative process of robust decision making in the face of uncertainty, with an aim of reducing uncertainty over time via system monitoring (Williams and Brown, 2012). Adaptive management involves developing conceptual models, based on specific assumptions about the resource system, and identifying actions that might be used to resolve the problem. Testing of underlying model assumptions against monitoring data provides a foundation for learning and improvement of management actions based on what is learned. The Elwha River Restoration Project involved the largest and unprecedented sediment release associated with a phased dam removal. This three-year project provided an excellent opportunity for learning more about the benefits and challenges of adaptive management in a real-time environment.

The Elwha River flows north from the Olympic Mountains for about 70 km and enters the Strait of Juan de Fuca at Angeles Point, about 10 km west of Port Angeles, WA. In 1913, Elwha Dam was built 7.9 km upstream from the river mouth, and then removed between September 2011 and April 2012. This 32-m-high concrete gravity dam had 30 m of head and formed Lake Aldwell, which had a storage capacity of 10 million m$^3$ at the time of removal. Glines Canyon Dam was completed in 1927, 21 km upstream from the river mouth, and was removed between September 2011 and October 2014. This 64-m-high concrete arch dam had 59 m of head and formed Lake Mills, which had a storage capacity of 32 million m$^3$ at the time of removal (Bountry et al., 2011). Both dams were constructed to produce hydroelectric power. The dams virtually eliminated bed-material sediment supply to the river reaches downstream, forming large deltas at the upstream end of each reservoir. The deltas were composed of clay to cobble-sized sediment, while the lakebeds were composed of mostly silt with about 15 percent clay. The reservoir sediment also contained all sizes of wood and litterfall. In 1992, the United States (U.S.) Congress passed the Elwha River Ecosystem and Fisheries Restoration Act, which authorized the U.S. Department of the Interior to purchase and remove the privately constructed Elwha and Glines Canyon dams to restore fish passage. Rather than sediment excavation, a river erosion plan was selected for dam removal that utilized the natural stream power of the Elwha River to erode and redistribute reservoir sediment during phased dam removal and reservoir drawdowns (ONP, 1996). At the time of removal, Lake Aldwell contained 4.9 million m$^3$ of sediment and Lake Mills contained 16.1 million m$^3$ (Randle et al., 2015a).

**Sediment Plan:** The sediment management objective was to use phased reservoir drawdowns to erode as much of the sediment as possible during dam removal and to redistribute a portion of the eroded sediment along the valley margins to form a series of varying height sediment terraces (Randle et al., 2012). Based on a field drawdown experiment in 1994 (Childers et al., 2000), numerical modeling (Randle et al., 1996), and a physical model study of dam removal rates (Bromley, 2007), drawdown increments of 4.6 m were selected with 14-day hold periods in between (Randle and Bountry, 2010). The rate of dam removal was designed to be fast enough that sediment impacts would affect only a few brood years of fish, but slow enough that the rate of reservoir sediment erosion and redistribution kept pace with the rate of dam removal. Three additional reservoir hold periods (1½ to 2 months per period) were incorporated into the final dam removal plan to limit the release of reservoir sediments into the downstream river during critical fish usage periods referred to as fish windows. Modeling indicated elevated downstream sediment concentration loads would continue to occur for a few years post-removal, but reduce over time with the occurrence of large floods. The river erosion alternative required the construction of mitigation measures, prior to dam removal, to ensure adequate water supply and treatment for downstream users during the period of increased suspended sediment concentration and turbidity. Mitigation was also required to address potential impacts to downstream flood stages from the deposition of coarse sediment on the river bed (aggradation). The plan allowed for reservoir hold periods to be lengthened if monitoring data indicated the pace of reservoir sediment erosion was not keeping pace with the rate of dam removal, or there was risk of exceeding mitigation measures.
Vegetation Plan: An active plan to re-vegetate the reservoirs was designed to preempt invasive species colonization and to plant native forest species to initiate forest succession (Chenoweth et al., 2010). However, vegetation establishment on deep layers of inorganic sediment after dam removal was not well understood in 2011. Although over 1,000 dams had been removed in the United States before 2011, very little research had gone into documenting vegetation colonization of dewatered reservoirs (Heinz Center for Science, Economics and the Environment, 2002). It was clear that natural recolonization of the reservoirs would be dependent on distance from seed sources (Halpern and Harmon, 1983). One of the few surveys of vegetation development after the removal of several small dams in Wisconsin revealed a rapid colonization of the former reservoirs by invasive species such as reed canarygrass (Orr and Stanley, 2006). The Elwha reservoirs are large and inundated more than just the floodplain; upland terraces and valley walls were also inundated. The Elwha reservoirs were also unique in how sediment had accumulated over the last 80-100 years along with all sizes of wood and litterfall. Estimates prior to dam removal suggested the valley walls would be covered in 0.3-1.5 meters of fine sediment (silt and clay) and the valley bottom would be covered in 3-18 meters of sediment (upper 3-6 meters would be coarse sands and gravels) by the end of dam removal. Such deep layers of sediment were expected to be water stressed after the reservoirs were drained. It was also anticipated that sediment texture would influence successional trajectories. Several studies have demonstrated a relationship between substrate texture and plant species performance (Harper et al., 1965; Grubb 1986; Keddy and Constabel 1986; Smith et al., 1995; Leps et al., 2000; Walker and del Moral 2003; Naiman et al., 2005; Michel and Helfield, 2011). Leps et al. (2000) found that fine textured substrates favor colonization by graminoids over forbs or woody species. If the fine-textured sediments favor grasses and coarse sediments are substantially water stressed, rates of succession to forests and the return of ecosystem processes to pre-dam levels may be delayed due to the slow colonization of woody species into the basin. With so much uncertainty, the revegetation plan called for deliberate and gradual planting, combined with intensive monitoring over a 7-year period, to respond to vegetation growth and mortality and to respond to reservoir sediment erosion.

