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Sediment impacts from the Savage Rapids Dam removal, Rogue River, Oregon

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ABSTRACT

Before a dam removal project is implemented, engineers are often asked to estimate the potential for impacts from the release of reservoir sediment. Field measurements, numerical models, and physical models are typically used to develop sediment impact estimates. This information helps decision makers to make informed decisions about when and how to remove the dam, whether to allow the river to erode the reservoir sediment, or to remove or stabilize the reservoir sediment prior to dam removal, or whether mitigation of the effects is needed. Although numerous dams have been removed, mostly small in size, few case studies on sediment impacts have been documented. Because there are limited case studies, dam removal regulators and stakeholders often err on the side of caution when selecting the level of preremoval analysis or determining whether the reservoir sediment needs to be removed prior to dam removal.

The purpose of this paper is to increase our knowledge base for application to future dam removals. The chapter discusses sediment impacts associated with the removal of the 11.9-m-high Savage Rapids Dam on the Rogue River near Grants Pass, Oregon. A unique factor to the Savage Rapids project was the construction and operation of a new diversion facility and water intake located immediately downstream of the dam, which introduced additional consequences associated with the release of reservoir sediment.

BACKGROUND

Three main-stem dams have been removed on the Rogue River in southwest Oregon to improve salmon and steelhead fish passage: Savage Rapids Dam at river kilometer (RK) 172 in 2009, Gold Hill Dam at RK 195 in 2008, and Gold Ray Dam at RK 203 in 2010 (Fig. 1). Savage Rapids Dam was 11.9 m high and 152 m long, Gold Hill Dam was 2.4 m high and 274 m long, and Gold Ray Dam was 11.6 m high and 110 m long. The only remaining main-stem dam, Lost Creek Dam, located at RK 246, serves as flood control for the upstream-most 30% of the basin. Savage Rapids Dam, the focus of this paper, was built in 1921 by the Grants Pass Irrigation District (GPID) to divert river flows for irrigation to canals located on both sides of the Rogue

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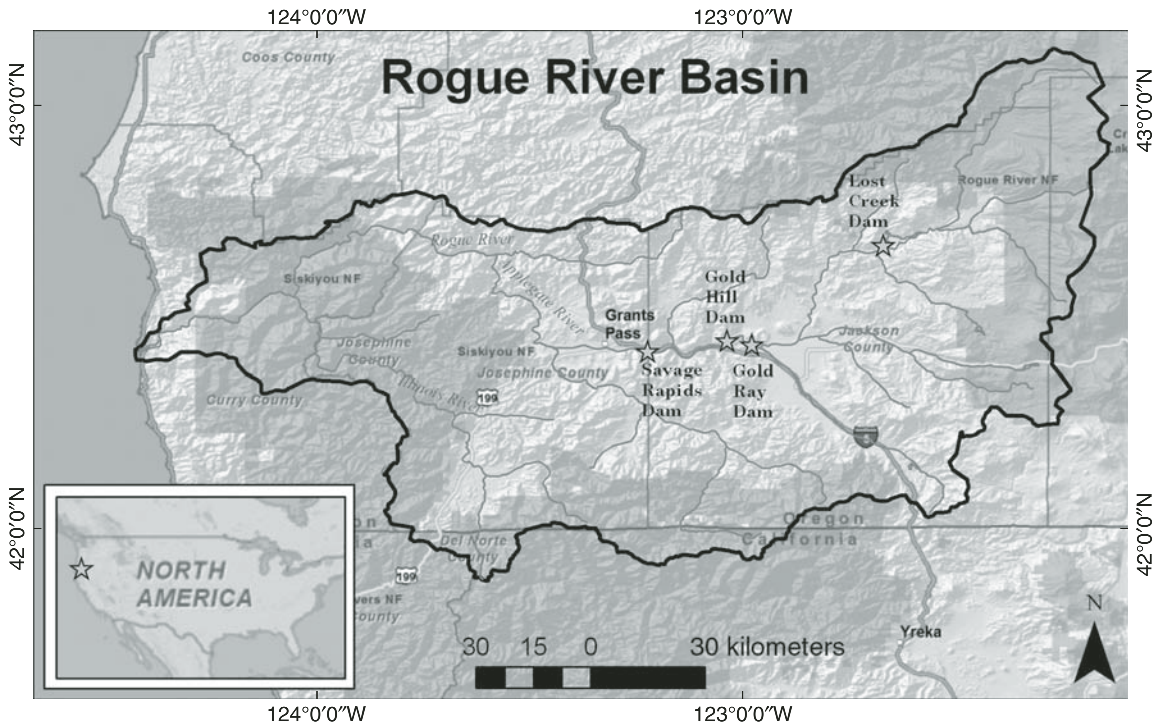

Figure 1. Location map for Rogue River.

River (Fig. 2). The dam created a permanent backwater pool that extended 0.8 km upstream. During the irrigation season (mid-April through October), wood stop logs were used to raise the reservoir 3.35 m, which created a reservoir pool 4.0 km in length. The reservoir was also utilized for recreational boating and fishing, mostly during the irrigation season. The dam did not provide any flood control or power generation.

An environmental impact statement (EIS) was accomplished in 1995, and it concluded that dam removal was the preferred alternative to reduce impacts to fisheries at Savage Rapids Dam. An amended 2001 Federal Court Consent Decree required GPID to cease using Savage Rapids Dam for water diversions by the end of the 2008 irrigation season. Congress authorized the U.S. Bureau of Reclamation to construct a new pumping plant to allow continued water supply to the district, which had to be completed prior to dam removal (Fig. 2). Following construction of the new pumping plant and intake during 2006–2009, a cofferdam was constructed, and the majority of the dam was removed between April and October 2009. A portion of the dam was left in place on the north side to save costs and help protect the new intake from high-velocity flood waters. The total project cost, including dam removal and construction of the new pumping plant and intake, was approximately $39.3 million.

Rather than excavating the sediment, the river was allowed to erode and transport the reservoir sediment downstream of the dam. This chapter presents the approach used to develop reach-scale estimates of the timing and magnitude of sediment impacts associated with dam removal, along with additional analysis done to help minimize future sediment impacts at the new GPID intake structure. Postremoval monitoring data are used to compare the preremoval estimates with observed sediment impacts.

