Sediment Transport Simulation of Klamath Dam Removals

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Abstract

Four Klamath River dams in California (Iron Gate, Copco I, Copco II, and J.C. Boyle) currently owned by PacifiCorp are scheduled for removal in 2021 by the Klamath River Renewal Corporation. Prior to the effort led by Klamath River Renewal Corporation, the Department of the Interior through the Klamath Hydroelectric Settlement Agreement conducted a study of the potential effects on the downstream river environment from removing these four dams. A one-dimensional model (SRH-1D) was used to simulate dam removal and the No Action Alternative of continued operation of the dams. With the dam removal eminent, a summary of the most important modeling results will assist in the development of efficient sediment monitoring efforts. It will also help to identify areas where numerical modeling can be improved after monitoring data is available. Lastly, a summary of the analysis will guide future dam removals studies.

The sediment stored in the PacifiCorp reservoirs is approximately 85% silt, clay and organic material that is 80 to 90 % water by volume and highly erodible. The remaining material is mostly sand with a relatively small amount of gravel present. Approximately 15 million cubic yards of sediment projected to be stored in the reservoirs by 2021. Based upon the SRH-1D simulations, drawdown of the four PacifiCorp Dams will release between one- and two-thirds of the approximately during the first year of drawdown. . If there is a wet year, more material will likely be eroded and if there is a dry year, less material will be eroded from the reservoirs. The river is expected to return to its pre-dam alignment at each reservoir and have a similar width to pre-dam conditions. The sediment that is left behind in the reservoirs would raise the floodplain terraces above the pre-dam conditions; as a result, the floodplains within the former reservoirs are expected to be inundated less frequently than typical floodplains in the basin.

Most of the reservoir sediment will be transported to the ocean during the period of concurrent drawdown at the four sites which will last from January 1, 2021 to mid-March, 2021. Silt and clay will be quickly mobilized during drawdown and transported downstream in suspension, temporarily impacting water quality. The maximum sediment concentrations during this period may be more than 10,000 mg/l downstream of Iron Gate, which is the most downstream dam. Tributaries entering Klamath River should significantly dilute these concentrations to less than 2,000 mg/l at the mouth of the Klamath River, approximately 190 miles downstream of Iron Gate Dam. Sediment concentrations are expected to resume to background levels by the end of the summer 2021 regardless of the hydrology over this time period. The erosion of reservoir sediment is limited to the first year because aggressive revegetation of the remaining reservoir sediment is planned immediately following dam removal, which will stabilize the sediment from erosion due to rainfall. In addition, the reservoir sediment dramatically increases its resistance to erosion once it dries out and consolidates.

The bed material within the reservoirs and just downstream of Iron Gate Dam is expected to have a high content (30 to 50 %) of sand immediately following reservoir drawdown until a

flushing flow moves the sand sized material out of the reach. The flushing flow will need to be at least 6,000 cfs , which is approximately a 2-yr flood (Reclamation, 2011), and last several days to weeks to return the bed to cobble and gravel with a sand content less than 20%. After the flushing flow, the bed is expected to maintain fractions of sand, gravel, and cobble, similar to natural conditions.

Introduction

Four dams (J.C. Boyle, Copco No. 1, Copco No. 2, and Iron Gate) constructed on the Klamath River in California between 1918 and 1962 are scheduled for removal in 2021. The dams were built and are currently owned by PacifiCorp and are scheduled for removal by the Klamath River Renewal Corporation. The locations of the dams within the Klamath River watershed are shown in Figure 1 and their characteristics are given in Table 1. The most downstream dam is located approximately 190 river miles upstream of the Pacific Ocean on the Klamath River.

One of the major concerns with large dam removals are the sediment impacts associated with them (Reclamation, 2017). Because of these concerns, the Department of the Interior through the Klamath Hydroelectric Settlement Agreement studied the effects of removing these four dams. Reclamation (2011) documents the detailed hydraulic and sediment studies evaluating the effects of dam removal and the current plan for dam removal is given by Klamath River Renewal Corp (2018).

The goals of summarizing here the most important results presented by Reclamation (2011) are to:

1. Assist the development of efficient sediment monitoring for the project.
2. Clearly document the predicted impacts so that after monitoring data are available they can be easily compared to the predictions and areas where models need to be improved can be identified.
3. Illustrate an example dam removal sediment analysis that can help scope and guide future dam removals.

Table 1. Properties of Klamath River Dams scheduled for removal (From PacifiCorp, 2004).

Item	**J.C. Boyle**	**Copco No. 1**	**Copco No. 2**	**Iron Gate**
Completion Date	1958	1918	1925	1962
Dam Location (RM)	224.7	198.6	198.3	190.1
Dam Type	Earthfill	Concrete	Concrete	Earthfill
Dam Height (ft)	68	126	33	173
Storage at Normal Pool Elev (acre-ft)	3,495	46,867	73	58,794

