9. Future Geomorphology and Sediment Transport Conditions

9.1. No Action Alternative

Under the No Action Alternative, J.C. Boyle, Iron Gate, and Copco 1 reservoirs will continue to trap sediment at rates similar to historical levels. We estimate that approximately 23.5 million yd^3 of sediment will be stored behind the dams by 2061 (Table 9-1). The trapping efficiency of J.C. Boyle Reservoir may slightly decrease as the reservoir capacity decreases but the rate at which this happens is uncertain and is not likely to change significantly by 2061. Stillwater (2010) estimated that approximately 24,000 yd^3/yr of sediment coarser than 0.06 mm is being trapped in the PacifiCorp reservoirs. This volume of sediment will continue to be trapped under future conditions and it is expected that the reach downstream of Iron Gate Dam will continue to be depleted of sediment. In all reservoirs, the maximum sediment thicknesses are measured at the downstream ends and progressively decrease in thickness toward the upstream end of the reservoir to where the amount of reservoir sediment is too thin to measure. Thus, it is likely that while sediment will continue to deposit over the entire reservoir, measurable amounts of sediment will progress upstream into areas where there is negligible accumulation, currently. It is likely that after the storage capacity reduces to a certain level, the aggradation in the reservoirs will stop and sediment will begin to pass through the reservoir pools.

Table 9-1. Future Total Sedimentation Rate in reservoirs.

Reservoir	Year Completed	Original Storage Capacity (acre-ft)	Current Sediment Volume (yd^3)	Sedimentation Rate (yd^3/ yr)	2061 Sediment Volume (yd^3)	% reduction in Storage Capacity
JC Boyle	1958	3,495	990,000	19,600	2,020,000	36
Copco 1	1918	46,867	7,440,000	81,300	11,600,000	15
Copco 2	1925	73	0	0	0	0
Iron Gate	1962	58,794	4,710,000	100,000	9,900,000	10
Total	-	109,229	13,140,000	201,000	23,500,000	13

At J.C. Boyle Reservoir, sediment deposition is greatest at the downstream end of the reservoir, reaching a maximum of 18-20 feet near the dam and decreasing to 0 feet of depth between RM 225 and 226. Measureable amounts of reservoir sediment were also recorded near RM 227, amounting to 8-10 feet. It is likely that these areas will continue to accumulate sediment and the extent of sediment deposition will continue to progress upstream toward the state highway bridge.

At Copco Reservoir, sediment thicknesses mostly range from 6-10 feet with maximum values at the downstream end of the reservoir, while 2-6 feet thicknesses are common at the upstream end of the reservoir and along the reservoir margins. Several deep scour holes still exist that were part of the historical channel and are not expected to fill in within the near future.

At Iron Gate Reservoir, sediment thicknesses reach a maximum value of 10 feet in the vicinity of Jenny Creek delta while other parts of the reservoir have thicknesses of 3-5 feet near Iron Gate Dam. Thicknesses decrease with distance from the dam to where they are negligible near the reservoir high pool. Sediment deposition is predicted to continue at similar rates in Iron Gate Reservoir with progressive accumulation toward the upstream end of the reservoir and in the vicinity of Jenny Creek, Scotch Creek, and Camp Creek as these tributaries mobilize sediment into the reservoir from upland areas.

Under the No Action Alternative, no significant erosion is expected to occur downstream of any of the PacifiCorp dams in the future. Any significant adjustment in river elevations would have already occurred in previous floods. The river planform and elevation is largely controlled by boulders and bedrock and only limited adjustment is possible. PacifiCorp (2004b) was unable to determine any significant change in river morphology downstream of Iron Gate caused by the dams. PWA (2009) analyzed USGS stream gage below Iron Gate and also found no significant change to the relationship between flow elevation and flow discharge since the construction of Iron Gate Dam.

Under the No Action Alternative, continued sediment armoring occurs downstream of Iron Gate Dam. Bed mobilization from Iron Gate Dam to Cottonwood Creek is expected to continue to decrease in the future as sediment is stripped from the reach. The future bed mobilization under the No Action Alternative is discussed in 9.2.3. As the bed mobilization in the reach between Iron Gate Dam and Cottonwood Creek continues to decrease, the existing terraces and sediment bars are expected to continue to be stable and become more vegetated.

9.2. Dam Removal Alternative

There will be two major effects of the dam removal on sediment transport:

1. Short term release of fine sediment stored behind the dams.

2. Long term resupply of natural fine and coarse sediment to the Klamath River that was previously trapped by the dams.

We will analyze both effects of dam removal using both one-dimensional (1D) and two-dimensional (2D) models. The 1D model used in the simulation is SRH-1D (Huang and Greimann, 2010) and the 2D model used in the simulations is SRH-2D. Previous analyses of Klamath Dam Removal have been performed by Stillwater Sciences (2008) and PWA (2009).

9.2.1. ONE-DIMENSIONAL SIMULATION OF RESERVOIR DRAWDOWN AND EROSION OF RESERVOIR SEDIMENT

River flows will erode significant quantities of reservoir sediment as the reservoirs are drawn down. The rate of reservoir drawdown and the erosion of sediment are largely determined by the hydrology and low level outlet capacity. The outlet capacity of each reservoir is given in Figure 9-1, Figure 9-2, and Figure 9-3. The outlet capacity is consistent with that assumed in Reclamation (2010b). Hydrologic routing during dam removal was performed using the RiverWare model of the system described in Appendix E. Documentation of Hydrology Simulations for the Klamath Dam Removal . The operations under the KBRA are assumed to govern the releases of water at Link Dam and Keno Dam. For the purposes of discussion, representative dry, median, and wet water years 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 water years were 2001, 1976, and 1984, respectively.

Two sets of simulations were performed.

1. Forty-eight 2-year simulations of the reservoir drawdown and following year. Forty-eight simulations were performed using every WY between 1961 and 2008.

2. Three 50-year simulations with the reservoir drawdown occurring the first year. Three simulations were performed using year 1976, 1984, and 2001 as the start years.

The short term release of fine sediment was simulated using SRH-1D (Huang and Greimann, 2010). There were two sediment models created: an upstream model extending from upstream of J.C. Boyle Dam to downstream of Iron Gate Dam, and a downstream model extending from Iron Gate Dam to the Pacific Ocean. The models were created from the respective HEC-RAS models of the same reaches. The reservoir sediment thicknesses where computed based upon the GIS

maps in Figure 5-35, Figure 5-36, and Figure 5-37. The thicknesses were increased to estimate the thickness in 2020, 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.

There are several types of data and model parameters required in SHR-1D. They can be divided into the following categories:

1. **Model Parameters**: Both unsteady flow and sediment transport are simulated for the drawdown. Sensitivity to time step was performed and decreasing the time step below 0.1 hours did not significantly change the results, so a time step of 0.1 hours is used for all drawdown studies.
2. **Upstream Boundary Conditions**: Flow information at the upstream end of the model is taken from the hydrologic simulations.
3. **Downstream Boundary Conditions**: The downstream end of the model is approximately ½ mile downstream of Iron Gate Dam. A fixed rating curve is used at this point.
4. **Internal Flow Controls**: The reservoir elevations at the dams are specified based upon the hydrologic routing model.
5. **Lateral Inflows**: Lateral inflows were taken from the hydrologic routing model.
6. **Channel Geometry and Roughness**: The Channel geometry is taken from the HEC-RAS model described in Section 4.1.1. The channel roughness is set to 0.04.
7. **Sediment Model Parameters**: Sediment model parameters control the number of bed layers used to represent the river bed, the implicit factor for sediment transport computations, and the number of sediment time steps performed for each hydraulic time step. We used four bed layers. In the reservoir, the upper two layers represented the reservoir sediment and the bottom two layers represented the pre-reservoir sediment. The default for the implicit factor is 1. The number of sediment time steps default value is 1. The frequency of checking the angle of repose condition is set here too. The default is checking at every time step. Also in this data group, the sediment size classifications are given and the sixteen sediment size classes 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 assumed for the fine material is 20 lb/ft^3, while the bulk density assumed for the non-cohesive material was 100 lb/ft^3.

   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 is 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.