RESERVOIR SEDIMENT CHARACTERIZATION

The first step in estimating potential sediment impacts was determination of the reservoir sediment volume and size gradation, and whether there were any contaminants. Initial estimates of reservoir sediment volume done in the 1990s ranged between 400,000 m^3 and 750,000 m^3. These estimates were based on the simple assumption that sediment had deposited in a wedge shape along the entire 4-km-long reservoir (irrigation pool). Because these estimates indicated potentially large sediment impacts, a more accurate estimate was needed. In 1999, drill cores and dive inspections along with a bathymetric survey were conducted to refine the thickness and spatial distribution of the sediment deposit. The new data indicated that the reservoir had actually only trapped sediment in the 0.8 km reach upstream from the dam. This occurred because the majority of sediment is transported through the Rogue River in the nonirrigation season, so no measurable deposition accumulated in the extended portion of the reservoir during irrigation season operations. In addition, drill-hole data indicated that rather than a uniform sloped channel segment, the area of reservoir sediment deposition contained a long rapid with a deep pool upstream. The previous

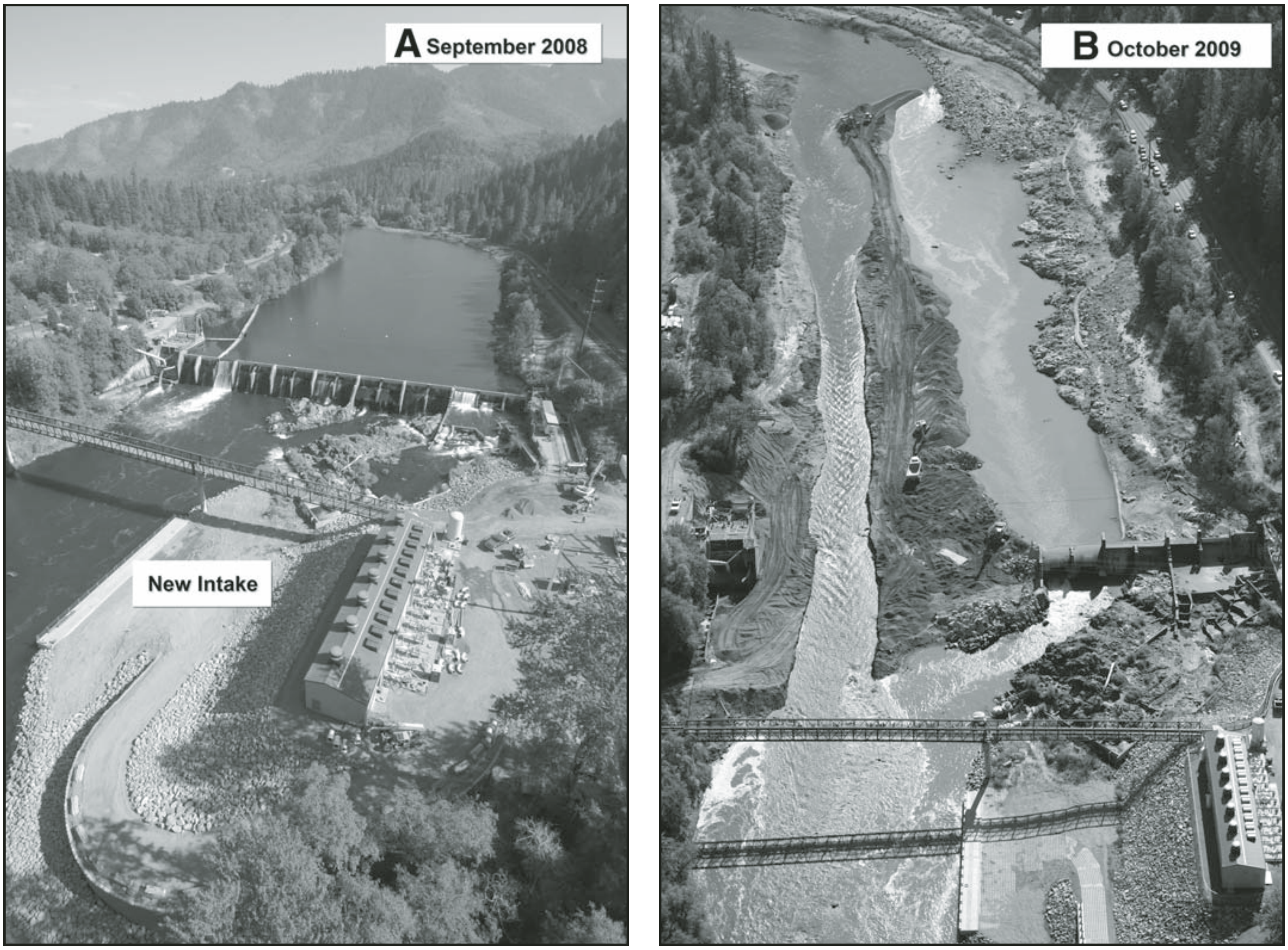

Figure 2. (A) A year prior to and (B) immediately after removal of Savage Rapids Dam (river runs from top to bottom).

volume estimate assumed a uniform river slope for computing a wedge-shaped sediment deposit. Based on these new data, the volume of reservoir sediment was estimated to be much smaller at 150,000 m^3.

Savage Rapids Reservoir likely filled with sediment in the first few floods following its construction in the 1920s. In the early 1900s, gold mining occurred in the upstream Rogue River Basin, which indicated there was a potential for finding contaminants in the reservoir sediment. GPID requested the chemical composition of reservoir sediment be tested to ensure that if it were released as a result of dam removal, it would not pose any risk to water quality, fish and wildlife, or human uses. During sediment collection by the drill rig in 1999, 25 samples were collected, which after analysis, showed that the reservoir sediment deposit consisted of 2% fines (silt- and clay-sized particles), 71% sand, and 27% gravel overall. Chemical testing confirmed that the sediment was equal to or less than background levels for arsenic, cadmium, mercury, copper, lead, mercury, iron, and zinc (U.S. Bureau of Reclamation, 2001).

PREREMOVAL ESTIMATES OF RESERVOIR SEDIMENT EROSION AND DOWNSTREAM TRANSPORT

GPID was concerned about how long it would take for coarse reservoir sediments to erode and potentially impact the new water intake. Fish regulating agencies were also interested in the length of time it would take the reservoir to be restored to ensure there were no fish passage barriers. Savage Rapids Reservoir was relatively narrow due to bedrock controls, i.e., only two to three times wider than the river. As a result of the narrow reservoir and insignificant amount of cohesive material, it was expected that following dam removal, nearly all of the reservoir sediment would be easily eroded by the river during floods.