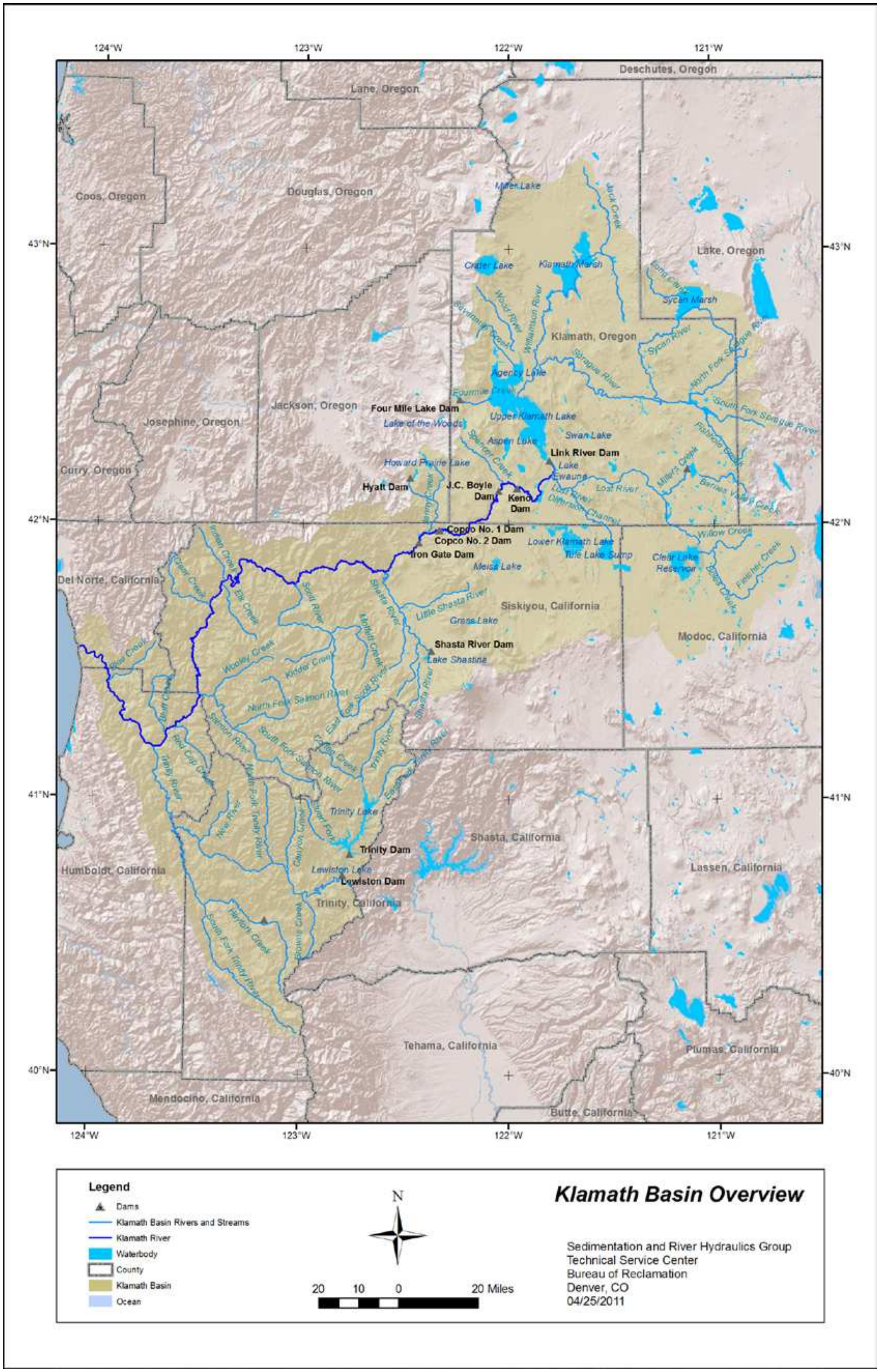

Figure 1. The Klamath River Basin and the dams scheduled for removal.

The Klamath River flows from its headwaters near Crater Lake, Oregon, to its confluence with the Pacific Ocean in northern California. The Klamath Hydroelectric Project (Project) is owned and operated by PacifiCorp, and includes four power generating developments along the mainstem of the Upper Klamath River between river mile (RM) 228 and RM 190, at J.C. Boyle, Copco No. 1, Copco No. 2, and Iron Gate Dams. The smaller East Side and West Side developments are located further upstream at the Bureau of Reclamation's (Reclamation's) Link River Dam at RM 254, and have been previously proposed by PacifiCorp for decommissioning. The Project also includes a re-regulation dam with no generation facilities at RM 233 (Keno Dam), and a small (2.2 MW) generating development on Fall Creek, a tributary to the Klamath River at RM 196.3. The installed generating capacity of the existing Project is 169 MW and, on average, the Project generates 716,800 MWh of electricity annually. PacifiCorp began relicensing proceedings before the Federal Energy Regulatory Commission (FERC) in 2000, with a proposal for continued operation of their facilities with new environmental measures. A Final Environmental Impact Statement (EIS) was issued by FERC in November 2007 which included Mandatory Conditions requiring the installation of new fish passage facilities at each dam, or the consideration of dam removal.

The Klamath Hydroelectric Settlement Agreement (KHSA) was completed in February 2010 for the express purpose of resolving the pending FERC relicensing proceedings by establishing a process for potential facilities removal and operation of the Project until that time (KHSA, 2010). Under the KHSA, the Secretary of the Interior would determine by March 31, 2012 whether the physical removal in 2020 of all or part of each of the facilities, necessary to achieve a free-flowing condition and volitional fish passage, would (a) advance restoration of the salmonid fisheries of the Klamath Basin, (b) be in the public interest, including the potential impacts on affected local communities and Tribes, and (c) not exceed $450 million, which is the total amount to be provided by Oregon and California for facilities removal under the State Cost Cap. The KHSA described the process for engineering and scientific studies, environmental review, and participation by the signatory parties and the public to inform the Secretarial Determination. The KHSA was linked to the Klamath Basin Restoration Agreement (KBRA) that required substantial federal funding to complete. There was subsequently no funding approved for the KBRA and therefore a revised KHSA was completed in 2016 that provides for decommissioning the hydroelectric dams through the traditional Federal Energy Regulatory Commission (FERC) approval process.

The Klamath River Renewal Corporation (KRRC), which is a private non-profit guided by 13 board members, was formed to take ownership of four PacifiCorp dams —J C Boyle, Copco, No. 1 & 2, and Iron Gate —and then remove these dams, restore formerly inundated lands, and implement required mitigation measures in compliance with all applicable federal, state, and local regulations (http://www.klamathrenewal.org). PacifiCorp will continue to operate the dams in the interim. Dams upstream of J C Boyle —Keno and Link River Dams —are not part of the KRRC project. PacifiCorp will transfer Keno Dam to the United States government under the amended KHSA, and both Keno and Link River dams will remain operational.

Methods

The necessary information to make predictions of dam removal impacts include:

1. Reservoir sediment characterization including its volume, distribution and gradations
2. Geometry and hydraulic characteristics of channel
3. Sediment model parameters
4. Reservoir drawdown and hydrologic scenarios

Each of these pieces of information were input into SRH-1D (Huang, J. and Greimann, 2010). SRH-1D (Sedimentation and River Hydraulics - One Dimension) is a one-dimensional mobile boundary hydraulic and sediment transport computer model for rivers and manmade canals. Simulation capabilities include steady or unsteady flows, internal boundary conditions, looped river networks, cohesive and non-cohesive sediment transport, and lateral inflows. The model uses cross section based river information similar to HEC-RAS (Brunner, 2008).

Sediment Characterization

Detailed reservoir sediment investigations were performed by Reclamation (2011) to collect samples of reservoir sediment to determine physical and engineering properties. They were also used to estimate the thickness of reservoir sediment throughout all major sections of each reservoir. Though not discussed in this paper, the collected samples were also used for screening-level analysis of organic and inorganic chemical compounds within the reservoir sediment and, where present, to determine the level and extent of contamination.

Barge and boat-supported drilling/sampling took place at fifty-five locations in J.C. Boyle, Copco No.1, and Iron Gate reservoirs. Sixty-nine samples of reservoir sediment and pre-reservoir deposits were collected for gradation analysis, Atterberg limits, and field moisture content; seventy-three samples of reservoir sediment were collected for chemical analysis; and nineteen undisturbed samples of reservoir sediment were collected in Lexan liners for testing engineering properties such as shear strength. In Copco No. 2 Reservoir, boat-supported sampling of reservoir sediment was performed at sixteen locations, from the dam upstream for about 1,000 feet. No sediment was observed in Copco No. 2 because it operates essentially as an after bay of Copco I and is much smaller. This paper focuses on the physical properties of the sediment and how these were used to simulate the expected sediment transport.

Sediment Thickness, Volume and Gradations

There were close to 30 total drill holes in each reservoir that provided direct measurements of sediment thickness. This information was used to extrapolate the sediment depth throughout the entire reservoir. The specific methods employed for each reservoir are given below. The total reservoir sediment volume measured in 2006 and 2009 was 13.15 million cubic yards with thickness ranging from a few feet up to 10 feet. The gradations were typically silt and clay with localized areas of sand deposition at tributary confluences and along the historical (pre-dam) channel alignments. The total volume is estimated to increase to 15 million cubic yards by 2021.

The sediment depth at J.C. Boyle Reservoir was determined by combining the sediment sample information with field observations. In the upper portions of the reservoir, little or no sediment was found during drilling except in one bend of the historical stream channel. The extent of the deposition was limited to the historical stream channel. The total volume of sediment in J.C. Boyle

Reservoir was estimated to be 990,000 yd^3 and a summary of the physical properties is given in Table 2.