8. **Upstream Sediment Boundary Conditions**: No sediment is assumed to enter in from the upstream boundary.
9. **Lateral Sediment Discharge**: No lateral sediment discharge is modeled in the upstream reach for the deconstruction simulations. Tributary sediment supplies were computed from results of Stillwater (2010). The tributary loads were assigned as described in Section 9.2.1.29-14
10. **Sediment Bed 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. The bed material gradations for the reservoir sediment are taken from Section 5.6.2.
11. **Water Temperature**: The assumed water temperature was 58º F. The sediment transport results are not sensitive to the water temperatures assumed in the model.
12. **Erosion and Deposition Limits**: No erosion and deposition limits are assumed in the model.
13. **Sediment Transport Parameters**: The Parker (1990) formula is used to compute gravel and larger sizes while the Engelund and Hansen (1972) formula is used to compute the sand sizes. The active layer thickness is set to 2 feet. The above water angle of repose is important to defining the stability of the reservoir sediment. The assumed angle of repose is 15º for most simulations, but some model sensitivity of this parameter is conducted.
14. **Cohesive Sediment Transport Parameters**: The erodibility parameters are described in Section 5.6.4. The 50th percentile values of the critical erosion shear stress and erosion rate coefficient are used in simulations. Model sensitivity of the erodibility parameter is conducted.
15. **Bedrock Geometry and Parameters**: SRH-1D allows the definition of bedrock and the pre-reservoir sediment in the reservoir reaches was assumed to be non-erodible bedrock.

Several drawdown scenarios were analyzed (Appendix K. Other Drawdown Scenarios Analyzed). The scenarios are largely determined by the start date of drawdown and whether or not Copco 1 Dam is notched at the beginning of drawdown or not until the dry summer months. The removal of Iron Gate and J.C. Boyle dams cannot begin before the dry summer months because of the risk of dam overtopping. Start dates of Nov 15, 2019 and January 1, 2020 were investigated.

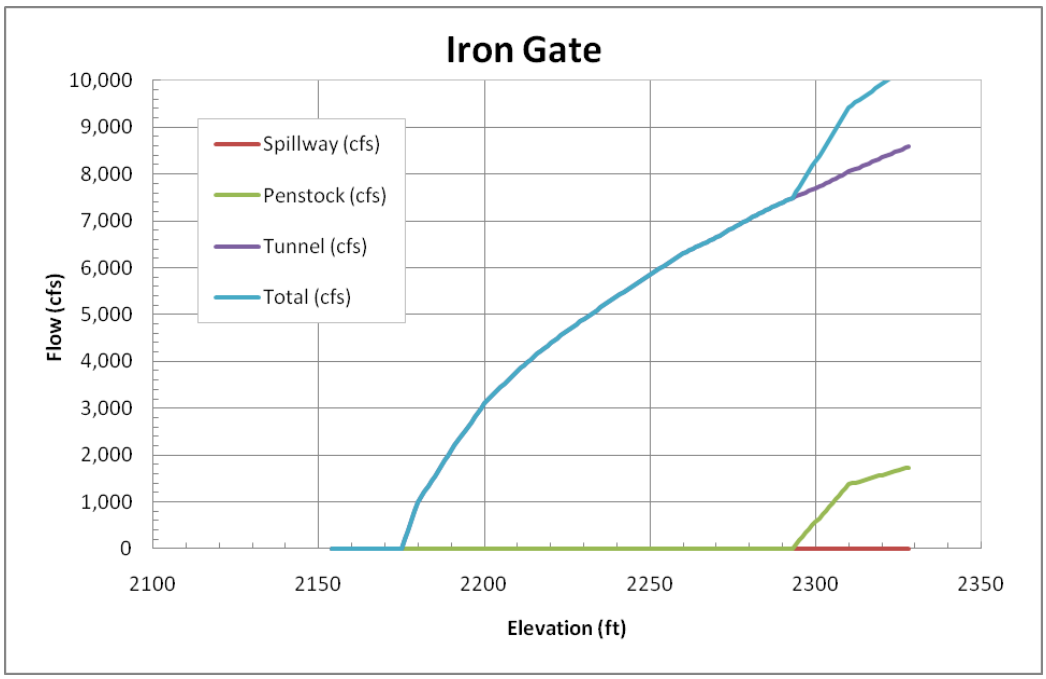


Figure 9-1. Outlet capacities at Iron Gate Dam.

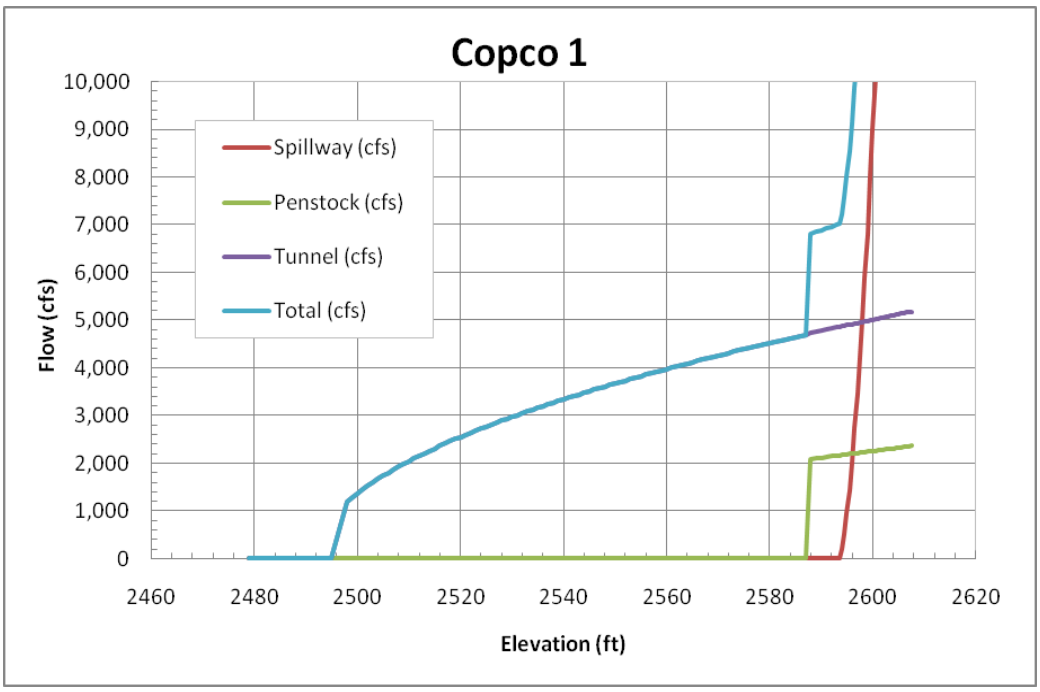


Figure 9-2. Outlet capacities at Copco 1 Dam.

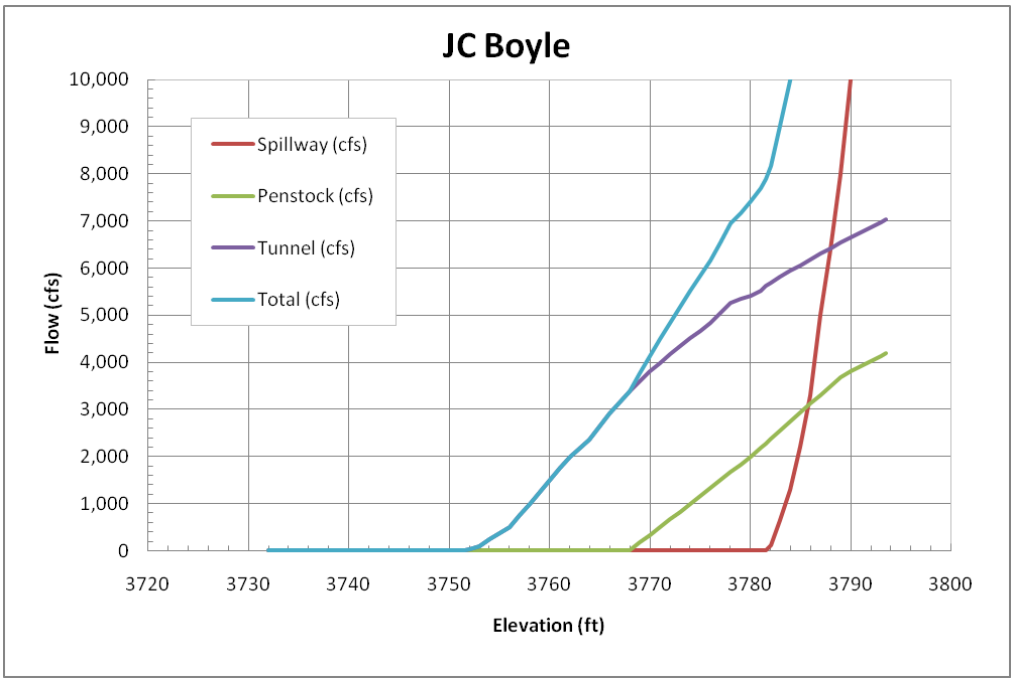


Figure 9-3. Outlet capacities at J.C. Boyle Dam.