To quantify the rate and extent of reservoir sediment erosion, a one-dimensional (1-D) hydraulic and sediment transport model (HEC6t) was utilized (USACE-HEC, 1993). Because the hydrology following dam removal was uncertain, both a wet and dry hydrology were used for modeling based on historical data at the Grants Pass gauging station located 8 km downstream (no major tributaries enter in this reach). With the dry hydrology, two floods were modeled in the first winter, with a mean daily flow rate of ~283 m^3/s. Drilling data were used to estimate the predam riverbed, below which the model was not allowed to erode. The 1-D model with dry hydrology estimated that 66% of 150,000 m^3 of reservoir sediment would be eroded from the first flood, and 75% of the reservoir sediment would erode within 1 yr (Fig. 3; U.S. Bureau of Reclamation, 2001). A wet hydrology was estimated to erode the reservoir sediment at an even faster rate. Both hydrologic scenarios indicated a small portion of reservoir sediment would remain in place even after a decade of simulation.

Fish regulating agencies and downstream landowners were concerned about where the eroded reservoir sediment would be deposited in the downstream river channel and how long it might be prevalent. The reservoir sediment estimate of 150,000 m^3 was equivalent to only 1–2 yr of average annual sediment load. The average annual sediment load was computed by determining the sediment transport capacity at a typical alluvial section, and reducing it by 30% to account for the proportion of the basin above Lost Creek Dam (assuming all coarse sediment is trapped in this reservoir). There are 18 pools of varying size between Savage Rapids Dam and the first major tributary and sediment source located 19.3 km downstream (the Applegate River shown in Fig. 1). The pools have an estimated cumulative storage capacity of 400,000 m^3, which is slightly more than double the estimated reservoir sediment volume. The first two major pools in the 2.6 km below the new intake and former dam are some of the larger pools and have an estimated capacity of ~115,000 m^3. Below the Applegate River, the river enters a canyon reach, which, based on a total stream power assessment, has a relatively high sediment transport capacity. Based on these simple calculations, it was expected that deposition from dam removal would only be detectable in the 19.3 km reach between the dam and the Applegate River and would largely occur in pools until flushed by high flow events.

Josephine County requested a flood impact analysis to verify that sediment aggradation would not result in increased flood stage. To accommodate the county's request for a flood impact study, the 1-D sediment transport model used for reservoir erosion was also utilized to estimate downstream river aggradation (U.S. Bureau of Reclamation, 2001). Initial 1-D model results indicated eroded reservoir sediment would be permanently deposited in downstream pools and not be scoured out even after a simulation of a 10 yr hydrograph including substantial floods (Fig. 4). Permanent filling of downstream pools from eroded reservoir sediment did not seem reasonable for long-term estimates because the Rogue River has existing deep pools. Further, field measurements from the U.S. Geological Survey (USGS) gauging station at Grants Pass showed a pool filling and scouring up to 2 m during a large flood in the 1990s (U.S. Bureau of Reclamation, 2001). Depth-averaged sediment transport models have a tendency to fill pools with sediment because of utilization of a single depth-averaged velocity at each cross section, which does not represent scour processes that can occur during floods. To account for this model limitation, the 1-D model was "primed"

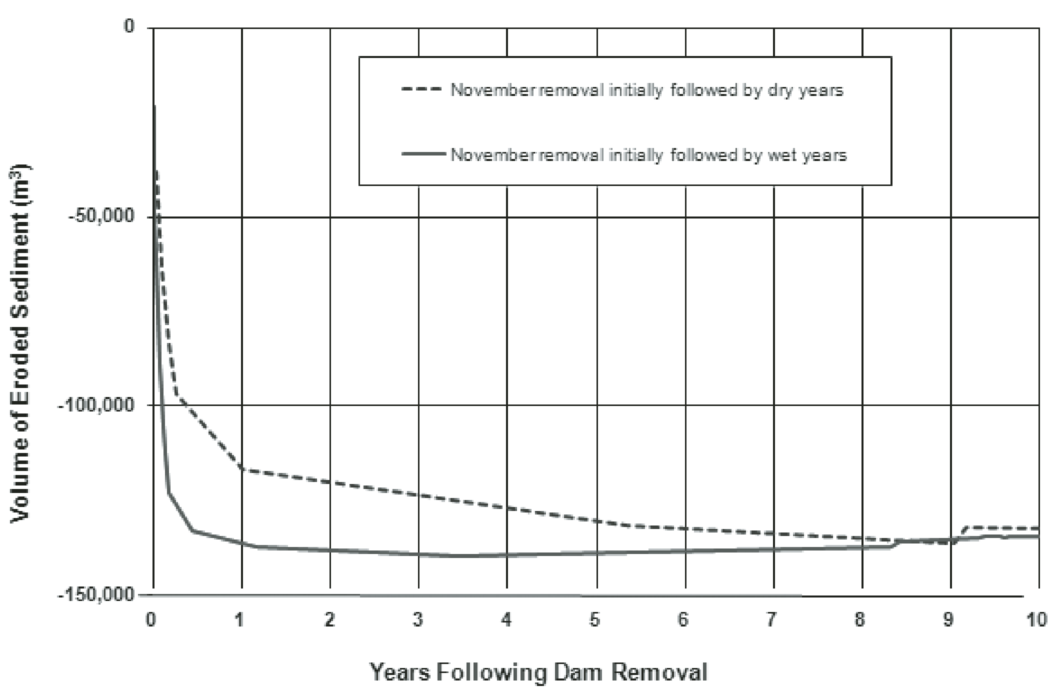

Figure 3. Modeled duration of reservoir sediment erosion following dam removal starting in November followed by a wet and dry hydrology.

to allow the pools to fill with background sediment load, and then the reservoir sediment erosion and downstream transport were simulated. The approach of limiting pool storage resulted in temporary deposition of only a few feet in downstream pools, which was eroded in the model simulation during high flows. The riverbed for ~1.6 km downstream of the dam was modeled as a continuous riffle because survey data were not available at the time of modeling, so limited deposition was estimated to occur. With the modified approach, reservoir sediment was estimated to be transported past the Applegate River (19.3 km downstream) within a 10 yr period. Dam removal followed by dry hydrology (infrequent, smaller storms) was estimated to take up to 10 yr to transport all of the sediment, whereas a wet hydrology took only a few years.

SEDIMENT BREACHING

The river was restored to its original position on 9 October 2009 by breaching the reservoir sediment deposit. October was selected because it was just before the start of the Endangered Species Act–listed Southern Oregon–Northern California Coastal Coho run into the Rogue River. Removing the dam in October would also provide an entire winter flood season to erode and transport reservoir sediments past the new GPID intake before irrigation needed to start in the spring. The contractor built a pilot channel with heavy equipment, which quickly restored the river position and limited potential fish stranding. Had there been no risks of blocking fish passage, a pilot channel would not have been required to initiate river erosion processes. In the month following dam removal, both natural and man-made debris was observed to erode from or become exposed in the former reservoir, including tires, logs, steel parts, and various other materials. A timber crib structure became exposed ~91 m upstream of the dam that was subsequently removed by the contractor after noticing it was causing a hydraulic drop within the pilot channel.