METHODS

Real-time monitoring of reservoir sediment erosion and export was accomplished through repeat topographic surveys that could be compared to pre-dam estimates of the valley bottom, and the pre-removal surveys completed in 2010. Surveys of channel slope and active channel width were accomplished using a real-time kinematic global position system (RTK GPS) during early dam removal, and later with more comprehensive methods such as LiDAR and photogrammetry. Changes in reservoir topography were tracked in a geographical information system relative to the 2010 surface (Bountriy et al., 2011), which was represented by polygons of unique size gradation, aerial extent, and thickness (Gilbert and Link, 1995). Volumetric changes in fine (silt and clay) and coarse (sand, gravel, and cobble) sediment were computed between measurements. A sediment budget model, relying on empirical relationships of slope and channel width related to discharge, was used to predict future sediment erosion volumes and downstream concentrations throughout dam removal (Randle et al., 2015b). The empirical relationships were frequently updated using real-time monitoring information. Time-lapse cameras throughout the reservoirs provided documentation on the occurrence of daily channel change that could be correlated with discharge measurements made at the United States Geological Survey (USGS) McDonald Bridge gaging station. The USGS also measured turbidity and suspended sediment concentrations (SSC) upstream of (background) and downstream of the dam sites (Magirl et al., 2014). Downstream river aggradation as a result of released reservoir sediment was measured using photogrammetry for above water areas and RTK GPS and sonar for below water areas. Staff gages were also installed at about 20 river cross-sections to track discharge-stage rating curves that were used as a surrogate to infer periods of aggradation (East et al., 2014).

Monitoring of how fish populations responded to dam removal was accomplished using a variety of methods. Adult salmon abundance and distribution during dam removal was monitored through a combination of sonar observations (LEKT and Denton, 2014), spawning ground surveys (McMillan and Moses, 2013; McMillan et al., 2014), and an adult capture weir (Anderson, et al., in preparation). Juvenile abundance and distribution was evaluated through a combination of smolt traps (McHenry et al., 2014), snorkel surveys, and electrofishing.

The slow drawdown of the dams provided a unique opportunity to adaptively manage the vegetation development as the reservoirs receded. In the first two years of drawdown, experimental plantings were installed to determine native species performance in the deep layers of fine and coarse sediments covering the original forest soils. Permanent plots were established in both planted and unplanted areas to determine the effectiveness of treatments compared to natural patterns of recovery. Since random plot distribution does not always provide a complete picture of the
evolving patterns of natural vegetation development, the restoration ecologist frequently visited the newly exposed surfaces throughout each of the first three growing seasons. Areas within 50 meters of seed sources were left to naturally regenerate. To monitor the performance of planted native species, 860 plants representing 6 species were tagged in the first year and 675 plants representing 5 species were tagged in the second year. Water availability was monitored throughout the year in the sediments of the former Lake Mills reservoir using a tensiometer.