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:

J.C. Boyle Dam

1. At J.C. Boyle Reservoir, the drawdown would also 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.

2. The removal of the earthen embankment would begin July 1, 2020. The river level will be between 3758 and 3760 feet during this period as the flows pass through the low level outlets. The dam embankment would be removed to about 3760 feet elevation at the upstream face (over 100,000 yd^3) in July and August (about 23 feet above bedrock at upstream toe), or as low as reservoir level will allow, to create an upstream cofferdam to ensure flood protection for flows through left abutment. The embankment materials downstream of cofferdam would be removed to the pre-dam channel grade, including concrete cutoff wall. The excavated rockfill

(from stockpile) would be placed on the downstream face of the upstream cofferdam for controlled breach of cofferdam embankment to a streambed elevation of 3737 feet, by notching below the reservoir level. Final reservoir drawdown would be achieved by natural erosion of the armored cofferdam and impounded sediments to the original streambed level.

Copco 1 Dam

1. Initiate drawdown at Copco Reservoir beginning 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.

2. 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.

Iron Gate Dam

1. Initiate drawdown at Iron Gate Dam 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 outlet capacities for the low level at Iron Gate are given in Figure 9-1.

2. The earthen embankment would be removed in July and August of 2020. The reservoir would be drawdown to the maximum extent by September 1, 2020 and rockfill would be placed on the downstream face of the cofferdam, which would be at an elevation of 2202 feet or lower. The cofferdam would be allowed to natural erode to the pre-dam stream bed elevation of approximately 2165 feet by notching below reservoir elevation.

9.2.1.1. Reservoir Elevations and Flows

J.C. Boyle Reservoir elevations for WY 2001, 1976, 1984 are given in Figure 9-4. The drawdown begins January 1, and is performed through the penstock and spillway gates. The subsequent drawdown below elevation 3780 feet occur through the low level outlet. Some refill of J.C. Boyle Reservoir occurs during the wet year (1984) during the spring runoff. Figure 9-5 shows the reservoir elevation at various exceedance levels for every day of the year for all WY from 1961 – 2008. An elevation of 3770 feet is rarely exceeded after February 1.

Copco Reservoir elevations are shown in Figure 9-6. Because the dam is notched as it is drawdown, flows exceeding the low level outlet capacity overtop the notched dam and do not significantly fill the reservoir. During the wettest years, there is some refill of the reservoir in December and January because of the depth of water necessary to overtop the spillway during peak flow events.

Iron Gate Reservoir elevations are shown in Figure 9-8. The reservoir is drawdown below 2186 feet by mid February and remains below that elevation for the dry and median year. For the wet year, there is some refilling of the reservoir during the spring runoff. Figure 9-9 shows the reservoir elevations for various daily exceedance percentages based upon the simulated flows using WY 1961 - 2008. The 25% exceedance elevation is below 2220 feet after mid-February. The reservoir may almost completely refill during the spring runoff for the wettest years.

The flows for the drawdown downstream of Iron Gate Dam are shown in Figure 9-10 for the WY 1976, 2001, 1984, and Figure 9-11 shows the flows for various daily exceedance values. The median flow expected during the drawdown period from January to mid-February is between 6,000 to 8,000 cfs. During wet years, the flow may be much higher and the model is not sufficiently refined to simulate the operations during extreme floods. If a peak flow event occurs during drawdown then the notching of Copco 1 Dam would be halted and the outflow exiting each of the reservoirs would be less than the inflow entering them. Engineering precautions would be put in place to ensure that the peak flow would not be increased by the drawdown process.

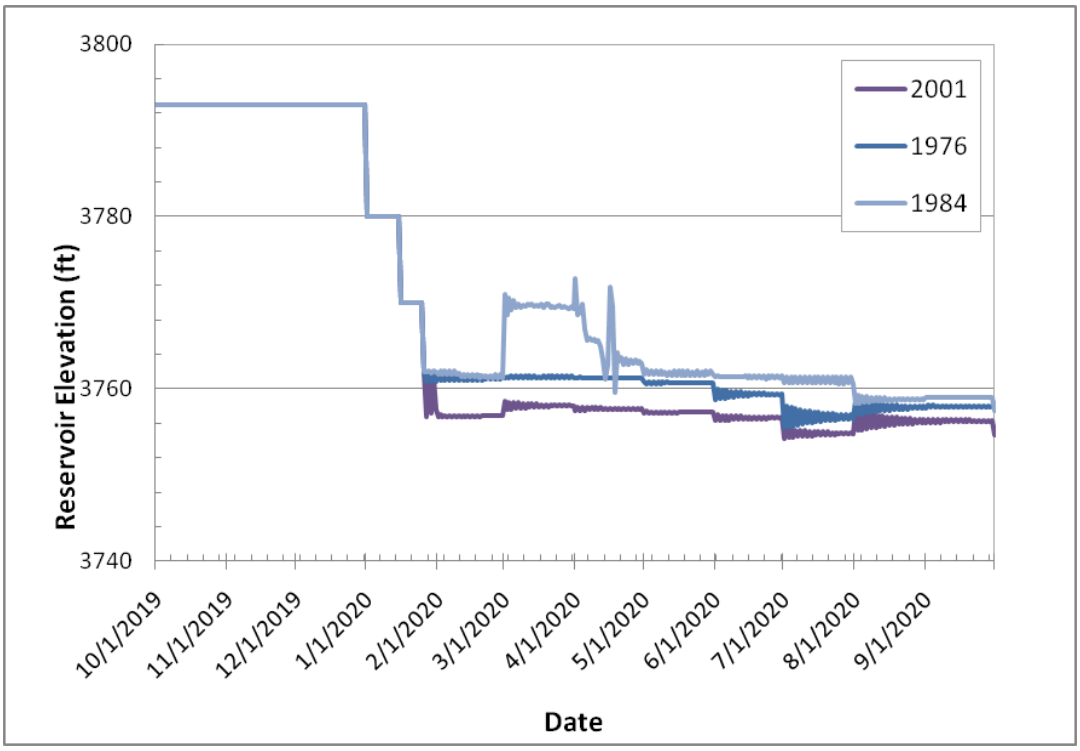


Figure 9-4. J.C. Boyle Reservoir elevation for typical Dry (2001), Median (1976), and Wet (1984) Years for Scenario 8.