An unexpected public reaction during the sediment breaching was the local excitement to be the first boaters to travel through the restored river section. Although there were posted signs and interviews in the paper recommending avoiding the river during construction, several jet boats and dories went through the site on the day the sediment breaching occurred. Because of the rapidly changing channel, exposed debris, and extremely turbid conditions, it was difficult to see river bottom conditions, making the conditions unsafe. Tragically, one fatality occurred as a jet boat traveled down the channel and hit something on the river bottom, causing the passengers to be thrown from the boat. The following day, a large group of around 100 people floated through the site. The river was much less turbid, and the group was able to carefully observe downstream conditions at the site, and there were no additional accidents, although one boat was not able to maintain the recommended path and was swamped. Large numbers of people were also observed to access the newly exposed bedrock to attempt to mine for gold that may have been in the sediment deposits.

RESERVOIR EROSION AND RIVER DEPOSITION MONITORING RESULTS

Monitoring data were collected to assess how reservoir sediment erosion and downstream deposition impacts compared with preremoval estimates. Time-lapse cameras and simple field observations proved very useful for documenting the speed and spatial extent of the initial reservoir sediment erosion. The river flow during the initial sediment breaching was ~37 m^3/s, and remained less than 57 m^3/s without any high flows through the end of December. A large portion of pilot channel erosion occurred within the first few days (Fig. 5). By the end of October, pilot channel erosion had slowed such that lateral widening was not detectable in the repeat photographs. Large portions of reservoir sediment remained on either side of the enlarged pilot channel.

On 1 January 2010, the first post–dam-removal flood peak of 300 m^3/s occurred (Fig. 6). Based on a March 2010 survey, ~50% (75,000 m^3) of reservoir sediment was eroded by the river from the initial headcut processes and the January flood. The eroded volume of 50% is slightly less than the 1-D model estimate of 66% for the first winter using a dry hydrology. The smaller volume of erosion may in part be due to the mean daily flow for the 1 January 2010 flood, which was ~200 m^3/s smaller than the first modeled mean daily flood value of 283 m^3/s. Other contributors are uncertainty in predam topography and the limitations of using a 1-D model to accurately compute the headcut and widening processes following dam removal, particularly in pool environments. Another small flood of similar magnitude occurred in June 2010, but only minimal reservoir sediment erosion occurred based on visual observations and a survey done in August 2010.

Following the January flood, "Savage Rapids" was fully restored above the dam, but to a higher elevation than estimated from drilling data (Fig. 7). The exposed rapid contains large sporadic boulders that were likely not captured in the drill-hole data. This highlights the difficulty in determining robust post-dam removal topography in a pool-riffle system with irregular bedrock outcrops and boulders. Drill-hole or probing data also penetrate to "refusal" or rock, which can sometimes go below the predam riverbed into the alluvial sediment layer. The reservoir sediment extended above Savage Rapids and had completely filled a historical pool. This pool was still full of reservoir sediment as of August 2010, even after the January and June floods (Figs. 7 and 8). The first winter floods were small—about half the magnitude of a 2 yr flood. During the second winter after dam removal (2010–2011), high flows reached a 2 yr flood frequency. It will be informative to see if these floods were of sufficient magnitude and duration to partially or completely scour the pool within the former reservoir, or if the pool sediment will require an even larger flood to erode.

Just downstream of the former dam, an ~5-m-deep scour hole had been created from water flowing over the dam (Fig. 7). Monitoring data show that the scour hole simply filled with sediment and did not cause an upstream bed lowering, largely

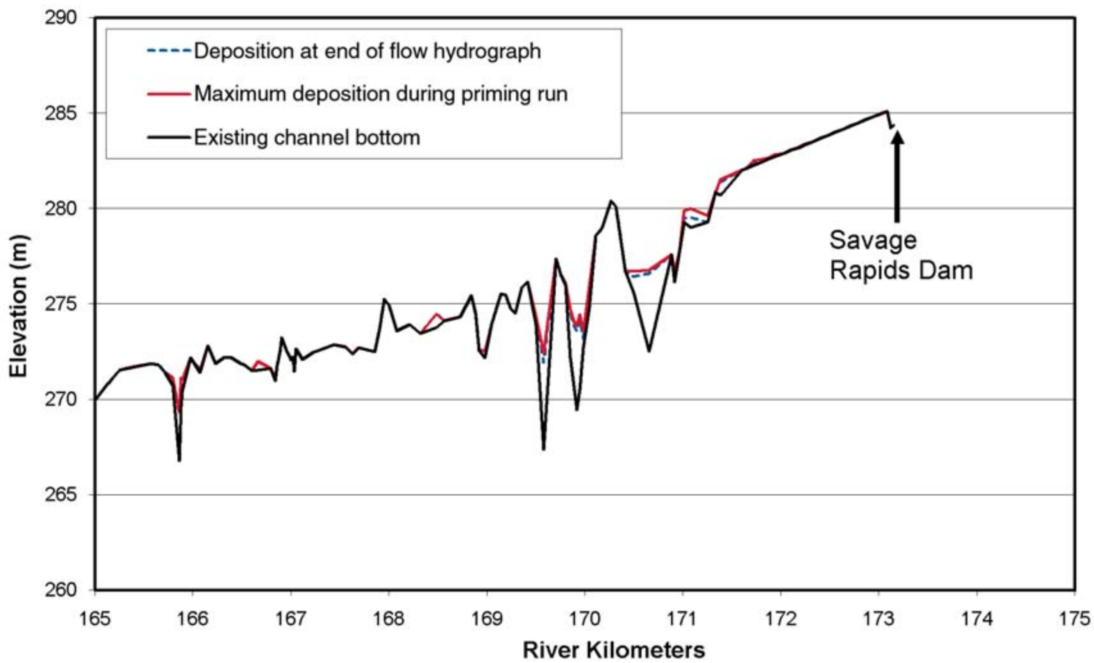

Figure 4. One-dimensional model results showing permanent deposition in pools if no modification to approach is included.