RESULTS

**Reservoir Drawdown and Sediment Release:** Elwha Dam was removed in the dry by periodically diverting the river, using cofferdams, through a spillway channel excavated in the left abutment. Lake Aldwell had one early drawdown in June 2011 followed by a 16 week hold period, and five additional drawdowns starting in September 2011 and ending in April 2012 when dam removal was completed. The hold periods after reservoir drawdown ranged from 2 to 8 weeks. During each reservoir drawdown, erosion of the reservoir delta occurred as a result of base-level lowering. The eroded sediment was re-deposited in the remaining lake, building new deltas that progressed downstream toward the dam site as the lake reduced in aerial extent and capacity. Downstream sediment releases were minor while sufficient trap efficiency remained in the lake, with a few minor peaks of sediment release during winter storms in November and December 2011 (Figure 1). By mid-March 2012, only 5% of the lake capacity was left and in April 2012 the sediment delta reached the dam site and bedload was released into the downstream channel. Suspended sediment levels in the downstream channel increased from mid-March to early July 2012, and then reduced to low levels as flows receded during late summer and fall. About 90 percent of the fine was transported to the sea, but some fine sediment deposited as thin coatings of mud along low-relief gravel bars and floodplain surfaces that were inundated during the spring 2012 snowmelt season (East et al., 2014). Sand and fine gravel released as bed-material load from Lake Aldwell resulted deposited in the larger downstream pools and eddies, but no aggradation of hydraulic controls (rifles and rapids) occurred.

The contractor completed the dam removal 4 months ahead of the government’s estimated schedule (Figure 1). No large floods occurred during this initial dam removal period, and monitoring data indicated no problems with water quality. As expected, delta progradation kept pace with the rate of dam removal and reservoir. Therefore, no adaptive management changes were made to the dam removal schedule. There were issues with cofferdam breaches during winter high flows, but dam removal proceeded. A large portion of the pre-removal Lake Aldwell delta remained in place throughout dam removal. The river quickly incised along the far right side of the delta into cohesive sediment layers during the first two drawdowns; no large floods occurred during reservoir drawdowns that were capable of laterally eroding across the entire wide delta. Adaptive management actions were considered on the Lake Aldwell delta such as a reservoir drawdown one year prior to dam removal that would include a winter flood season. A center pilot channel was also considered during fall 2011 to encourage additional erosion of the Lake Aldwell delta during the dam removal period. Resource managers determined an early drawdown was not procedurally possible before June 2011, and no pilot channel was implemented because the amount of sediment remaining in the Lake Aldwell delta was small enough that impacts would be tolerable if erosion occurred after dam removal. Additionally, the Lake Mills sediment release was expected to be much larger and of greater focus for the adaptive management efforts. Monitoring data showed that small amounts of lateral erosion and channel incision did continue in Lake Aldwell during the two years following dam removal. The most extensive lateral erosion of the remaining delta occurred during a 3-year winter flood in December 2014.

On Lake Mills, a physical model (Bromley, 2007) predicted that excavation of a center pilot channel on the delta was necessary to prevent the river from incising on the valley margin and leaving tens of meters of delta sediment in place. Because of the larger delta size relative to Lake Aldwell, the first adaptive management action in September 2010 was to excavate a center pilot channel along the upstream portion of the delta, block off the main channel along the edge of the delta with a constructed log jam, and remove an existing log jam at the head of the delta to divert river flow into the pilot channel. A large flood followed in December 2010 that widened and deepened the pilot channel and refilled the reservoir. However, the pilot channel was successful in becoming the primary delta channel with a center alignment.
Figure 1 Monitoring results during June 2011 to September 2014 versus pre-project model assumptions for equivalent time periods using four different hydrograph assumptions: a) actual measured river discharge during dam removal compared with range of discharges assumed in model scenarios, b) Lake Mills actual drawdown compared with four model scenarios (differing rate dependent on hydrology), c) Lake Aldwell drawdown compared with model scenarios (same rate regardless of hydrograph), and d) actual suspended sediment load compared with maximum of four model scenario predictions.