At Copco I and Iron Gate, an equation was developed to extrapolate measured sediment depths to locations without measurements. Beginning with the downstream end of the reservoir, a relative station (X) was calculated for each sample, where is $X = 0$ at the downstream end of the reservoir and $X = 1$ at the upstream extent of the reservoir. The relative depth with respect to each station (Y) was calculated by setting the minimum bed equal to 1 and the highest elevation in the cross section below normal pool equal to 0. The following function (Eq 1) was then fit to the observed data:

$$D = (a - bX^c)Y^d \qquad \text{Eq (1)}$$

where, D = sediment depth (ft)

X = relative stationing along reservoir

Y = relative depth within cross section ($=z/H$), where z is the vertical distance from the water surface, and H is the maximum depth at that cross section

a, b, c, d= fitted parameters

For Copco Reservoir, the relationship yielded an R^2 value of 0.84 and a root mean squared error of 1.1 ft. An estimate of the uncertainty of this volume was computed by multiplying the average error of the regression equation by the area of the reservoir. This equated to an uncertainty of 1.5 million yd^3, or 20 %. For Iron Gate Reservoir, the relationship yields an R^2 value of 0.54 and a root mean squared error of 1.0 ft. This equated to an uncertainty of 1.3 million yd^3 or 29 %. The absolute error was similar between Copco and Iron Gate, but the relative error at Iron Gate was significantly higher because the sediment thickness were significantly lower.

Maps of the final sedimentation depth in Copco I and Iron Gate are given in Figure 2 and 3. Notable in the maps of sediment deposition is the lack of large coarse deltas because little coarse sediment is supplied to this reach. Upper Klamath Lake traps all of the coarse material in the upper watershed. Further, there is a long, low gradient section of the Klamath River below Upper Klamath Lake that stores sediment. There are some tributaries that feed small amounts of coarse material to J.C. Boyle, but that is all trapped in J.C. Boyle. There are no large tributaries between J.C. Boyle and Copco I. Jenny Creek and a Lower Tributary supply some coarse sediment into Iron Gate Reservoir as evidenced by the relative thicker and coarser deposit at the delta location (Figure 3). The data collected at these tributaries were analyzed separately.

The average sediment size gradations of the sediment were based upon the gradations of the sampled drill cores. The samples were separated into the upper and lower sections of each reservoir and the major tributaries were also analyzed separately. The average gradation data of each of these zones is given in Table 2.

The sediment stored in the PacifiCorp Reservoirs is approximately 85 % silt, clay and organic material that is 80 to 90 % water by volume and, as a result, has an unusually low dry bulk density of about 20 lb/ft^3. The only locations with high sand content are at the head of J.C. Boyle Reservoir and in the tributary deltas in Iron Gate. There is also gravel present in the tributary deltas such as Spencer Creek in J.C. Boyle Reservoir, Jenny Creek at Iron Gate Reservoir, and other small watersheds that contribute sediment, but it is difficult to estimate the volume because it is much smaller than the volume of fine material.

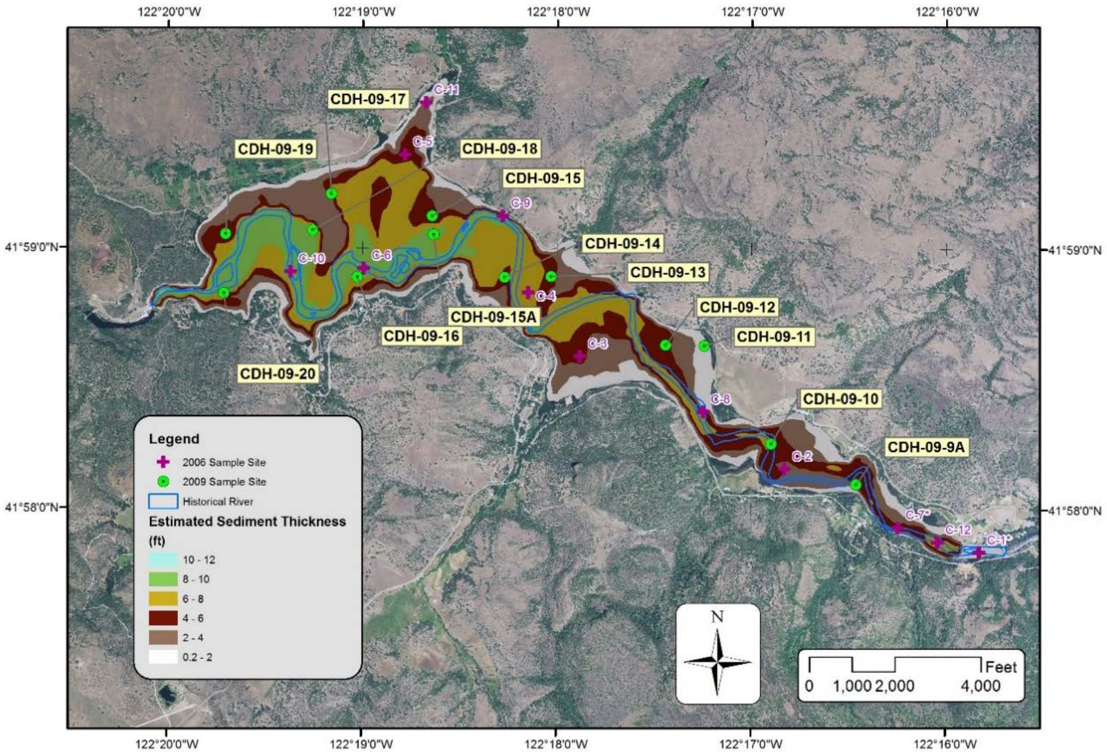

Figure 2. Copco I estimated sediment thickness and sample site locations and historical (pre-dam) river alignment.

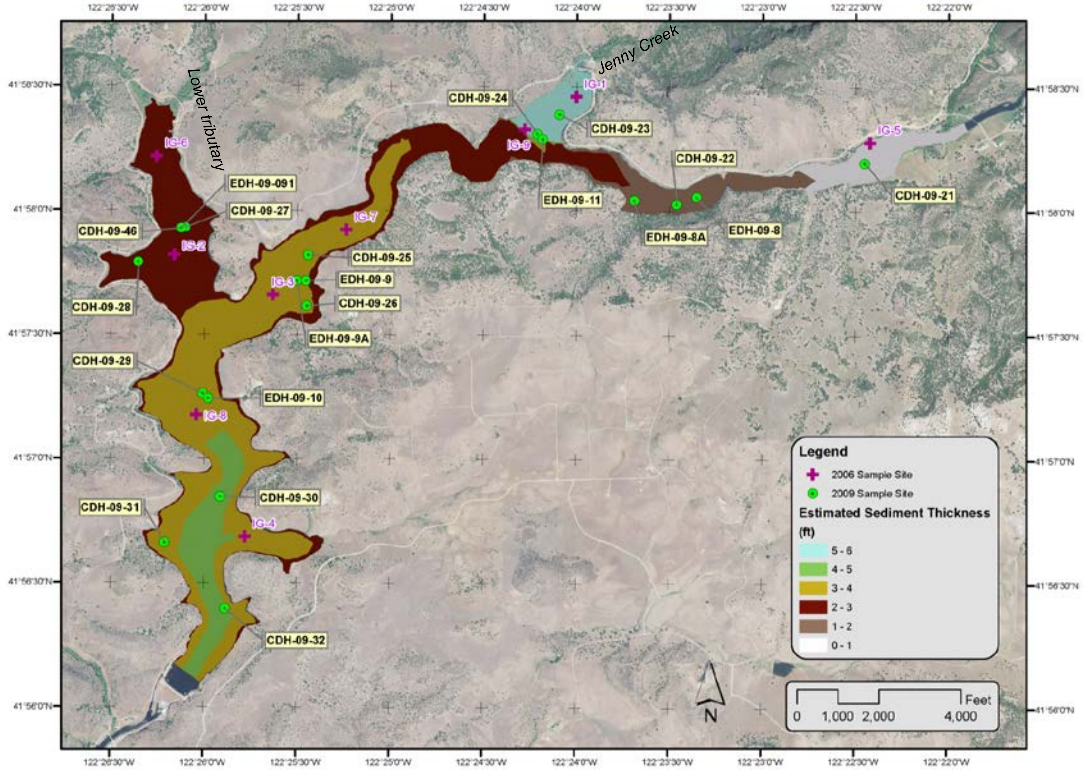

Figure 3. Iron Gate Reservoir estimated sediment thickness and sample site locations.