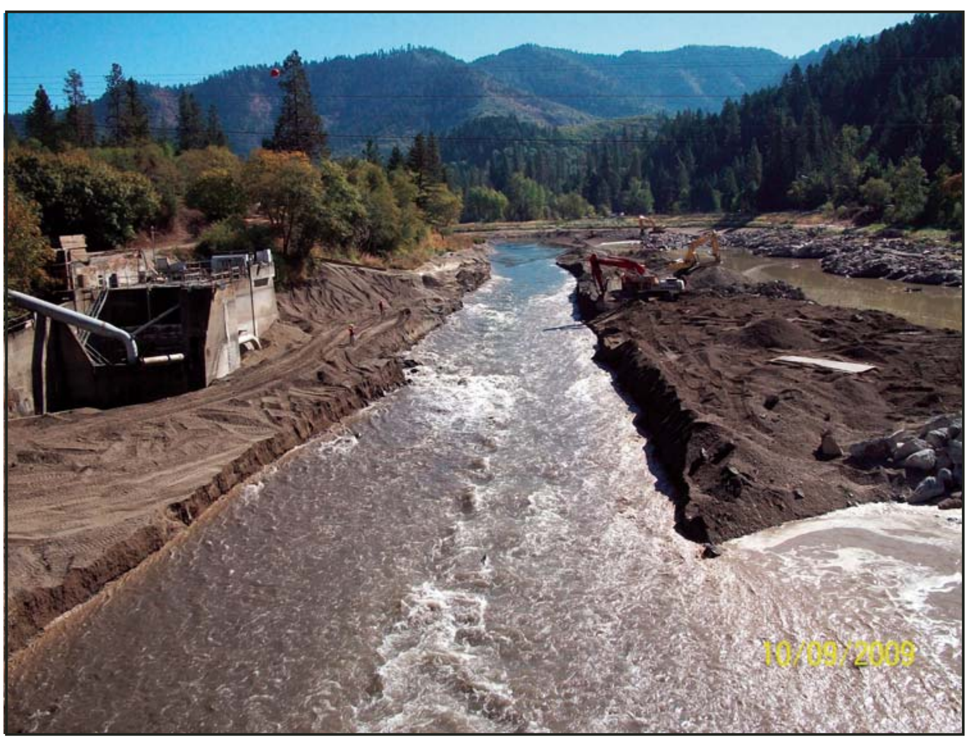

Figure 5. Looking upstream on 9 October 2009 at pilot channel erosion.

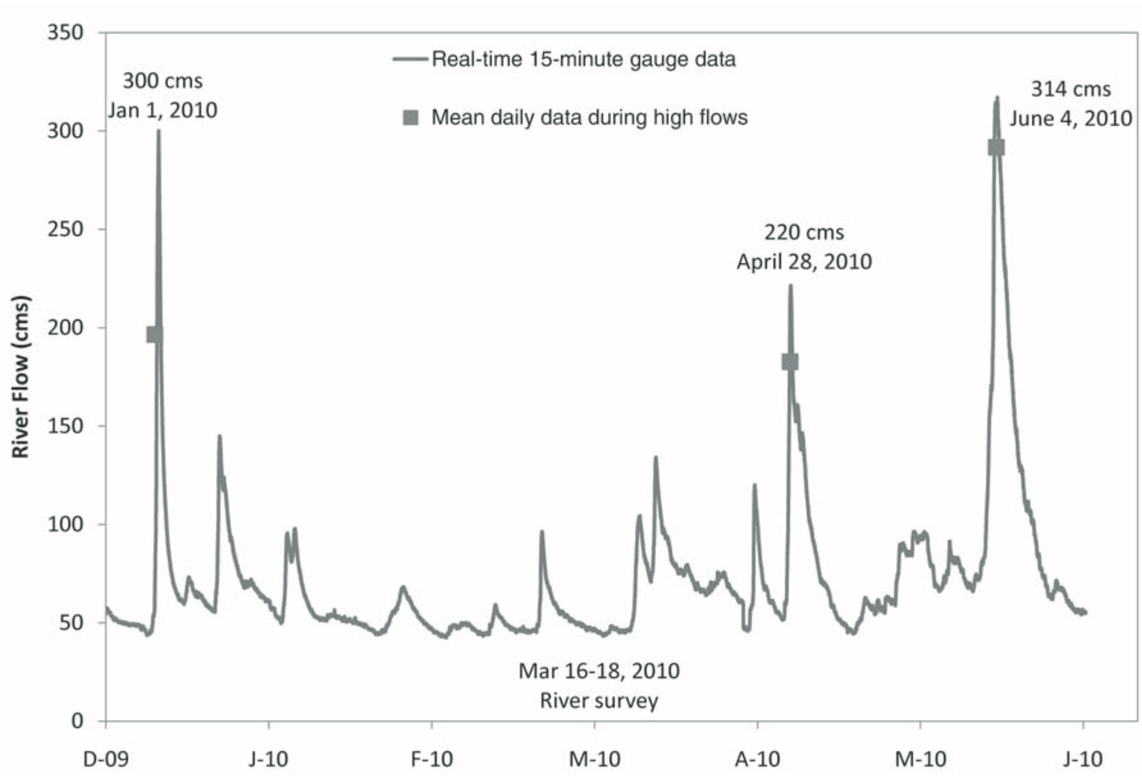

Figure 6. Real-time and mean daily provisional stream flow data for December 2009 to June 2010 from the Grants Pass U.S. Geological Survey gauge (14361500) ~8 km downstream of Savage Rapids Dam. cms—cubic meters per second.