An early reservoir drawdown of Lake Mills occurred during July 2011 followed by a 10 week hold period. Starting in September 2011 through April 2012, the first 21 m of Glines Canyon Dam was removed using a hoe ram sitting on a barge while flow was diverted through the gated spillway or through notches cut into the dam crest. The remaining 37 m of Glines Canyon Dam was removed using drill and blast techniques to cut notches on alternating left and right sides of the arch dam. Nine reservoir drawdown increments occurred following dam removal notches between October 2011 through October 2012 when the sediment delta reached the dam. The first hold period of 10 weeks occurred in November and December 2011. Although the first November-December fish window was not required, the hoe ram broke and dam removal had to be temporarily halted until new equipment could be brought to the site. After dam removal resumed in January 2012, hold periods ranged from 2 to 3 ½ weeks, except for the May-June fish window, which resulted in a 10-week hold period. The pace of Glines Canyon Dam removal began to
reach the dam site. A new round of predictions was made using the sediment budget model to evaluate varying rates of continued dam removal. The contractor was allowed to continue at a faster pace through October 2012, but adaptive management was used to reduce the total possible dam removal rate by one-third. The coarse sediment delta reached the dam after the last allowed blast in October 2012 (Figure 1). At that point, adaptive management was used to halt additional dam removal while new predictions and monitoring occurred to evaluate the first major sediment impacts to downstream water quality and river stage. Rates of sediment release were high until late December 2012 when flows reduced, but then increased with each set of subsequent high winter and spring snowmelt flows. Sediment released into the downstream river not only filled pools, but also aggraded the entire river bed causing the stage-discharge relationships to increase by up to 1 m as the sediment wave passed through. Although peak concentrations of fine sediment did not exceed predictions, the surface water intake designed prior to dam removal became overwhelmed in winter 2012 due to long duration and high volumes of silt, clay, sand, gravel, and organic material entering the plant. Dam removal had to be halted for one year until solutions could be implemented that reduced the amount of sediment entering the water treatment plant.

During the one year hold period, vertical incision up to 9 m and tens of meters of lateral erosion continued in Lake Mills despite the lack of additional base-level lowering at Glines Canyon Dam. The continued reservoir sediment erosion resulted in several years of average annual sediment load being released past the dam site during the one year hold period. Dam removal blasting resumed during fall 2013 with reservoir drawdowns during October 2013, January 2014, February 2014, and the final blast in August 2014. Adaptive management did not have to be used in the final year of dam removal because improvements to the water diversion and treatment plant were successful and river-bed aggradation had reduced. Channel aggradation did result in minor flooding of low relief campgrounds along with bank erosion in many locations along the river. Similar to Elwha Dam, large boulders were also present in the narrow canyon downstream of Glines Canyon Dam, possibly originating from construction activities in the late 1920s. These boulders created a new hydraulic control that increased river water surface upstream from the dam site after removal. Adaptive management was implemented to blast some of the boulders, but others continue to constrict the canyon and increase upstream water stage, possibly impacting fish passage.

At the end of the three year dam removal period, monitoring data indicated about half of the available 21 m³ of Lake Aldwell and Lake Mills sediment had been eroded and released downstream. Actual river flows during the three year dam removal period never exceeded the 2-year flood for the Elwha River. The annual background suspended sediment load (fine sand, silt, and clay) was only 2 to 6% of the suspended sediment load released from the reservoirs. The largest background suspended sediment load occurred during a March 2014 storm, but was still only 3% of sediment load eroded from the reservoirs. Sediment erosion and release above background levels continued in the year following dam removal, particularly during the 3-year flood in December 2014.

**Fisheries:** The Elwha Project fisheries restoration plan assumed that mainstem water quality conditions below Glines Canyon Dam would be detrimental to natural fish production, particularly as there is very limited clean water refugium below Elwha Dam (Ward et al., 2008). Salmonids are sensitive to suspended sediment loading, and have been found to exhibit behavioral changes at concentrations as low as 100 ppm, while mortality directly related to turbidity has been seen at concentrations of 1000 ppm (Cook-Tabor, 1995). These effects are exacerbated by the duration of the exposure. Due to concerns regarding elevated turbidity loads during dam removal, the fish restoration plan relied on two fish hatcheries for protection of fish stocks during the sediment-impact period and to help initiate re-colonization following dam removal.

The intent of the fish windows were to provide extended periods of clean water (≤100 FNU) when salmonids (both hatchery and natural origin) could migrate into the river as adults or emigrate from the river as juveniles (Ward et al., 2008). The May-June fish window was specifically designed to accommodate emigration juveniles of all species, as well as the upstream migration of adult native steelhead. The August-September fish window was designed to accommodate the upstream migration of adult Chinook salmon and pink salmon, while the November-December fish window was designed to coincide with the upstream migration of adult Coho salmon, chum salmon, and hatchery origin steelhead (a program which was ultimately discontinued prior to the beginning of dam removal). Adult hatchery origin salmon were expected to recruit naturally to their hatchery of origin, although plans were also made to capture and relocate adults from the river to the hatcheries as necessary. Natural origin adults were expected to either migrate upstream to the best available habitat, or stray into the hatcheries as they sought out cleaner water.
Actual turbidity during the fish windows differed substantially from the modeled conditions (Figure 2; Table 1), being significantly higher than anticipated during the winter and spring periods, or lower than anticipated during the summer periods. More importantly, releases of hatchery fish were not consistently timed with the fish windows, due to either their age of release (yearling Chinook released in April vs fingerling Chinook released in June) or more rapid maturation in the hatchery than originally anticipated (Coho releases in April rather than May).