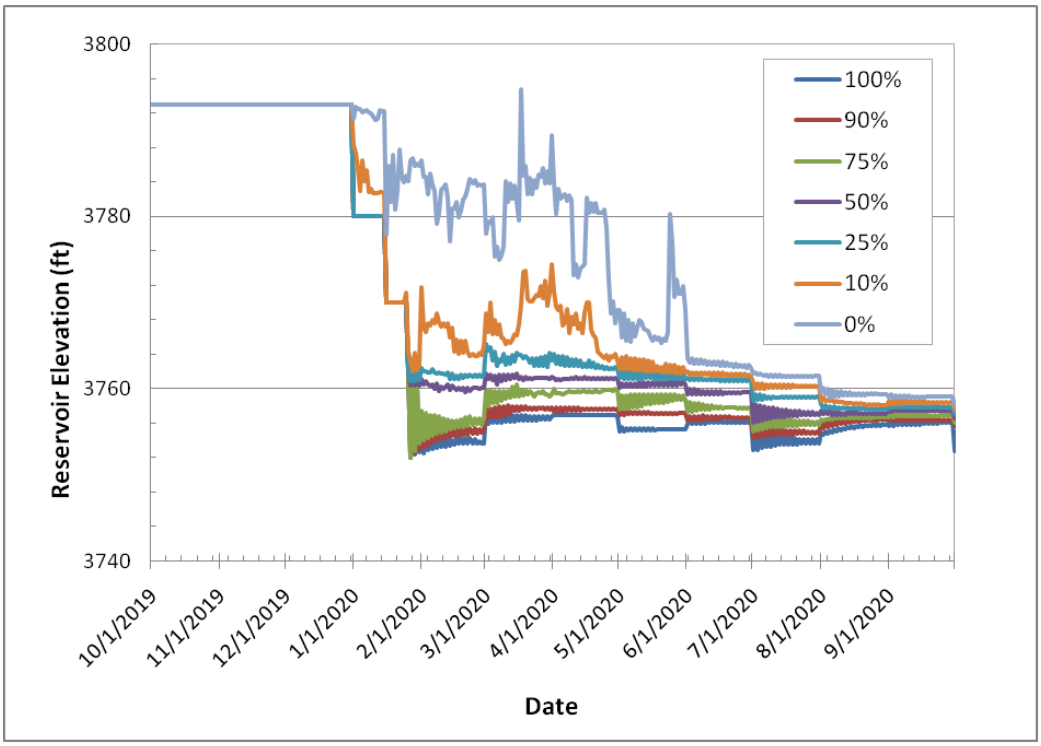


Figure 9-5. J.C. Boyle Reservoir exceedance elevations for WY 1961 to 2008 for Scenario 8.

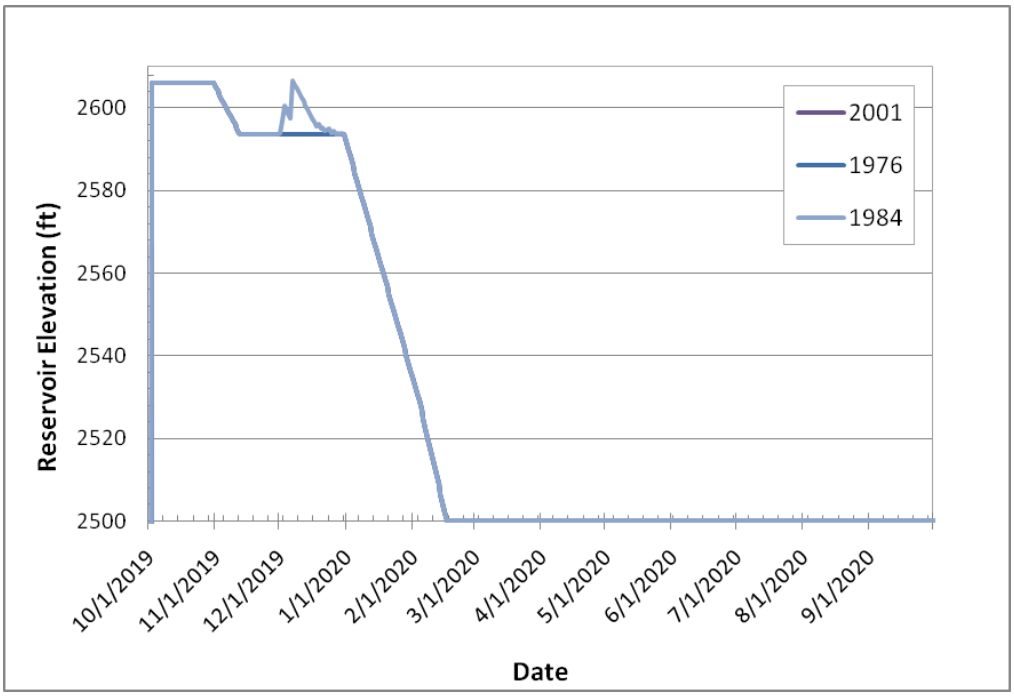


Figure 9-6. Copco Reservoir elevation for typical Dry (2001), Median (1976), and Wet (1984) years for Scenario 8.

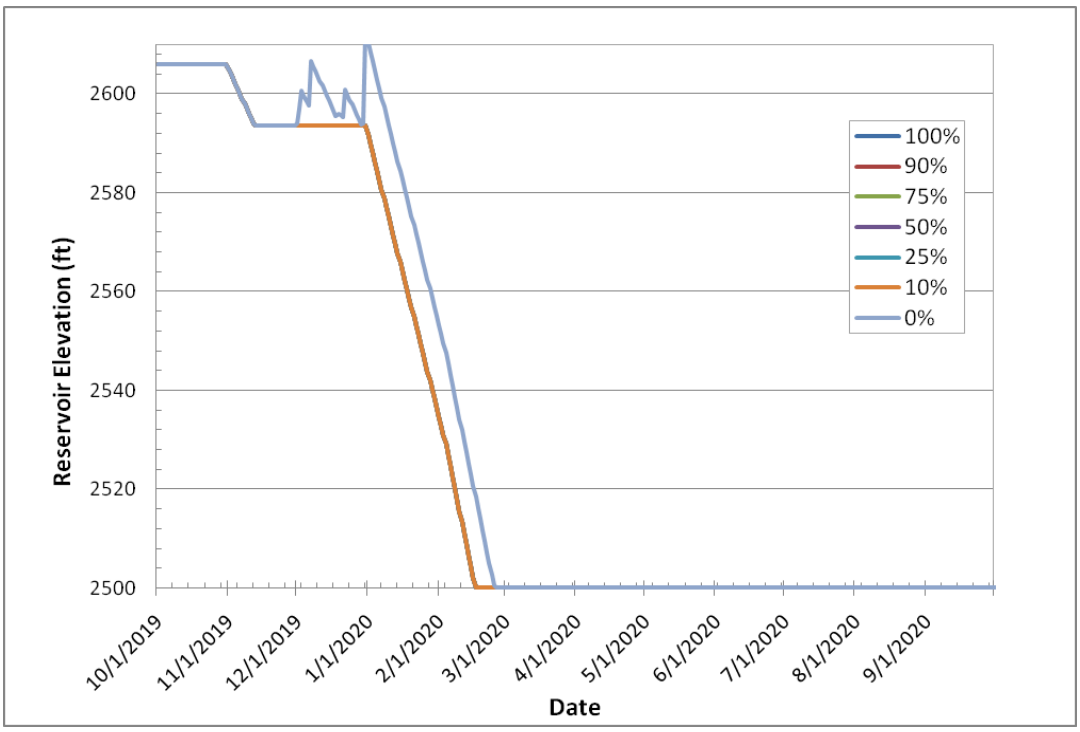


Figure 9-7. Copco Reservoir exceedance elevations for all years from 1961 to 2008 for Scenario 8.