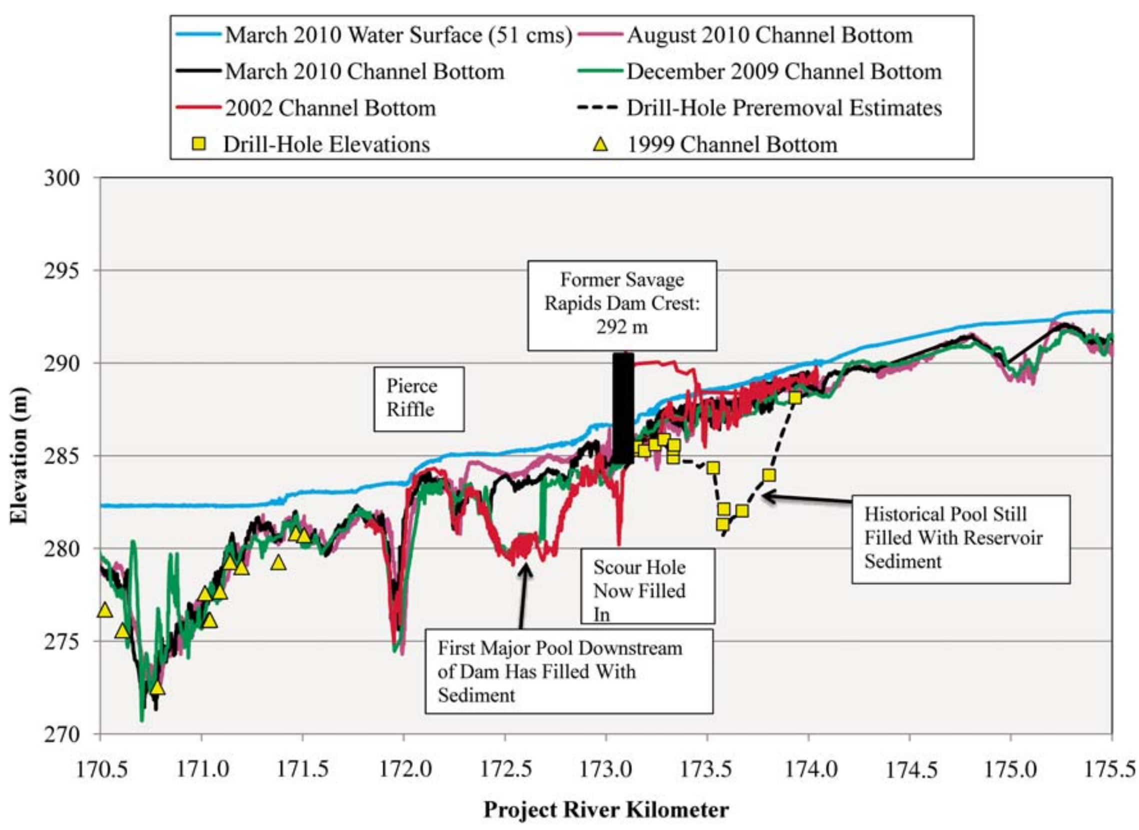

Figure 7. Longitudinal profile of erosion and deposition following dam removal. cms—cubic meters per second.

Figure 8. Sediment conditions at Savage Rapids Dam as of July 2010.

because of the bedrock controls in Savage Rapids. Further downstream of the dam, the first large river pool (also 5 m deep), which had partially filled with sediment from the low-flow reservoir sediment erosion (October through December), had nearly completely filled with reservoir sediment after the January 2010 flood (as measured in March 2010; Fig. 7). After the June 2010 flood, the first pool completely filled in, but filling of pools further downstream was not detected. This first major pool is estimated to have a storage capacity of 40,000 m^3, accounting for about half of the measured reservoir sediment erosion. Downstream riffle crests remained free of deposition as estimated by the 1-D model.

LOCAL SEDIMENT IMPACTS AT THE PUMPING PLANT

GPID considered locations for the new pumping plant and intake within their existing property ownership, which extended ~0.5 km downstream and ~1 km upstream. A location upstream of the majority of reservoir sediment would have reduced the potential for burial and turbidity impacts following dam removal. However, because the pumping plant and intake had to be constructed and be operational prior to dam removal, constructing the plant upstream of the dam would have required building large cofferdams in the reservoir pool that were cost prohibitive. Further downstream of the dam, private land ownership was prevalent, and there were no options for construction sites. As a result, GPID selected a single pumping plant location on the south (left) side of the river immediately downstream of the dam, with a pipe bridge to carry water for delivery to a canal on the opposite side.

The greatest challenge in designing the intake ahead of dam removal was the uncertainty in postremoval channel topography. The selected pump intake location was in the immediate path of the eroding reservoir sediment. Bedrock outcrops that had the potential to cause eddies and deposition in front of the intake were buried under the reservoir sediment, making their configuration unknown. The U.S. Bureau of Reclamation design engineers requested a two-dimensional (2-D) hydraulic model, SRH-2D, be utilized to refine the alignment and position of the pumping plant in the river to avoid potential eddies from the bedrock outcrops (U.S. Bureau of Reclamation, 2006; Lai, 2008, 2010). Additional topographic data were gathered to fill data gaps from the prior 1-D sediment transport modeling in the 1.6 km downstream of the dam. Drilling data were used to develop a postremoval topographic surface in the reservoir, assuming for modeling purposes that all of the reservoir sediment had already been eroded and transported past the intake. Only limited drilling data were available in the bedrock areas.

Despite uncertainties in the exact bedrock configuration within the reservoir, the 2-D model estimates confirmed that there was a potential for hydraulic eddies at the selected intake site (Fig. 9). Conceptually, it was assumed that a uniform flow line was needed along the south shoreline to limit potential future deposition in front of the intake. Evaluation of a number of alternatives with the 2-D model indicated that shifting the intake ~9 m farther out into the river would reduce the potential for sediment deposition without substantially blocking navigation or fish passage in the river channel. Shifting the intake into the main river flow would also improve the ability to meet fish sweeping velocity criteria of 0.61 m/s established by fish regulating agencies. The sweeping velocity is the flow velocity component parallel to the screen face with the pump turned off, which is designed to prevent fish from being swept into the intake. Excavation of bedrock outcrops as part of dam removal was also considered as a modeling alternative, but this was not adopted because there