![Figure 2 Predicted versus actual suspended sediment loads upstream of (background) and downstream of (actual SSC) the dam sites. Actual data is based on provisional USGS measurements (Magirl, 2014).](image)

<table>
<thead>
<tr>
<th>Fish Window During 3 Year Dam Removal</th>
<th>Mean of 4 model scenarios</th>
<th>Actual Turbidity</th>
<th>Actual Discharge Exceeded Mean Annual</th>
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<tr>
<td></td>
<td>% Fish Window Exceeding</td>
<td>% Fish Window Exceeding</td>
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<td></td>
<td>&gt;100 FNU</td>
<td>&gt;500 FNU</td>
<td>&gt;1000 FNU</td>
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<tr>
<td>1 - Nov to Dec, 2011</td>
<td>45%</td>
<td>3%</td>
<td>1%</td>
</tr>
<tr>
<td>2 - May to June, 2012</td>
<td>22%</td>
<td>3%</td>
<td>3%</td>
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<tr>
<td>3 - Aug to Sept, 2012</td>
<td>74%</td>
<td>31%</td>
<td>19%</td>
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<tr>
<td>4 - Nov to Dec, 2012</td>
<td>66%</td>
<td>44%</td>
<td>30%</td>
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<tr>
<td>5 - May to June, 2013</td>
<td>7%</td>
<td>6%</td>
<td>3%</td>
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<tr>
<td>6 - Aug to Sept, 2013</td>
<td>11%</td>
<td>2%</td>
<td>1%</td>
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<tr>
<td>7 - Nov to Dec, 2013</td>
<td>17%</td>
<td>11%</td>
<td>5%</td>
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<tr>
<td>8 - May to June, 2014</td>
<td>6%</td>
<td>1%</td>
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<td>9 - Aug to Sept, 2014</td>
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The largest mean-suspended sediment loading during any given fish window was nearly 35,000 tons/day, during the Nov-Dec window in 2012 (Figure 2). During this time, turbidity exceeded 100 FNU continuously and exceeded...
1,000 FNU nearly 50% of the time (Table 1). The models had predicted that turbidity would exceed 100 FNU about 66% of the time and 1,000 FNU about 30% of the time. While turbidity and suspended sediment concentrations were substantially higher than projected, Coho and chum salmon moved into the river opportunistically, but tended to recruit primarily to the hatchery facilities. There was little indication that any Coho volitionally moved upstream of the Elwha Dam site (McMillan and Moses, 2013). Suspended sediment concentrations were also significantly higher than modeled during the May-June fish window of 2013. Although the mean concentrations were lower than those observed during the 2012 Nov-Dec window (~22,000 tons/day), turbidity greatly exceeded modeled conditions (Table 1). Turbidity exceed 100 FNU 100% of the time (modeled at 7%), exceeded 500 FNU 77% of the time (modeled at 6%), and 1,000 FNU 28% of the time (modeled at 3%).

While certain cohorts of hatchery fish were released during the spring fish windows (e.g. fingerling Chinook), other cohorts were released prior to the fish window (yearling Chinook, Coho). In April 2013, periods of high turbidity were associated with large scale observations of juvenile Chinook mortality following their release from the WDFW hatchery. Returns of Coho salmon in the fall of 2014 (originating from juveniles emigrating during the spring of 2013) were significantly lower than anticipated (PFMC, 2014). Conversely, turbidity and suspended sediment concentration during the summer fish windows was significantly lower than modeled; rarely exceeding 100 FNU and never exceeding 500 FNU (Table 1). This was conducive for Chinook and pink salmon upstream migration and spawning. Spawning ground surveys conducted in the mainstem channel and larger tributaries during the late summer of 2012, 2013, and 2014 observed 217, 765, and 1,310 redds respectively. Many of these redds were located in the mainstem channel above the Elwha Dam site (LEKT et al., In preparation). Unlike Coho salmon, very few Chinook recruited to either hatchery facility. The majority of adults needed for hatchery broodstock were collected from the river and transported to the WDFW hatchery.