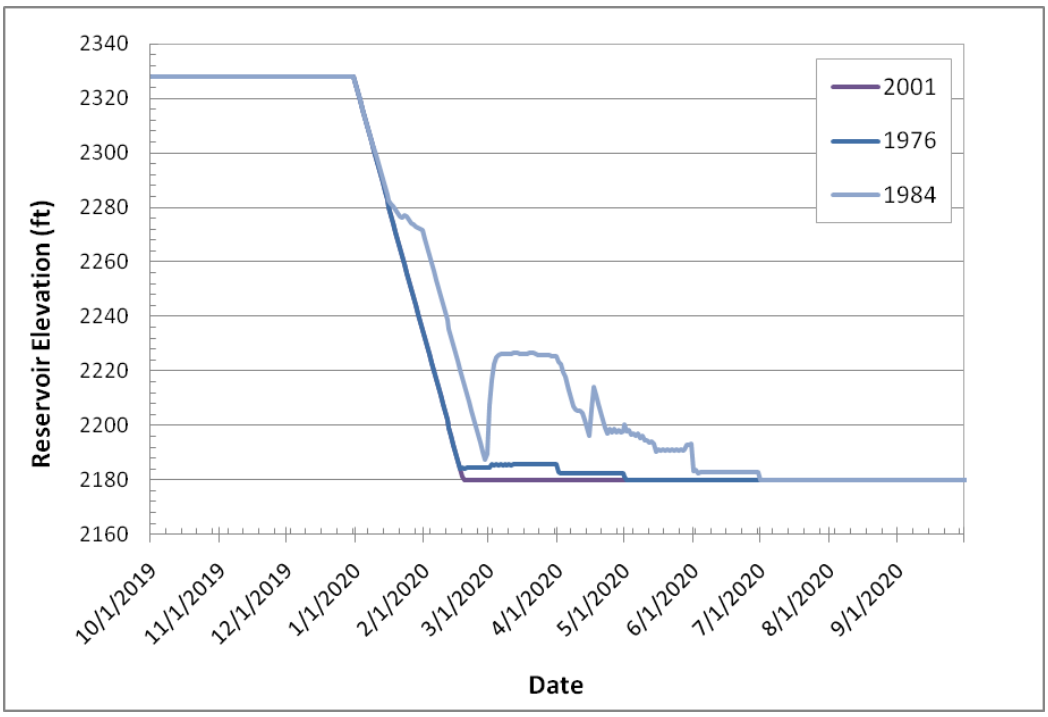


Figure 9-8. Iron Gate Reservoir elevations for typical dry (2001), median (1976), and wet (1984) years for Scenario 8.

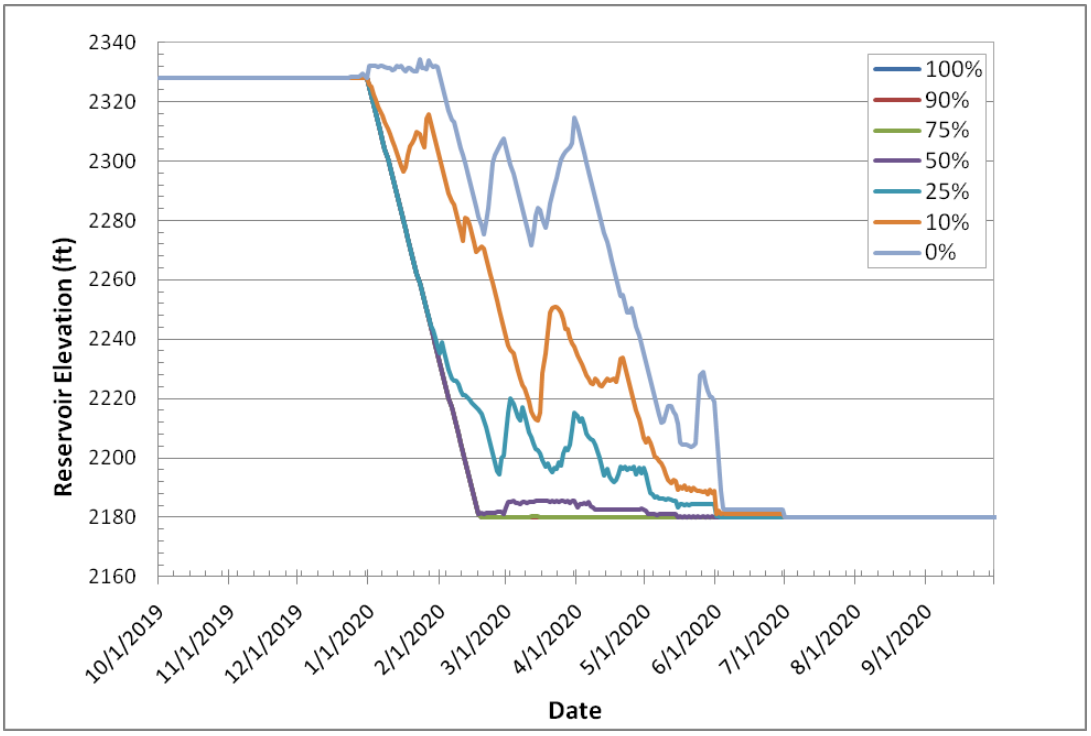


Figure 9-9. Iron Gate Reservoir exceedance elevations for all years from 1961 to 2008 for Scenario 8.

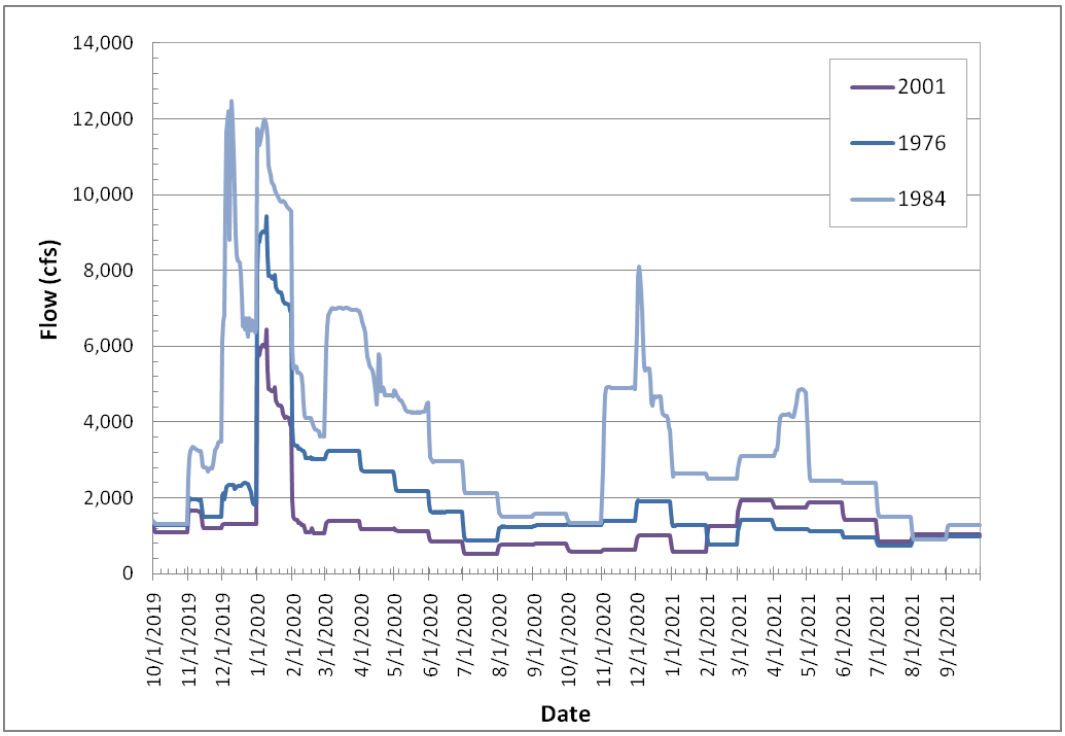


Figure 9-10. Flows downstream of Iron Gate Dam years 2001, 1976, and 1984 for Scenario 8.

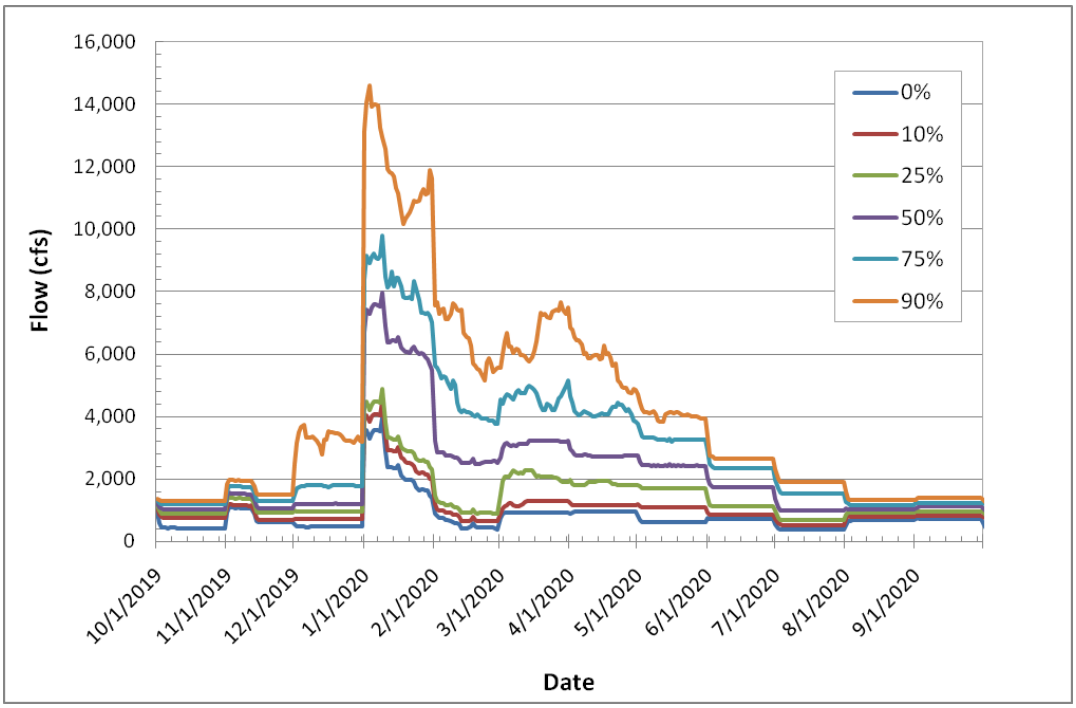


Figure 9-11. Iron Gate Reservoir exceedance elevations for all years from 1961 to 2008 for Scenario 8.