Table 2. Estimated Physical properties of reservoir sediment for Klamath River Dams as measured in 2006 and 2009.

Reservoir	Location	Volume (yd^3)	Silt and Clay (%)	Porosity (-)	Dry Bulk Density (lb/ft^3)	Estimated Dry Weight (tons)
JC Boyle	Upper	380,000	44	0.82	29.5	151,000
	Lower	620,000	88	0.90	16.3	136,000
Copco I	Upper	810,000	73	0.88	19.2	210,000
	Lower	6,630,000	88	0.88	18.7	1,674,000
Iron Gate	Upper	830,000	78	0.83	27.0	303,000
	Lower	2,780,000	86	0.88	19.8	743,000
	Jenny Creek	300,000	75	0.73	44.4	180,000
	Lower Trib	800,000	94	0.88	19.3	208,000
All		**13,150,000**	**85**	**0.87**	**20.3**	**3,605,000**

Erodibility

The timing and magnitude of predicted reservoir sediment transport is controlled by the erosive forces applied to the sediment and its erodibility. The equation used to predict the erosion of cohesive sediment erosion in SRH-1D is:

$$E = k_d(\tau - \tau_c) \qquad \text{Eq (2)}$$

where E = erosion rate,

k_d= erosion rate constant,

τ = shear stress, and

τ_c = critical shear stress.

For SRH-1D modeling, the constants in the above equation were directly measured using a jet test as described in Simons et al. (2010). The samples were collected by a 9-inch Ponar sampler. These samples were repacked in the lab and tested using a jet test device described in Simons et al. (2010). The results from the repacked samples of Simons et al. (2010) are shown in Figure 4 and the range of results is given in Table 3. Both wet (~80% water content similar to field conditions) and dried samples were tested and as expected dried samples showed significantly less erodibility than the wet samples. The simulations of erosion during drawdown used the Moist Sample's results. The base SRH-1D simulation used the median erodibility parameters; then a sensitivity analysis was performed using the 25th and 75th percentiles. The volume and timing of predicted reservoir sediment erosion in SRH-1D was not significantly affected by changing the erodibility parameters within this range. This is because the erosive forces computed in the 1D hydraulic model under riverine conditions are significantly higher than the range of measured critical shear stress. The rate of sediment erosion is largely dependent upon the drawdown rate and whether the sediment is exposed to flowing water. It is less dependent upon small changes to the critical shear stress and erosion rate constant.

Table 3. Summary of jet tests on sediment from all reservoirs from Simons et al. (2010).

	τ_c (Pa)	k_d (cm^3/N-s)
Moist Sample		
Minimum	0.000	0.23
25th Percentile	0.032	0.57
50th Percentile	0.21	0.82
75th Percentile	1.18	1.23
Max	4.83	5.6
Dry Samples		
Minimum	1.2	0.04
25th Percentile	2.7	0.12
50th Percentile	5.9	0.16
75th Percentile	17.8	0.32
Max	113.6	0.59

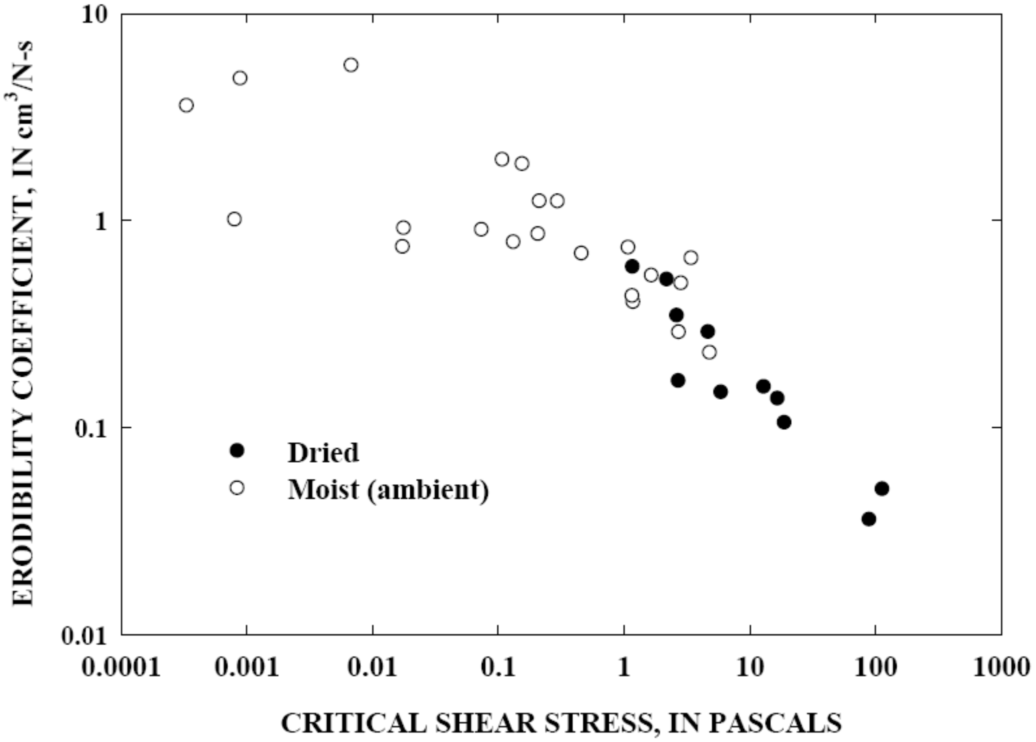

Figure 4. Measured critical shear stress (τ_c) and erodibility coefficient (k_d) for moist and dried samples (From Simon et al. 2010).

Fall Velocity

The fall velocity is used to determine the deposition rate of the sediment when shear stresses are low. During drawdown, the sediment eroded from the upper portion of the reservoir can redeposit in the lower pool. Deas et al (2010) collected samples of the sediment contained in the water column at one site upstream of Copco Reservoir, three sites within Copco Reservoir and one river site downstream of Iron Gate Dam. The samples were taken to a lab where the fall velocity of the particles were measured with a Laser In-Situ Scattering and Transmissometry with Settling Tube (LISST-ST) in a bench-top setting. The LISST-ST measures the settling rates and particle size distribution of the samples. The mean settling rate of the sediment sampled from the reservoir sites was 0.55 m/d (0.006 mm/s) and the average for the river sites was 2.7 m/d (0.03 mm/s).

Geometry and Hydraulic Characteristics of Channel

The model extents were from about 10 miles upstream of JC Boyle Dam and to approximately 17 miles downstream of Iron Gate Dam. The model includes both riverine and reservoir sections. The channel geometry is taken from LiDAR collected in 2010 and bathymetry collected by boat in the river as described in Reclamation (2012). The reservoirs were surveyed in 2001 by JC Headwaters, Inc. (2003). A continuous terrain was then generated by combining the LiDAR with the bathymetric data. Cross sections were then generated at an interval of approximately every 500 ft for the first 8 miles downstream of the Iron Gate and then increasing to 1000 ft downstream of that.