Snapshot overview of vegetation establishment results on Mills and Aldwell: Phased dam removal and reservoir drawdown had a profound impact on the successful establishment of planted and natural vegetation; although sediment texture and distance from seed sources were important factors. The most likely explanation for the rapid colonization and high survival of planted species was the high water availability in the sediments due to the gradual reservoir drawdowns. The reservoirs left behind saturated sediments and a slowly-declining water table during the early phases of dam removal. In particular, the hold periods during the 2012 growing season (May, June, August, and early September) in the Lake Mills benefitted the establishing plants. High water availability proved critical to the germination and establishment of vegetation and to the performance of planted native species in both the fine textured surfaces and the coarse terraces.

However, over time, sediment texture has proven to impact vegetation. In general, vegetation establishment (tree species included) was rapid on fine-sediment surfaces and slow on coarse-textured terraces covering the valley bottom. The newly exposed valley slopes covered in fine sediments benefit from close proximity to seed sources. Natural regeneration was swift in most areas. Bare ground declined rapidly. In 2012, the first full growing season for most of the valley slopes; bare ground was 78%. Bare ground declined to 28% in 2013 and to 9% in 2014. The decline in bare ground is not exclusively the result of colonization by herbaceous species. Tree species were a significant component of the natural vegetation; with red alder (Alnus rubra) dominating many sites covered in fine sediments in both the former Lake Aldwell reservoir and the former Lake Mills reservoir. Woody species cover is increasing each year, from a low of 1% in 2012, 14% in 2013 to 57% in 2014. Planted sites also performed well on the valley slopes, with survival rates of 92% in 2012 and 96% in 2013 (Whisman, 2013; Calimpong, 2014).

Vegetation recovery on the coarse terraces has been slow. Most of the coarse terraces are not only water stressed, but are also far from seed sources. As a result, substantial natural regeneration has been limited. Bare ground on coarse terraces is declining slower than on fine sediment sites. In 2013, the first year of substantial exposure of coarse sediment in the former Lake Mills reservoir, bare ground was 90%. In 2014, bare ground declined to 77%, mostly as a result of planting and seeding efforts. Survival of planted species in the deep terraces of coarse sediment was high in 2012 and 2013 (88% and 90% respectively), most likely due to the water available during drawdown. In 2014, when the river had nearly dropped down to its pre-dam elevation, plant survival on the coarse sediments was extremely low, only 42%. This was due in part to unusually high summer temperatures (over 3 degrees Fahrenheit above average in July, August and September) and below average precipitation. However, some species performed surprisingly well. Black cottonwood and Nootka rose (Rosa nutkana) both had a 73% rate of survival on coarse terraces in 2014, demonstrating significant drought tolerance.
Natural vegetation colonization patterns were strongly influenced by the reservoir drawdown timing. The season of drawdown influenced the composition and rate of vegetation establishment. Drawdowns that occurred during the late fall and winter months were relatively slow to be colonized by vegetation. On fine sediment sites, red alder eventually colonized sites within 100 meters of mature trees. The most rapid and prolific establishment resulted from reservoir drawdowns that occurred during the seed dispersal of Salicaceae species. Willow (Salix species) and black cottonwood (Populus balsamifera ssp. trichocarpa) have very short-lived seed with very specific germination requirements tied directly to river discharge patterns in late spring (Naiman et al., 2005). Seeds are dispersed long distances by wind and water in May and June. Once seeds are saturated, they remain viable for only 2-3 days and must find appropriate sites to establish, usually newly exposed gravel bars in floodplains. Because reservoir drawdown was gradual over two years, there were two opportunities for substantial cottonwood and willow establishment during drawdown. The first opportunity was in 2011 when the first 4.5 to 5.5 meters of reservoir drawdown occurred in both reservoirs from June 2-11. The rate of drawdown created the perfect environment for seed germination and establishment. The wave action from the lake deposited saturated seed of cottonwoods and willows in perfect rows on the newly exposed shoreline (Figure 3a). In the former Lake Aldwell, mean sapling densities at these sites by the end of 2013 were 56,100 stems per acre and were over 2 meters tall. Most of the saplings were cottonwoods with a significant component of Sitka willow (Salix sitchensis). In 2012, a similar establishment event occurred in the former Lake Mills reservoir in both fine and coarse sediments. The most remarkable establishment was on a coarse-textured terrace that formed during drawdown in the former Lake Mills. Thousands of cottonwood seedlings successfully germinated and established on newly deposited sediments slowly drying during the summer of 2012. As dam removal progressed, the terraces became perched approximately 15 meters above the water table. Three years later the cottonwoods are thriving, having successfully established in xeric conditions (Figure 3b). The plants are small (less than 1 meter tall), but healthy and are one of the few woody species to naturally occur on the coarse terraces. On other coarse terraces not exposed during the late spring, cottonwood and willow establishment is limited to seasonal creeks meandering across the terraces.