9.2.1.2. Background Sediment Loads

The sediment transport was simulated using SRH-1D for all the years between WY 1961 and 2008. Sediment concentrations were computed throughout the entire Klamath River from Iron Gate Dam to the Pacific Ocean and were compared against the "background" concentrations, which are the sediment concentrations that the river normally experiences. The incoming sediment concentrations supplied by tributaries downstream of Iron Gate Dam were computed using the sediment load information of Stillwater Sciences (2010). A sediment rating curve was developed in the form of $Q_s = aQ^b$ such that the annual loads as given in Table 5-2 are reproduced by the flow duration curve. The calculated value of $b = 2.3$ was 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 loads.

Comparison between the concentrations computed in SRH-1D with the assumed tributary contributions and those computed by using the sediment relationships in Table 5-3 is presented in Figure 9-12 for the Orleans gage and in Figure 9-13 for the Klamath gage. The values predicted with SRH-1D are generally lower than those from the sediment rating curves at the Orleans gage. Therefore, the SRH-1D model is generally expected to underestimate the background sediment concentrations.

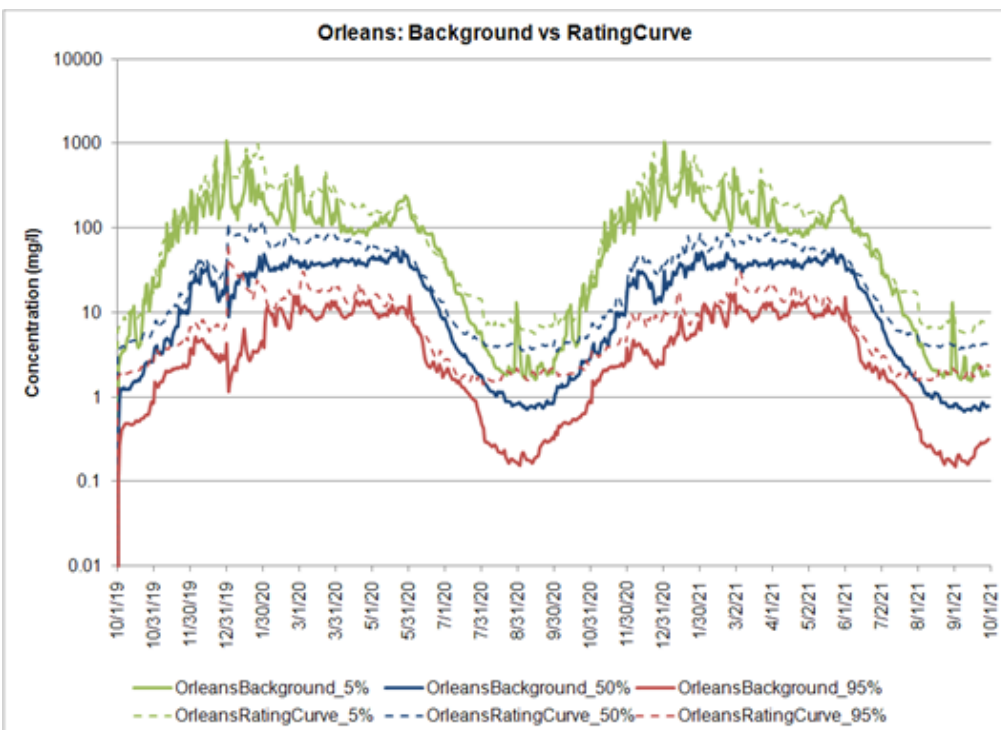


Figure 9-12. Comparison between sediment concentrations computed in SHR-1D for background conditions (Background) and those computed from the sediment rating curves at Orleans on the Klamath River (RatingCurve).

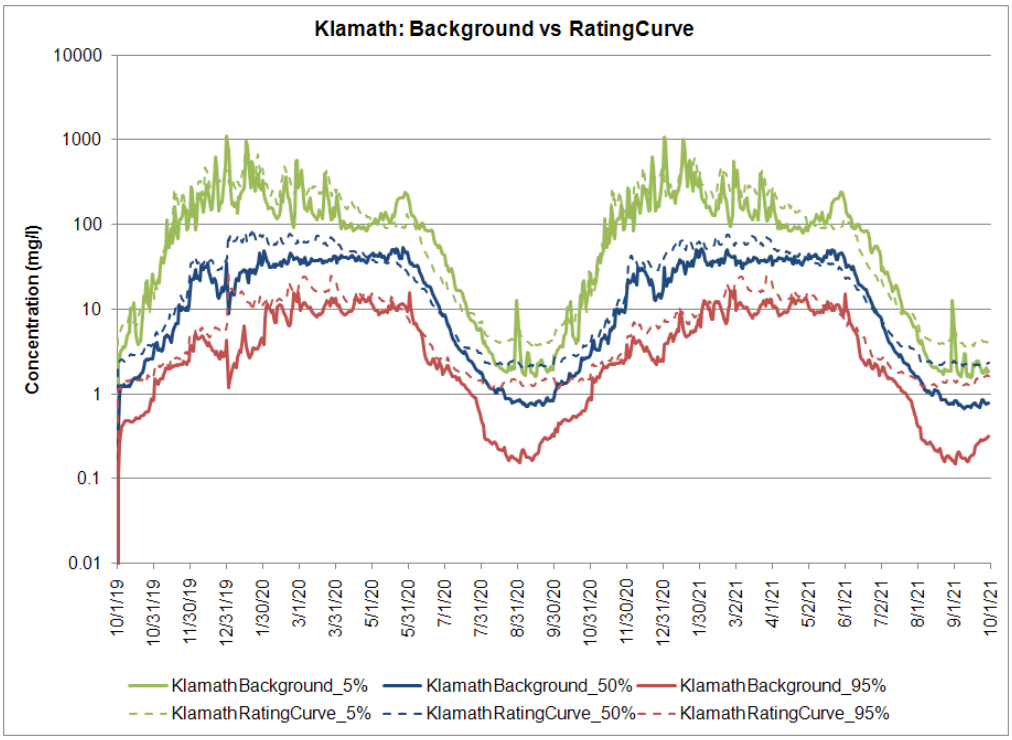


Figure 9-13. Comparison between sediment concentrations computed in SHR-1D for background conditions and those computed from the sediment rating curves at Klamath on the Klamath River.

9.2.1.3. Concentrations during Dam Removal

The concentrations for the drawdown scenarios are discussed below and for the purpose of this report, the following definitions are uses:

- **high** concentrations are greater than 1,000 mg/l.
- **medium** concentrations are between 100 and 1,000 mg/l.
- **low** concentrations refer to concentrations at or below 100 mg/l.