Channel and overbank roughness were calibrated to two different datasets. Channel roughness was calibrated to longitudinal profile data that was collected during the bathymetric survey, and the overbank roughness was calibrated to stream gage data. Daily flow data from the United States Geological Survey (USGS) gages (#11516530, 11520500, 11517500, 11519500) corresponding to the data collection period (10/11/09 – 10/18/09) were run in the hydraulic model. A range of channel roughness values were applied to the geometry and the resulting water surface elevations were compared to the measured water surfaces from the survey. One value for channel roughness from Iron Gate Dam to Happy Camp was unable to match the surveyed water surfaces. A relationship between reach-average bed slope and roughness was developed such that the modeled water surface elevations matched the surveyed water surface elevations to an acceptable level. The channel roughness ranged from 0.03 to 0.05. Generally, the higher slope reaches had higher roughness due to the larger bed material and presence of bedrock outcrops.

Sediment model parameters

There are several sediment model parameters necessary as input into the model. A brief description of the most important ones is given below.

Tributary sediment supplies were computed from results of Stillwater (2010), who estimated the annual loading to the Klamath River from tributaries. sediment rating curve was developed in the form of $Q_s = aQ^b$, where Q_s is the sediment load and Q is the flow rate, such that the annual loads are reproduced by the flow duration curve. The value of b was fixed at 2.3 based upon developing best matches to the observed sediment rating curves in the mainstem. The value of a was computed to match the annual sediment load.

There were four bed layers used to represent the reservoir sediment and river bed sediment. In the reservoir, the upper two layers represented the reservoir sediment and the bottom two layers represented the pre-reservoir sediment.

The sediment size classifications range from 0.00002 mm to 2048 mm in diameter. One size class is used to represent the silt/clay fractions, which is assumed to be all sediment smaller than 0.0625 mm. Sediment larger than 0.0625 mm is separated into size classes separated by powers of two starting at 0.0625 mm. The bulk density was taken from the average bulk density in Table 2, while the bulk density assumed for the non-cohesive material was 100 lb/ft^3, which is typical for sandy material. Bed material gradations for the river reaches are taken from Reclamations sampling in 2009 downstream of Iron Gate and PacifiCorp's (2004) bed material information upstream of Iron Gate (Reclamation, 2012).

The reservoir sediment thicknesses were taken from the estimates described previously. Because the sampling occurred in 2006 and 2009, but the removal was planned to occur in 2020, the thicknesses were increased to estimate the thickness in 2021, when dam removal will occur. This increases the sediment volumes in the reservoirs by 24% at Iron Gate, 12% at Copco, and 22 % at J.C. Boyle. It is estimated that there will be 15 million yd^3 of sediment stored behind the three reservoirs by 2020. SRH-1D allows the definition of bedrock and the pre-reservoir sediment in the reservoir reaches was assumed to be non-erodible bedrock.

The erosion rate of the cohesive fractions is controlled by Eq. 1 as described previously. For non-cohesive sediment (assumed to be all sediment greater than 0.0625 mm) the Parker (1990) bedload equation is used to predict sediment transport movement if D50 is greater than 2 mm, while the Engelund and Hansen (1972) formula is used to predict the movement if the D50 is less than 2 mm.

The above water angle of repose is important to defining the stability of the reservoir sediment. Geotechnical tests indicated that the angle of repose was above 25°, but Strauss (2010) indicated that this is likely an upper estimate and that the actual value could be significantly lower. Samples indicated the samples rapidly increase in shear strength when drained. As a simple test, a container of the moist sample was tipped at a 15° a day after placement. The slope was maintained and the sediment did not show any significant movement. Therefore, as long as the sediment is freely drained, the sediment should an angle of 15° or greater shortly after drawdown and the assumed angle of repose is 15° for most simulations, but some model sensitivity of this parameter is conducted using an angle of repose ranging down to a value of 5°.

The time step was chosen by decreasing the time step until results were not significantly affected. The chosen time step was 0.1 hours. The downstream end of the model is a fixed rating curve based upon a larger scale hydraulic model.

Reservoir drawdown and hydrologic scenarios

The SRH-1D model is run in unsteady mode meaning that the storage effects of the reservoir are taken into account. The input flows to the model were taken from a separate hydrologic routing model called RiverWare that accounted for project operations at Link Dam and Keno Dam located upstream of JC Boyle. The model uses historical measured inflows into Upper Klamath Lake and then operates Link Dam (impounding Upper Kalmath Lake) according to assumed operational rules. Details on the hydrologic assumptions and model is found in Reclamation (2012). Two sets of simulations were performed:

1. Forty-eight separate simulations of the reservoir drawdown extending into following year. The forty-eight simulations represented the range of observed water year types between

water year (WY) 1961 and 2008. These simulations were used to assess the short term impacts of dam removal, particular the sediment concentrations in the first two years following dam removal.

2. Three 50-year simulations with the reservoir drawdown occurring the first year. Three simulations were performed using representative Wet, Dry, and Median WY types. The representative Wet, Dry, and Median WY were defined as the 90%, 50%, and 10% exceedance of the March to June flow volume at Keno Dam on the Klamath River. The Dry, Median, and Wet WY were 2001, 1976, and 1984, respectively.

The primary objective of the preferred drawdown scenario was to limit the period of high sediment concentrations to the months of January to early March. Details of the deconstruction can be found in the Detailed Plan Report (Reclamation, 2010). The preferred drawdown scenario has the following activities for each dam. These scenarios are what was simulated in this paper, but the actual drawdown scenarios and the year of removal will be different as described in KRRC (2018).

At J.C. Boyle Reservoir, the drawdown is assumed to begin January 1, 2020 and would occur through the penstocks and gated spillway from a normal pool elevation of 3793 feet to 3780 feet at a rate not to exceed 3 ft/d. On January 13, one of the low level outlets of J.C. Boyle Dam would be opened by removing the concrete stoplogs that block the outlet and the reservoir would be drawdown to an elevation of 3770 feet. The second of the low level outlets would be opened January 20, 2020 and the reservoir would be drawdown to an elevation of 3762 feet.

The drawdown at Copco Reservoir is assumed to begin November 1, 2019 at rate of 1 ft/d from normal pool of about 2606 feet to 2590 feet, which is 3 feet below spillway crest. The spillway gates and superstructure would be removed once the pool is lowered below the crest and their removal would be complete by January 1, 2020. The original low level outlet used for stream diversion during the construction of Copco No.1 Dam would be used to bring the reservoir level below the spillway crest.

The drawdown of Copco Reservoir would resume January 1, at a rate of approximately 1.75 ft/d to an elevation of 2529. Below an elevation of 2529, the drawdown rate would be increased to 2.25 ft/d until it reaches the pre-dam river elevation. The drawdown at Copco Reservoir would primarily occur through the low level outlet. The dam would be notched by removing concrete sections and the spillway will be removed to ensure that the drawdown rates are accomplished and the reservoir does not refill.

Drawdown at Iron Gate Dam is assumed to initiate on January 1, 2020 at a rate not to exceed 3 ft/d. The low level outlet at Iron Gate would be used to drawdown the reservoir. The earthen embankment would be removed in July and August of 2020.

Results

Three main results are summarized here: the erosion and deposition volumes, the sediment concentrations and the bed material changes. The primary reach of impact will be below Iron Gate Dam to the Shasta River and this reach is shown in Figure 5 showing Iron Gate Reservoir and tributaries to the Klamath River which are used for reference in the following sections.