![Figure 3 Vegetation growth in newly exposed reservoirs: a) Seedlings of cottonwoods and willows established during the June 2011 drawdown in the former Lake Aldwell reservoir - photograph taken September 12, 2011; b) three-year old cottonwood seedlings established in 2012 on a high terrace in the former Lake Mills reservoir - photograph taken September 16, 2014.](image)

Many of the coarse textured terraces are not only water stressed, but are also far from seed sources. As a result, substantial natural regeneration has been limited and tends to be restricted to small seasonal creeks that are scattered across the landscape. The cover of bare ground at coarse sediment sites is much greater than on fine sediment sites. In 2013, the first year of substantial exposure of coarse sediment in the former Lake Mills reservoir, bare ground was 90% of the reservoir surface. In 2014, the bare ground declined to 77%, mostly as a result of planting and seeding efforts. Survival of planted species in the deep terraces of coarse sediment was high in 2012 and 2013 (88% and 90% respectively), clearly benefitting from the water still available during drawdown. In 2014, when the river was nearly down to its original elevation, plant survival on the coarse sediments was extremely low, only 42%. This was due in part to unusually high summer temperatures (over 3 degrees Fahrenheit above average in July, August
and September) and below average precipitation. However, some species performed surprisingly well. Black cottonwood and Nootka rose (*Rosa nutkana*) both had a 73% rate of survival in 2014, demonstrating significant draught tolerance.

**DISCUSSION**

Outcomes of phased dam removal were assessed for the Elwha River adaptive management program to evaluate how actual dam removal results compare to expectations from pre-project predictions. Differences in actual and expected results are investigated to identify which, if any, of the possible causes identified in adaptive management literature occurred: incorrect assumptions, poorly executed actions, changed environmental conditions, inadequate monitoring, or some combination of these causes (Williams and Brown, 2012).

**Sediment Erosion during Early Drawdown and Dam Removal While a Lake Remained:** Adaptive management is most successful when the ability to control the system with management decisions and actions is high. For the case of the Elwha Dam and Glines Canyon Dam removals, the greatest control on sediment release was both predicted and found through monitoring data to be prior to and during the phased-drawdown period while a lake still remained. Prior to dam removal, the early drawdowns on both lakes and pilot channel excavation on Lake Mills delta were effective at increasing the amount of sediment eroded and retained in the lake. This matched pre-project model assumptions of the benefit of early drawdown and starting delta channel along center alignment. However, we learned through monitoring that the effectiveness of early drawdown on sediment erosion rates and magnitude could have been increased by implementing the early drawdown prior to high flow periods, rather than at the after. Additionally, monitoring data indicated that reservoir sediment erosion tended to occurred when flows exceeded the mean-annual flow of 42 m$^3$/s and were not limited to occurrence of large floods (see Figure 1). Early drawdown was implemented after snowmelt recession. Dam removal started at both sites during the low flows of September 2011. Implementing the first drawdowns prior to the high flow period of the year (October through June) would have allowed more erosion to occur while the reservoirs still remained. This is consistent with other dam removal literature documenting that timing dam removal with hydrology of the river basin can be an effective tool (Cannatelli and Curran, 2012).

**Sediment Impacts during Fish Windows after Lake Was Lost:** More efficient construction methods at both dam sites resulted in a faster base level lowering and delta progradation to the dam sites than government estimates. For Lake Aldwell, the delta reached the dam just as the May-June snowmelt period and fish window was beginning. Discharge exceeded the mean-annual flow and was capable of eroding sediment 90-100% of the May-June fish windows, and a wider range of 7-87% during the November-December fish windows (see Table 1). The combination of faster reservoir drawdown and long duration flows effective at eroding and transporting sediment resulted in higher than anticipated sediment loads during the high flow fish windows and thus higher than expected impacts to fish. By adjusting the rate of dam removal, sediment impacts could have been shifted and potentially spread out to occur over the summer or following winter during high flows. The sediment delta reached Glines Canyon Dam just before the November-December fish window, 3 to 12 months ahead of the assumed schedule in pre-project model runs. The Lake Mills sediment volume released was large enough that the river needed several months during winter and snowmelt flows to transport the reservoir sediment through the downstream river channel. Given the large volume of reservoir sediment, it was not likely possible to minimize sediment impacts during the high-flow fish windows after the lake was lost in November-December or May-June. Monitoring data showed that despite the halting of dam removal after the lake was lost, higher than predicted sediment erosion volumes continued to occur and be released downstream even during a one-year long hold period. Channel incision was deeper, and knickpoint migration continued at a slower rate, than predicted during the year-long hold period. The incision was deeper because the reservoir-sediment grain size was finer with depth. The river in the middle of the reservoir incised as much as 9 m during the one-year hold period. The knickpoint migration tended to stall when river discharge was less than the mean-annual flow. Lateral erosion into the coarse and non-cohesive sediment terraces was much greater than predicted. A slower rate of dam removal would have reduced the sediment concentrations released downstream, but prolonged the duration of impact.