The sediment concentrations results below Iron Gate for the dry, median, and wet years are given in Figure 9-14, Figure 9-15, and Figure 9-16. It is expected that the maximum concentrations are under predicted because the model does not represent the variability that will existing during drawdown. For example, bank failure is assume to occur gradually during the drawdown process. In reality, a large bank failure may occur and suddenly add a large volume of sediment to the river. This high concentration will quickly dissipate but may cause a rapid spike in concentration. The concentrations in the plot are best interpreted as daily average concentrations that may vary significantly throughout the day.
Under a dry year, the initial drawdown of Copco 1 Reservoir beginning November 1 until January 1 will only produce low sediment concentrations downstream of Iron Gate Dam. There is little sediment that would be mobilized with a drawdown of only 16 ft. Also, the effective trap efficiency of Copco and Iron Gate reservoirs in series is between 75% and 94% (See Section 5.6.6). Therefore, the majority of the sediment mobilized during this initial drawdown of Copco will be trapped within Copco and Iron Gate reservoirs. When reservoir drawdown recommences on January 1, the concentrations will increase to around 3,000 to 5,000 mg/l and remain at that level through January. Beginning early February, as the reservoirs approach the low level outlets the concentrations will begin to increase and will reach nearly 14,000 mg/l in mid February as the reservoirs are almost fully drained. After this period, the concentrations will gradually decrease and be at low levels by the end of June. The recovery to low concentrations will take longer during a dry year then a wet year. This is because the silty/sandy material is more slowly mobilized under low flow conditions.

Under a median year, the response is qualitatively very similar to a dry year. The primary difference is that the additional flow will reduce concentration through dilution. The sediment concentrations in January at Iron Gate Dam are expected to be around 2,000 to 4,000 mg/l and the maximum concentration in February is expected to be around 10,000 mg/l. In addition, the system will recover to background concentration levels quicker and background concentrations will be reached by beginning of May.

Under a wet year, the concentrations downstream of Iron Gate Dam will rapidly increase to above 1,000 mg/l beginning January 1. The concentrations will likely be around 2,000 mg/l during the month of January and gradually increase to a

maximum of 7,000 mg/l in mid to late February when the reservoirs are drawdown to their low level outlet elevations. In March, the concentrations will rapidly decrease to low levels until the wet spring runoff mobilized sediment and causes Iron Gate Reservoir to refill partially. The subsequent draining of the reservoir will create medium concentration levels and the concentration will gradually decrease to low levels after the spring runoff is complete.

A comparison between Scenario 8 and background concentrations for dry, median, and wet years at Iron Gate, Seiad Valley, Orleans, and Klamath stream gages is given in Figure 9-17, Figure 9-18, Figure 9-19, and Figure 9-20, respectively.

The maximum concentrations at Seiad Valley are near 9,000 mg/l for dry years, 6,000 mg/l for median years and 4,000 mg/l for wet years. The duration of high concentration is longest for the dry years where concentration remains above 100 mg/l until May, whereas, the concentrations decrease to below 100 mg/l by April for the median year and March for the wet year. The concentrations increase in May and June for the wet year, but this also corresponds to higher background concentrations and the increase above background is relatively minor.

The maximum concentrations at Orleans are approximately 2,000 mg/l for the median and wet years and about 5,000 mg/l for the dry years. The background concentrations at Orleans will typically be around 100 mg/l, but will spike to around 1,000 during high flow events.

The maximum concentrations at the Klamath gage are approximately 1,500 mg/l during a dry year and median year. The maximum concentration during a wet year is approximately 800 mg/l, which corresponds to typical concentrations during high flow. The concentrations are typically near background levels by March under a wet year and by May under a dry and median year.

The amount of sediment delivered to the estuary during Dam Removal and under Background Conditions (No Action) is given in Figure 9-21 for WY 1961 to 2008. There is between 1.1 to 2.7 million tons of sediment eroded from behind the PacifiCorp dams depending upon the type of water year. With the dams in place, there is between 100,000 tons of sediment to more than 16 million tons of sediment delivered to the ocean in a given year. Therefore, the relative importance of the dam removal on the sediment concentrations is entirely dependent upon the year type. If there is wet year, the additional sediment load from the dam removal at the estuary will be relatively small. If it is dry year, the additional sediment load from dam removal will be relatively large. The amount of sediment delivered to the ocean as the result of dam removal is expected to less than the average annual supply to the ocean.

The sediment concentration at a 50% and 10% percent exceedance level for every day of the year are given in Figure 9-23 and Figure 9-24, respectively, for the year

of dam removal and the year after dam removal. The 50% and 10% exceedance levels for the background conditions are also given.

At the Iron Gate gage, the 50% exceedance levels reach approximately 10,000 mg/l in February and drop to below 500 mg/l by end of March. At Orleans, the 50% exceedance levels reach about 1,500 mg/l in February and drop to below 100 mg/l by April, which is near background levels. At Klamath, the 50% exceedance level reach 800 mg/l in February and drop to near background levels by April.

The 10% exceedance values under the Dam Removal Alternative Scenario 8 are around 13,000 mg/l at Iron Gate, 2,500 mg/l at Orleans, and 1,100 mg/l at Klamath. Background levels by April for the Orleans and Klamath locations are attached.

Sensitivity Analysis

A sensitivity analysis of the sediment concentration to various sediment transport parameters was conducted. The following simulations were performed in which a parameter or equation was altered:

1. The above water angle of repose is set equal to 5 degrees instead of 15.
2. The above water angle of repose is set equal to 10 degrees instead of 15
3. The cohesive sediment critical shear stress is increased to 0.025 lb/ft^2 (1.2 Pa) from 0.0042 (0.2 Pa).
4. The cohesive sediment critical shear stress is decreased to 0.0006 lb/ft^2 (0.03 Pa) from 0.0042 (0.2 Pa).
5. The non-cohesive sediment transport rates are calculated using the Wu et al. (2000) transport equations.
6. The non-cohesive bedload sediment transport rates are calculated using The Wilcock and Crowe (2004) equation instead of the Parker (1990).
7. The non-cohesive sediment transport rates are calculated using the maximum of the Parker (1990) transport equation and Engelund-Hansen transport equation for each size fraction.

The resulting fine sediment concentration is shown Figure 9-25 and the sand sediment concentration is shown in Figure 9-26.

Decreasing the angle of repose to 5 degrees decreases the maximum concentration and increases the duration of fine sediment concentration impacts. The period of fine sediment concentrations over 1,000 mg/l is not increased significantly, but the period that fine sediment concentrations are over 100 mg/l is increased by several months. The duration of sand concentration over 1,000 mg/l is increased

by approximately two months. The response is somewhat complex and not entirely intuitive. However, the basic reason for this behavior is that Copco Reservoir contains a relatively large volume of sand that re-deposits in Iron Gate reservoir as both are drawdown. The sand then remobilizes as Iron Gate is completely emptied. If the angle of respose is very low, then almost all the sand is remobilized and enters the river channel. The carrying capacity during a median WY is relatively small and it takes a long time to empty the sand from the reservoir. This scenario is considered unlikely and this is why a very low angle of repose was not used for the simulations. The angle of respose of drained sand is typically 30 degrees or greater (Craig, 1987; Garcia, 2008). The model currently assumes one angle of repose for all material types throughout the duration of the simulation and therefore cannot simulate one angle of repose for saturated clay and one for sand. Because the model cannot simulate these detailed processes, the base simulation (angle of repose of 15 degrees) is considered more representative. PanGeo (2008) stated that the aggraded sediments at the edged of the river channel will likely remain stable on a slope of 18 degrees (3H:1V).

Decreasing the angle of repose to 10 degrees has a similar effect to reducing the angle of repose to 5 degrees, though the quantitative difference to the base simulation is much less.

Decreasing or increasing the critical shear stress of the fine sediment has little effect on the sediment concentrations. The 25th and 75th percentile of the measured critical shear stress of the moist samples was used and the resulting sediment concentrations downstream were essentially identical to the base simulation.

If the Wu et al. (2000) equation is used to compute the non-cohesive sediment transport, the simulated total concentration is very similar but the peak sand concentration is smaller and it take about a month longer for the sand concentrations to decrease below 100 mg/l. However, the differences are considered slight and the fine sediment concentrations are very similar. If the Wilcock and Crowe (2003) equation is used instead of the Parker (1990) equation, the results for the fine sediment are very similar, but there is overall less sand transport.