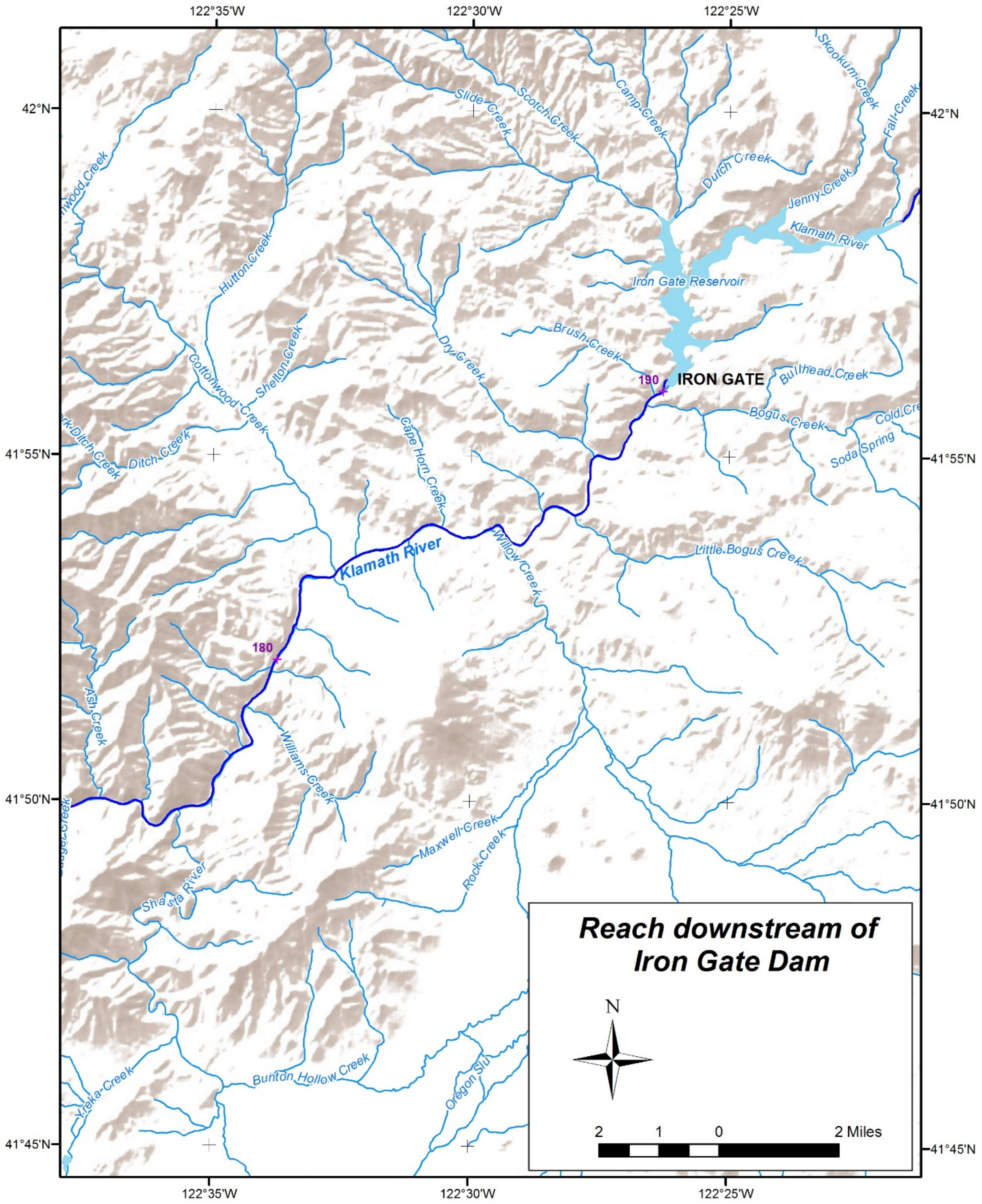

Figure 5. Klamath River reach below Iron Gate Dam, which is the most downstream dam being removed.

Reservoir Erosion and Downstream River Deposition

Based upon the SRH-1D simulations, drawdown of the four PacifiCorp Dams will release between one- and two-thirds of the approximately 15 million cubic yards of sediment projected to be stored in the reservoirs by 2021 (Figure 6). If there is a wet year, more material will likely be eroded and if there is a dry year, less material will be eroded from the reservoirs. The river is expected to return to its pre-dam alignment at each reservoir and have a similar width to pre-dam conditions. The sediment that is left behind in the reservoirs may raise the floodplain terraces above the pre-dam conditions and the floodplains are expected to be inundated less frequently than typical floodplains in the basin. High flows are expected to gradually widen the floodplain through bank erosion and surface erosion, but this process may occur slowly over several decades depending on the frequency and magnitude of floods. This two-phase process where the majority of sediment is first eroded during the initial drawdown and then additional erosion occurs only during episodic flows is similar to that described by East et al. (2018) and Collins et al. (2017).

After dam removal, the model predicted an average of 1.5 feet of streambed deposition from Bogus Creek to Willow Creek (0.5 to 4 miles downstream of Iron Gate Dam), and less than 1 foot of deposition from Willow Creek to Cottonwood (4 to 8 miles downstream of Iron Gate Dam). Downstream of Cottonwood Creek at all locations, there was less than 0.25 feet of deposition predicted and is considered not significant. The results for a dry start year and wet start year are very similar.

The deposition is expected to be relatively permanent as gravel is resupplied to the reach because it is likely that likely that some amount of streambed erosion has occurred downstream of Iron Gate Dam and natural resupply of gravel to the reach would be expected to restore the bed profile that was there prior to dam construction.

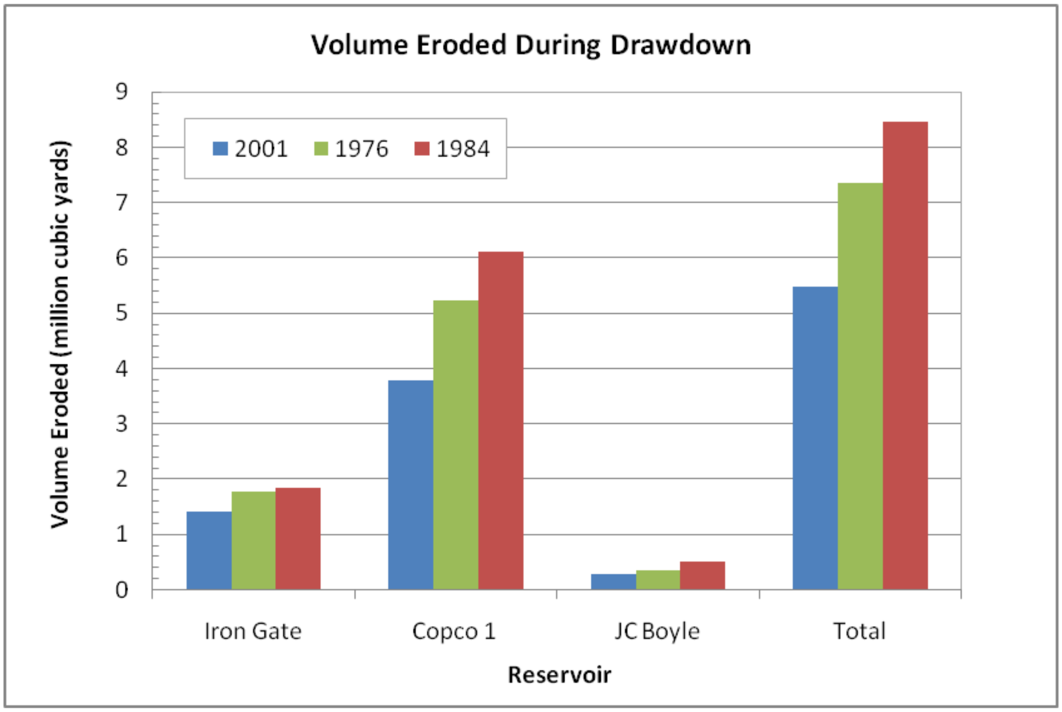

Figure 6. Estimated erosion volumes from each reservoir during drawdown period. WY2001 is a dry year, WY 1976 is a normal year, and WY 1984 is a wet year.