**Vegetation Establishment versus Drawdown Timing:** In general, vegetation establishment benefits tremendously from a gradual reservoir drawdown. Timing of drawdown also significantly impacts the rate of response and species composition and can lead to extensive establishment of Salicaceae species. The pattern of Salicaceae establishment,
visits have also showed us the need to focus management on coarse-sediment terraces and allow valley slopes to ensure our goal of accelerating forest development is being met. Our plots and the general observations from site continue to thrive after three years. Annually monitoring the changes to bare ground and species cover allows us to The valley slope areas far from seed sources that were planted during drawdown had high rates of survival and first two years allowed the rapid pace of natural recolonization on most of the valley slopes to occur unhindered. Adaptive management of the vegetation during dam removal proved successful. The gradual planting plan in the first two years allowed the rapid pace of natural recolonization on most of the valley slopes to occur unhindered. The valley slope areas far from seed sources that were planted during drawdown had high rates of survival and continue to thrive after three years. Annually monitoring the changes to bare ground and species cover allows us to ensure our goal of accelerating forest development is being met. Our plots and the general observations from site visits have also showed us the need to focus management on coarse-sediment terraces and allow valley slopes to predominantly recover naturally. Tagging plants early in the project provided critical information that allowed us to shift our plant production to species best suited to plant into the coarse terraces.

Implementation Challenges of Adaptive Management for Dam Removal: A challenge of utilizing adaptive management during a real-time construction project was the need to incorporate new predictions with real-time monitoring data in a timely manner. The combined effect of implementing adaptive management that changed reservoir drawdown schedules with the lack of a large flood occurrence resulted in the need for more model iterations than planned to move forward with management decisions. Although the added model runs posed budget and time challenges, the adaptive management method of incorporating new knowledge from monitoring experience as the project moved forward was successfully utilized for each management decision on reservoir drawdown schedule. Another challenge was cross-coordination of multiple disciplines to help inform management decisions during dam removal. We formed an interdisciplinary team to discuss monitoring results and predictions so varying perspectives could be incorporated and used to get consensus on technical recommendations associated with dam removal. The most beneficial monitoring data that either confirmed or changed assumptions used for predictions was documentation of changing river width, elevation, and slope and corresponding river discharge hydrographs. Evolving monitoring methods from quarterly survey profiles and cross-sections to continuous and more frequent coverage with photogrammetry increased the accuracy of computations and better captured the non-uniform channel geometry. Time-lapse photography and collection of aerial photography was crucial to help with interpretations of complex and rapid changes in channel morphology that included super-imposed rounds of incision and lateral erosion from multiple drawdowns. Suspended sediment and bedload data (collected by partner agencies and Reclamation using research funds), along with staff gates and river profile surveys greatly improved monitoring information and our ability to analyze downstream sediment transport as part of the adaptive management program.

CONCLUSIONS

Through the use of key monitoring data and updated predictions, adaptive management was successfully implemented on the Elwha Dam removal project to control the rates of reservoir sediment erosion. Pre-project predictions were crucial to establishing mitigation measures, setting the initial pace of dam removal, and establishing the monitoring plan. We did not have to alter the type of real-time sediment monitoring data, but did benefit from improved methods that captured greater complexity at more frequent intervals than planned. The level of adaptive management control on downstream sediment release, and thus impacts to flooding, water quality, and fish, was highest while the reservoirs remained and eroded sediment was largely contained. Vegetation growth benefited from the timing and rate of phased drawdown on both reservoirs, but was not planned to coincide with vegetation seed dispersal. While suspended sediment concentrations exceeded modeled expectations during a number of the fish windows, conditions during the May-June window of 2013 were of the greatest concern to hatchery and natural origin juveniles. This was exacerbated by the fact that releases of hatchery yearling Chinook,
hatchery Coho, and hatchery chum salmon occurred prior to the beginning of the fish window, as fish were
smolting. Future adaptive management projects may benefit by analyzing what if implementation scenarios in pre-
project planning that could result in increased or shifted timing of dam removal rates and associated sediment
impacts, overlaid with vegetation growth seasons and fisheries considerations.

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