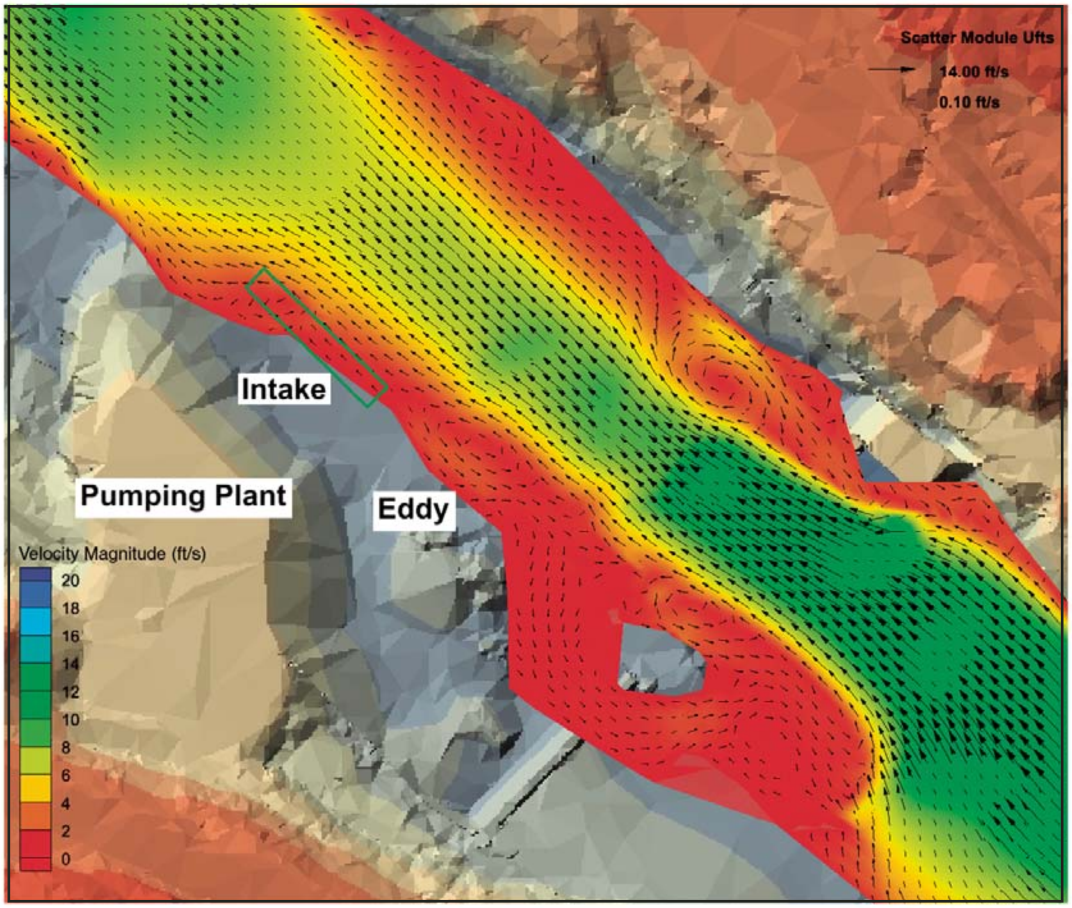

Figure 9. Two-dimensional model velocity results showing depth-averaged velocity (ft/s) at 238 cms (cubic meters per second) and estimated eddy upstream of intake (left bank) prior to shifting the intake farther out into the river. Ufts is the model-computed directional velocity vector in ft/s.

was a lot of uncertainty in the extent of bedrock that could not be resolved until the dam was removed.

Because of the uncertainty in dam removal, modeling reports noted that some excavation of reservoir sediment may be needed in front of the intake if the first winter flood season did not scour the sediment. However, the need for potential excavation was not highlighted in summary discussions to stakeholders, and no adaptive management plan was developed. Once the sediment was breached in October 2009, the intake was closely monitored to ensure that operation could again start in the spring of 2010. In the 3 mo low-flow period following dam removal, no sediment impacts occurred at the intake, and all deposition was limited to the opposite (north) side of the river channel. The January 2010 flood just reached the threshold of sediment transport for this reach of the Rogue River. As a result, eroded reservoir sediment was not transported very far and was deposited immediately in front of the GPID intake. To ensure intake operation started up in April, deposited sediment was excavated to clear out a channel in front of the intake (Fig. 10). Because no prior adaptive management plan had been developed, negotiations had to occur expediently with regulating agencies while ensuring there was limited or no impact to fish.

It is estimated that 7500–11,500 m^3 of sediment were excavated and relocated in February 2010, ~5%–8% of the total 150,000 m^3 of reservoir sediment volume (Fig. 10). To eliminate potential fish stranding pools, a portion of the excavated sediment was used to fill in irregular bedrock floodplain topography immediately upstream and downstream of the remaining dam. The remaining excavated sediment was pushed into the riffle downstream of the intake. As the reservoir sediment was excavated, it was observed that the native bedrock extended farther out into the river channel than expected, creating eddies along the south shoreline where the intake was located (Fig. 10). Discharge and velocity measurements accomplished by the USGS Medford, Oregon, office indicated that large boulders (presumably native) within Savage Rapids and along the south shoreline resulted in more river flow being directed to the north, away from the intake. To encourage more flow to be directed toward the intake, a small portion of the boulders in Savage Rapids was relocated and used to armor the fill area upstream of the remaining north

Figure 10. Looking upstream near the end of the February 2010 excavation work, noting bedrock that extended farther out than estimated.

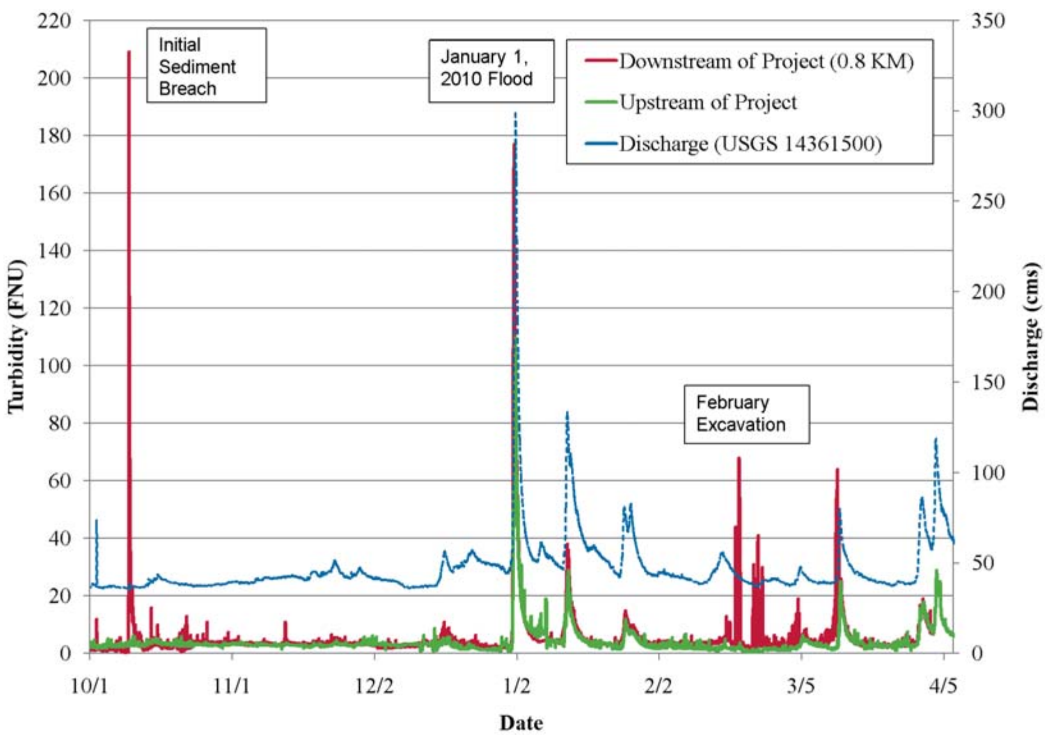

Figure 11. Measured turbidity following dam removal. cms—cubic meters per second. FNU is the turbidity measurement unit, and stands for Formazin Nephelometric Unit, measured scattered light at 90° from the incident light beam with an infrared light source.

dam section. Additionally, a small section of the exposed bedrock was chipped off to encourage a more uniform flow path along the face of the intake.