Sediment Concentrations

The sediment concentration immediately downstream of Iron Gate Dam (the most downstream dam) are shown for the Dry, Median and Wet WY types in Figure 7, 8, and 9, respectively. The highest concentrations and longest durations occur during the Dry WY because there is less water to dilute the reservoir sediment. Because the sediment is fine and quite erodible, even low flows are able to erode significant amounts of sediment. The peak concentrations in the Dry WY exceed 10,000 mg/l while the peak concentrations during the wet year are below 8,000 mg/l. Most of the reservoir material will be transported to the ocean during the period of drawdown which will last from January 1, 2021 to mid March, 2021. Sediment concentrations are expected to return to background levels by the end of the summer 2021 regardless the hydrology over this time period. Aggressive revegetation of the reservoir material is planned immediately following dam removal, which will stabilize the sediment from erosion due to rainfall. In addition, the reservoir sediment dramatically increases its resistance to erosion once it dries out.

Assuming average flows from the tributaries during the drawdown, it is likely that the peak concentrations will be less than 2,000 mg/l at the mouth of the Klamath River. It is assumed that the majority of the fine material (silts and clays) will not deposit in the Klamath River and they will behave as essentially wash load.

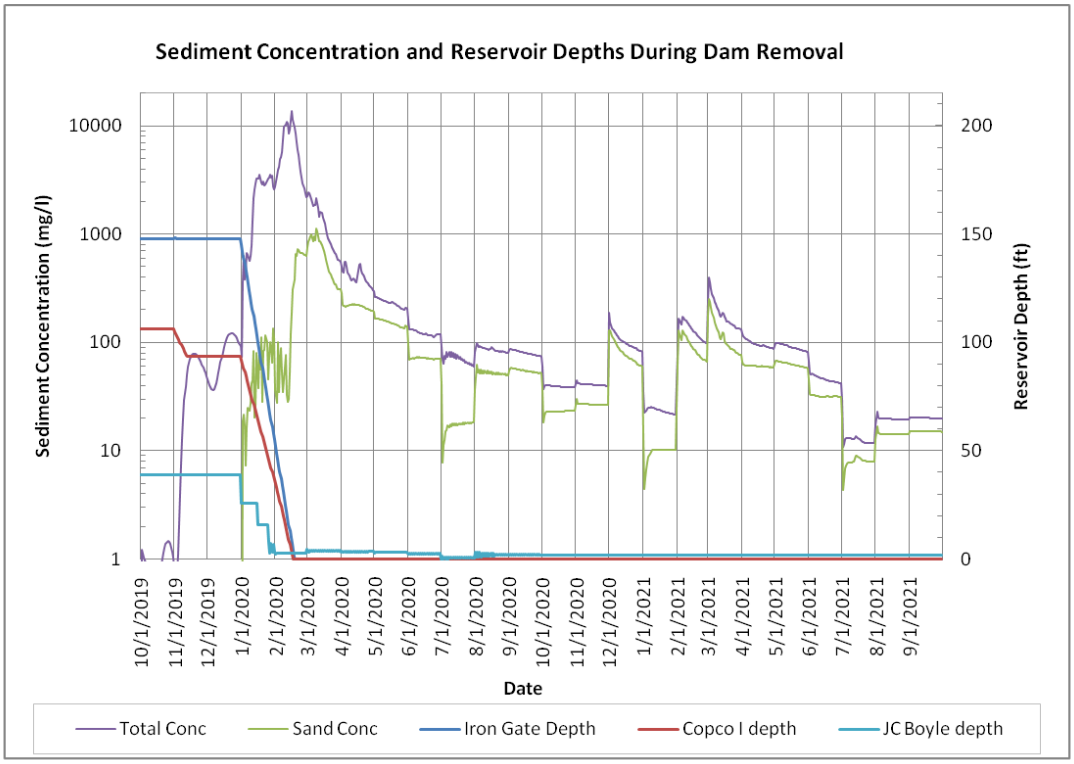

Figure 7. Estimated sediment concentrations downstream of Iron Gate Dam resulting from reservoir drawdown during Dry Water Year.

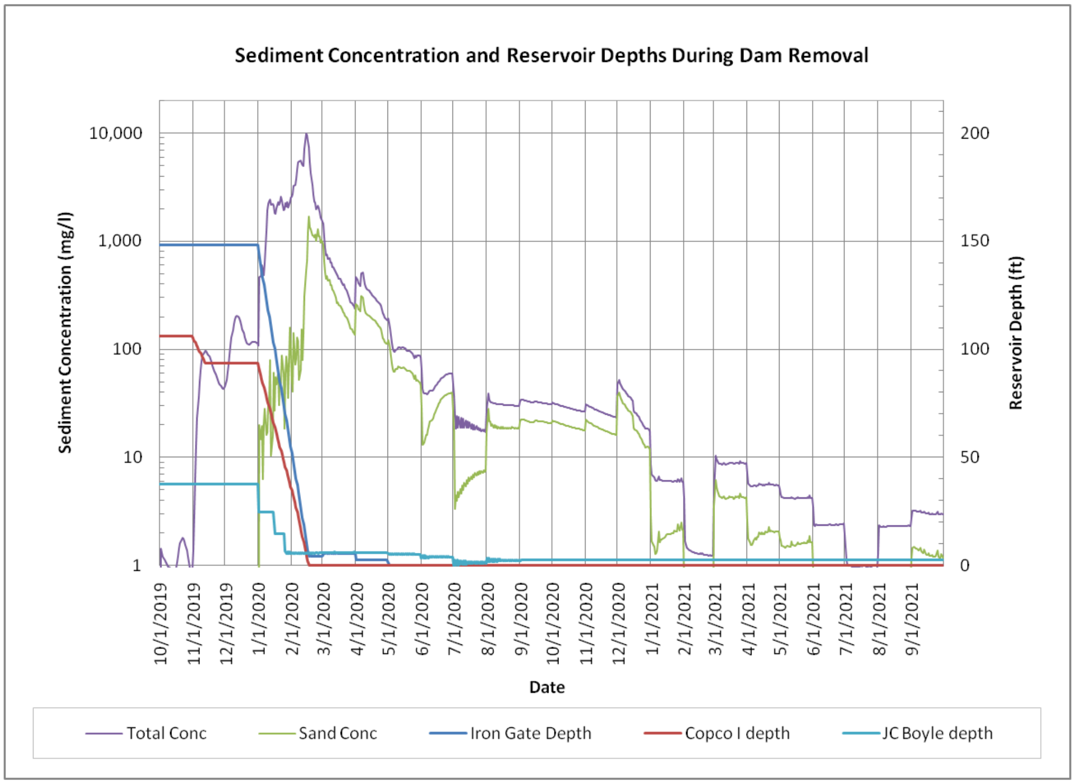

Figure 8. Estimated sediment concentrations downstream of Iron Gate Dam resulting from reservoir drawdown during the Median Water Year.

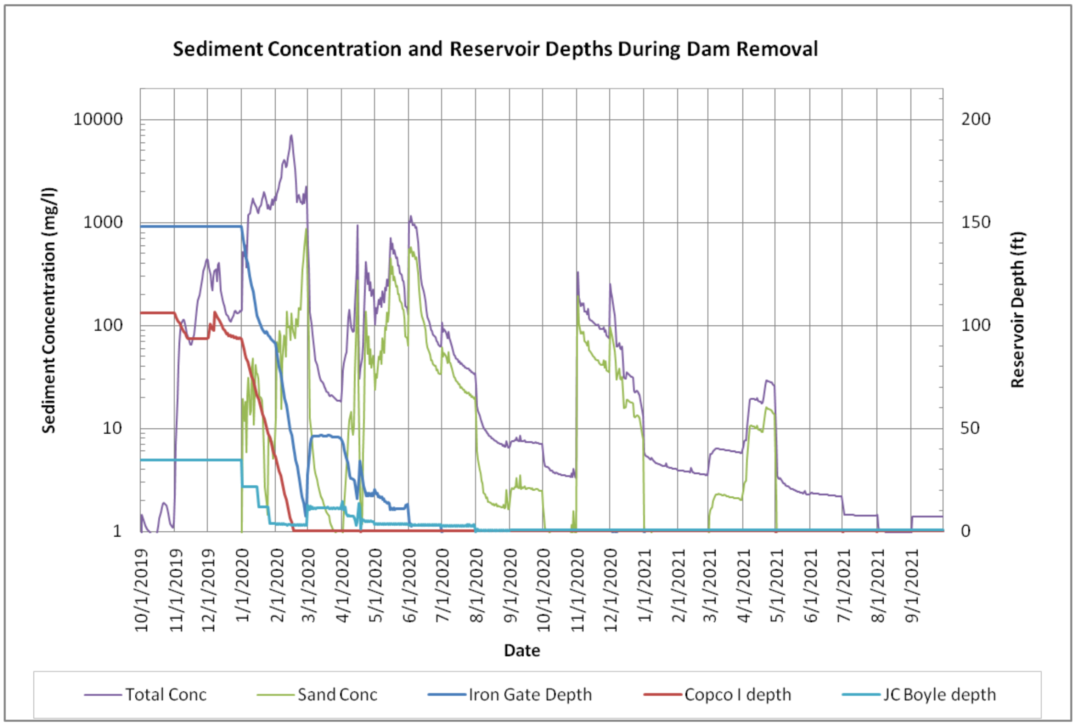

Figure 9. Estimated sediment concentrations downstream of Iron Gate Dam resulting from reservoir drawdown during the Wet Water Year.

Bed Material

While the vast majority of the reservoir deposit is silt, clay and organic material, approximately 15% of the 15 million cubic yards or 2.3 million cubic yards is sand. There is also some gravel expected to be present in the reservoir deposit, but it is difficult to get an estimate of it because the relative volume of the gravel is so much smaller. The modeling assumed that the gravel would be supplied at the transport capacity based upon the measured bed material in the reaches downstream of Iron Gate.

The percentages of bed material within various size classes in the reach downstream of Iron Gate to Willow Creek (approximately 4 miles) for the simulations with the Median and Wet WY are given in Figure 10 and Figure 11. The bed material within this reach is expected to have a high content (30 to 50 %) of sand immediately following reservoir drawdown until a flushing flow moves the sand sized material out of the reach. The flushing flow is expected to have to be at least 6,000 cfs and occur for several days to weeks to return the bed to dominantly cobble and gravel with a sand content less than 20%. After the flushing flow, the bed is expected to maintain fractions of sand, gravel, and cobble similar to natural conditions.

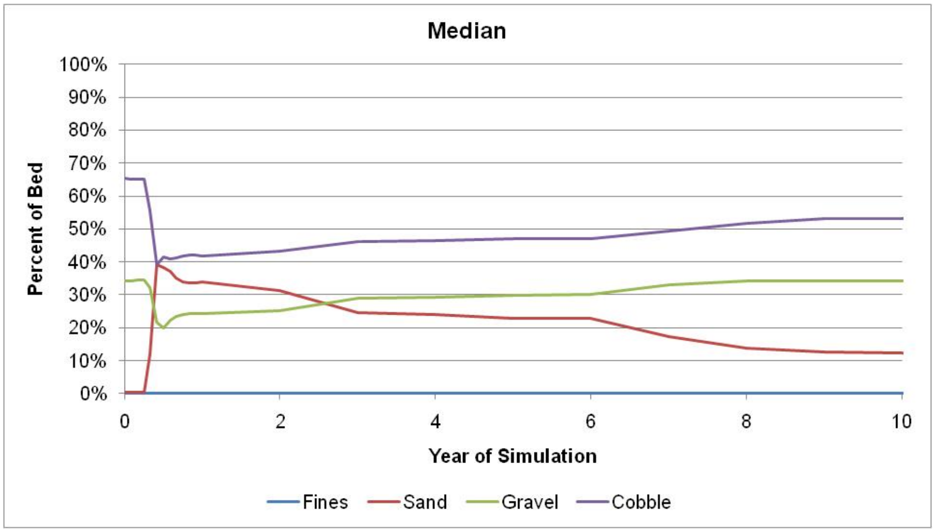

Figure 10. Percentage of bed material in various size classes in the reach between Iron Gate Dam and Willow Creek as a function of time from start of dam removal for the Median Water Year start.

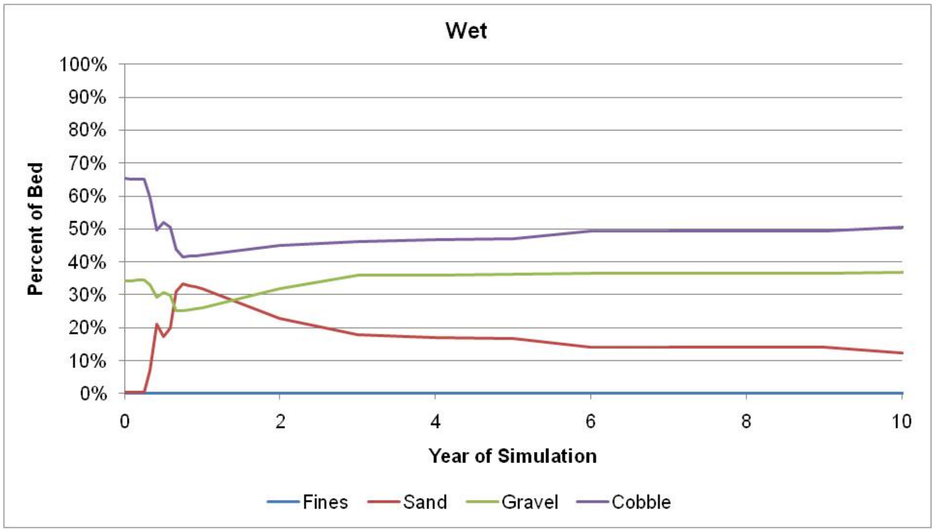

Figure 11. Percentage of bed material in various size classes in the reach between Iron Gate Dam and Willow Creek as a function of time from start of dam removal for the Wet Water Year start.

Conclusions

The PacifiCorp dams Iron Gate, Copco I, Copco II, and J.C. Boyle located on the Klamath River are scheduled for removal in 2021. Reclamation (2011) detailed the sediment transport dynamics expected after dam removal based on SRH-1D model simulations. The most important results from that study have been summarized here to assist in the development of monitoring plans for the project, to provide clear expectations against which the monitoring results can be compared, and to summarize the analytical procedures so they can be referenced in future large dam removal studies.

It is expected that the high concentration of sediment resulting from dam removal will mostly be confined to the drawdown period because the sediment stored behind the dams is very erodible and has a high water content. The expected concentrations will largely be a function of the flow rates during the drawdown period as this will determine the dilution of the eroded sediment. The remaining reservoir sediment is expected to have dramatically increased resistance to erosion once reservoir drawdown is complete because it will consolidate and be aggressively revegetated.

Some deposition of sandy material is expected in the reach immediately downstream of Iron Gate dam, but normal (2-yr) flood flows should restore the river bed to an equilibrium condition dominated by gravel with less than 20% sand in the surface bed material. There will also be some permanent aggradation of this reach, but this is expected to be no more than 1 to 1.5 ft and is the result of the natural resupply of gravel material to the reach from further upstream.

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