In April 2010, an additional flood of 220 m^3/s occurred that was even smaller in magnitude than the January flood (Fig. 6). This flood reworked additional reservoir sediment, and dive teams and remote cameras revealed that a small amount of sediment had been deposited in the pool adjacent to the intake. The amount of deposition from the April 2010 flood was visibly not as widespread as had occurred from the January 2010 event. About 1500 m^3 of sediment (1% of total reservoir volume) were again excavated and placed in the downstream riffle to ensure the intake could properly function at the end of April. The combined cost of the February and April excavation was less than 0.5% of the total project cost.

At the end of the 2010 irrigation season, the intake was closed shut for the winter. The larger floods that occurred during the 2010–2011 winter season and removal of the upstream Gold Ray Dam in 2010 have the potential to contribute additional coarse sediment load past the GPID intake. GPID has recently purchased an excavator to help with potential future excavation needs at the intake. It is expected that future deposition impacts will diminish relative to the initial impacts immediately following dam removal.

WATER QUALITY

Because of the limited amount of fine sediment and expected short duration, preremoval estimates of water-quality impacts were limited to a conceptual model. Immediately after dam removal, suspended sediment concentrations were expected to be high relative to background levels, particularly because the sediment breaching occurred during a low-flow period. However, concentrations were expected to quickly subside and subsequently increase in diminishing levels above background and only with a larger flood than had occurred previously. Best practice measures were included during construction activities to minimize impacts. Silt fences were placed downstream of areas being disturbed that could result in increased suspended sediment concentrations.

Monitoring included turbidity measurements to provide an indication of the duration of water-quality impacts upstream and downstream of the dam removal (Fig. 11). The initial turbidity caused by the pilot channel erosion reached 200 times background levels only a couple hours after breaching the sediment. By 5 p.m., turbidity had lowered to less than 50 times background levels, and by the next morning, less than 20 times background levels. Within 3 days following sediment breaching, turbidity had returned to near background levels, all of which occurred during low-flow conditions.

During the January 2010 flood, the turbidity was ~1.6 times background levels. Turbidity was generated at the project site during the February 2010 excavation work that occurred in low flow, but it was quickly diminished after excavation stopped. GPID has not had any operational impacts as a result of the elevated turbidity, largely because the sediment breaching and reservoir sediment erosion occurred during nonirrigation periods. The City of Grants Pass operates a water treatment plant ~8 km downstream of Savage Rapids year-round but was able to effectively treat elevated suspended sediment concentrations caused by this project.

The turbidity recorder downstream of the dam was located in the first major pool, which became completely filled with eroded reservoir sediment. In future projects, it is recommended to have at least two downstream turbidity recorders, one near the project site and one farther downstream out of the potential sediment deposition area.

SUMMARY AND CONCLUSIONS

The removal of Savage Rapids Dam was a unique learning opportunity to compare preremoval estimates of sediment impacts with post–dam-removal monitoring data. Had a water intake not been constructed immediately downstream of the dam, predam removal estimates of sediment impacts could have been adequately addressed with a conceptual model and simple mass balance computations. Mitigation for short-term, localized sediment impacts following dam removal would also not have been needed. Summary discussion is presented here on developing the reservoir sediment volume estimates, estimating reservoir erosion and downstream deposition following dam removal, suspended sediment impacts, and incorporation of an adaptive management plan and safety issues immediately following dam removal and throughout the first flood season.

Computing an accurate reservoir sediment volume is crucial in estimating potential reservoir sediment impacts. Using simple wedge-based approximations of reservoir sediment volume without consideration of seasonal operations of the dam and predam river morphology resulted in conservatively high estimates. Additional field data and incorporating knowledge of seasonal reservoir operations reduced uncertainty of the sediment volume estimate. However, even with state-of-the-art drilling equipment, uncertainty was still present due to irregular bedrock outcrops and difficulty in distinguishing the top of predam riverbed alluvium from reservoir sediment deposits.

The 1-D sediment transport model utilized was able to quantify timing of reservoir sediment erosion, but the uncertainty in hydrology following dam removal made it difficult to estimate short-term, localized impacts. The 1-D model accurately predicted that deposition in the downstream river would not occur on hydraulic controls (riffles), and, therefore, would not increase future flood stage as a result of released reservoir sediment. However, the 1-D model uses a depth-averaged approach that could not accurately predict the magnitude or duration of deposition in downstream pools. For this project, a conceptual model with simple mass balance calculations of reservoir erosion and downstream deposition would have sufficed for analyzing general trends and potential impacts. Because of the pumping plant intake that was immediately downstream of the dam, this particular project required additional data collection and modeling for design that would not have been required based solely on concerns regarding reach-scale sediment impacts. In future projects with features that have a high risk to sediment impacts in close proximity to the dam, it is recommended that state-of-the-art tools be considered. Incorporation of a physical model, field test, or more advanced numerical modeling tool such as 2-D sediment models may improve the estimating capability (Lai and Greimann, 2010).

Savage Rapids would have benefited from the use of an adaptive management plan because of the inherent uncertainties in short-term, localized estimates. The potential for sediment mitigation work in the first winter following dam removal was alluded to in technical reports, but it was not clearly communicated, and, therefore, it was unexpected by stakeholders and regulators. Although the excavation work required was a fraction of the total project cost (less than 0.5%) and relatively easy to implement, it temporarily reduced the credibility of the project and required special provisions to implement from a regulatory perspective. Had an adaptive management plan been collaboratively developed prior to dam removal, it may have lessened the difficulties in implementing relatively minor and short-term mitigation resulting from a dry winter.

Because of the small percentage of fines in the reservoir sediment, suspended sediment impacts were of short duration. Measured turbidity associated with dam removal lasted only a few hours to days and dissipated quickly in the downstream direction. The timing of the reservoir sediment breach was planned to occur when limited salmon and steelhead were present in the downstream river in order to minimize any potential effects to fisheries. Short-term turbidity impacts occurred during post-removal sediment excavation activities and during high flows, but turbidity impacts are diminishing with each subsequent flood. For similar dam removal projects with limited fine sediment and a reservoir sediment volume that is similar to the annual coarse sediment load of the river, extensive impact analysis prior to dam removal or more elaborate monitoring of suspended sediment may not be needed.

In future dam removal projects, more aggressive education and collaboration on safety concerns during and immediately following a dam removal project would benefit local boaters, particularly when the site is easily accessible and in public view. Education is needed for all boater levels of the dynamic and unknown conditions specific to a dam removal project, including uncertainties that may arise due to unexpected debris and turbidity conditions that prevent observation of flow conditions. Posting information at entry points to the river could be incorporated in addition to direct communication at the site itself.

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