Using the maximum of Parker (1990) and Engelund-Hansen (1972) to compute the non-cohesive sediment transport rate for each size fraction did not show significant differences from using the Parker (1990) equation if the bed is composed of gravel and the Engelund-Hansen (1972) equation if the bed is composed of sand.

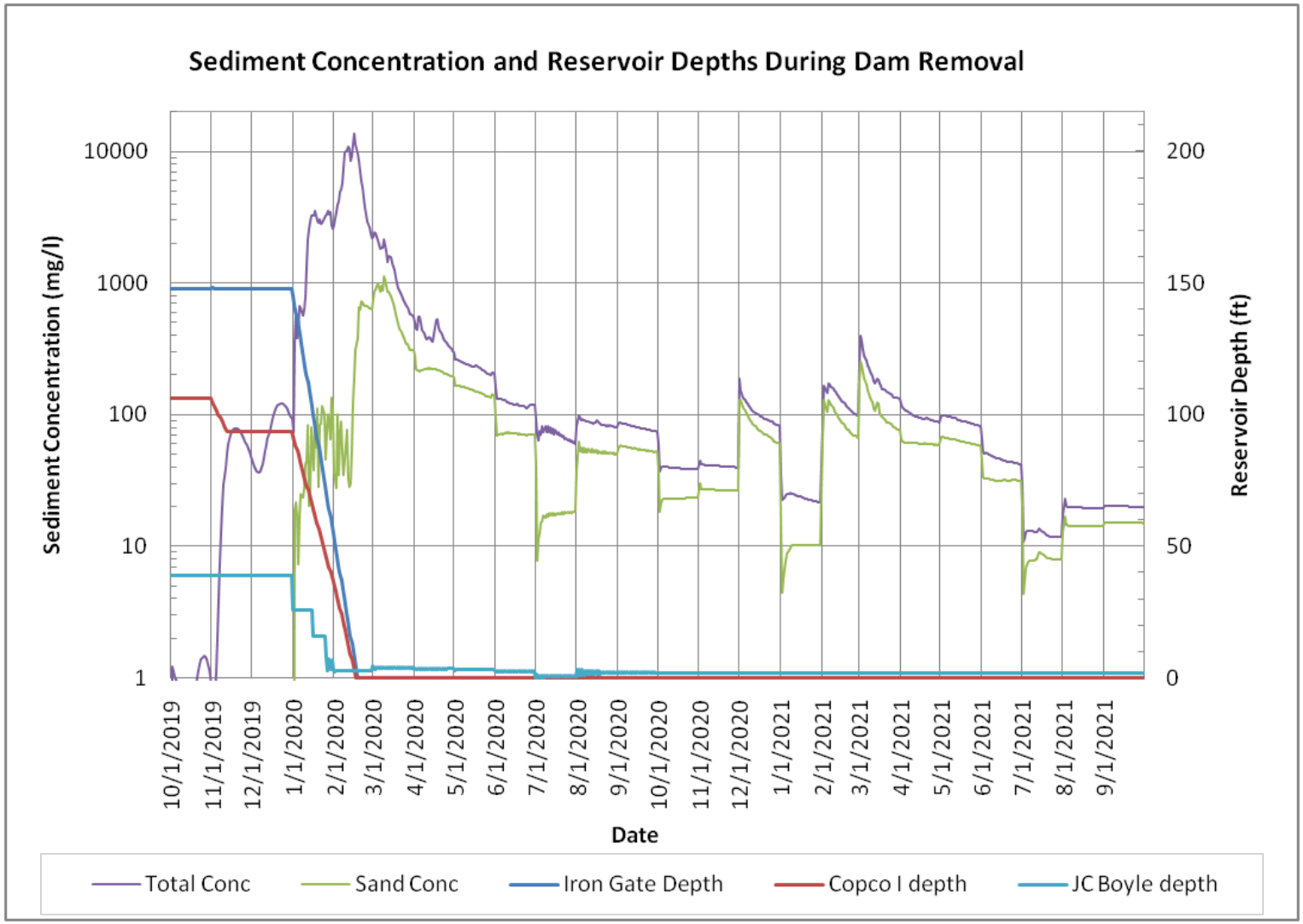


Figure 9-14. Simulated reservoir depths and sediment concentration below Iron Gate Dam for WY 2001 (Dry year) for Scenario 8.

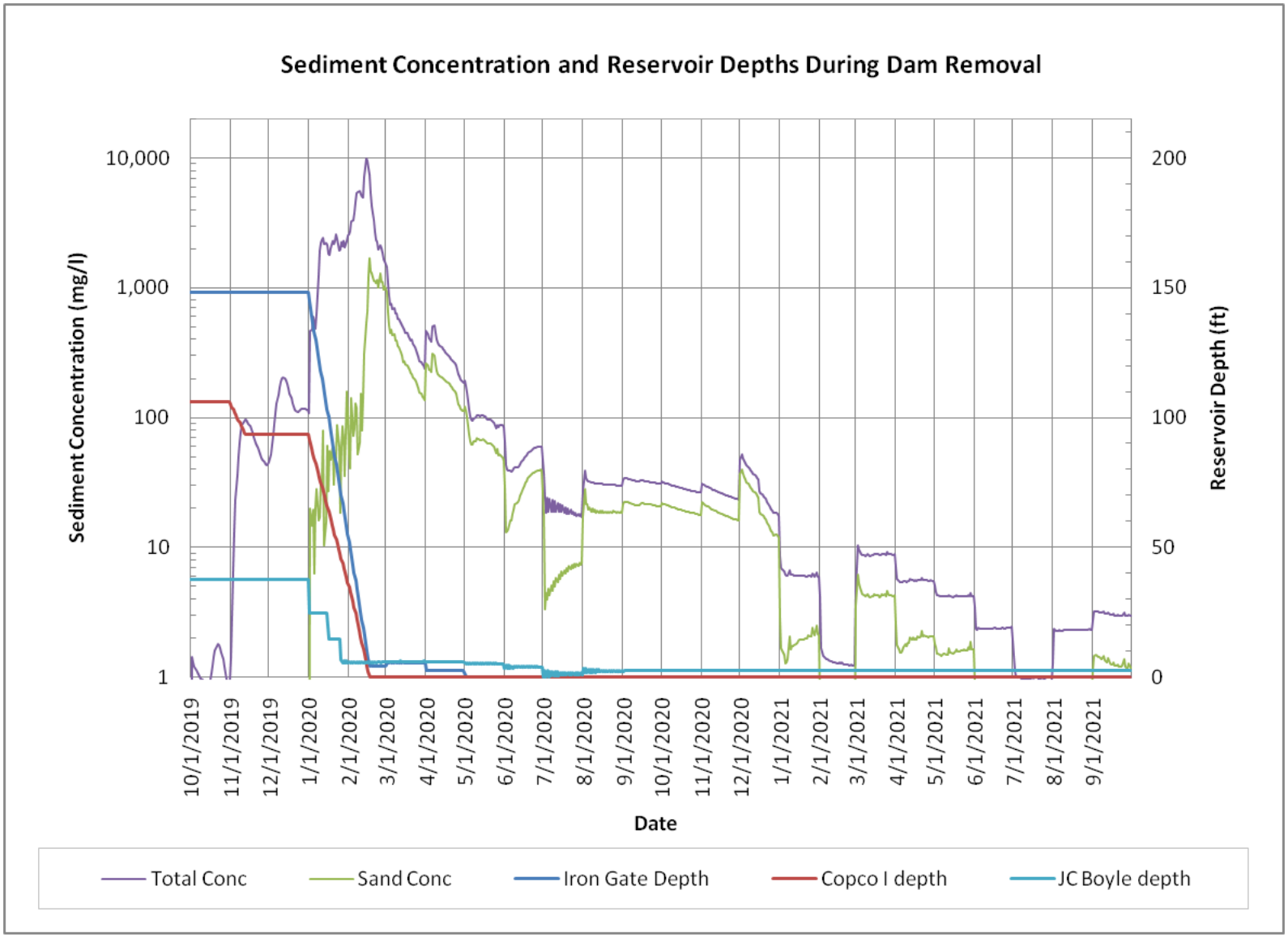


Figure 9-15. Simulated reservoir depths and sediment concentration below Iron Gate Dam for WY 1976 (Median year) for Scenario 8.

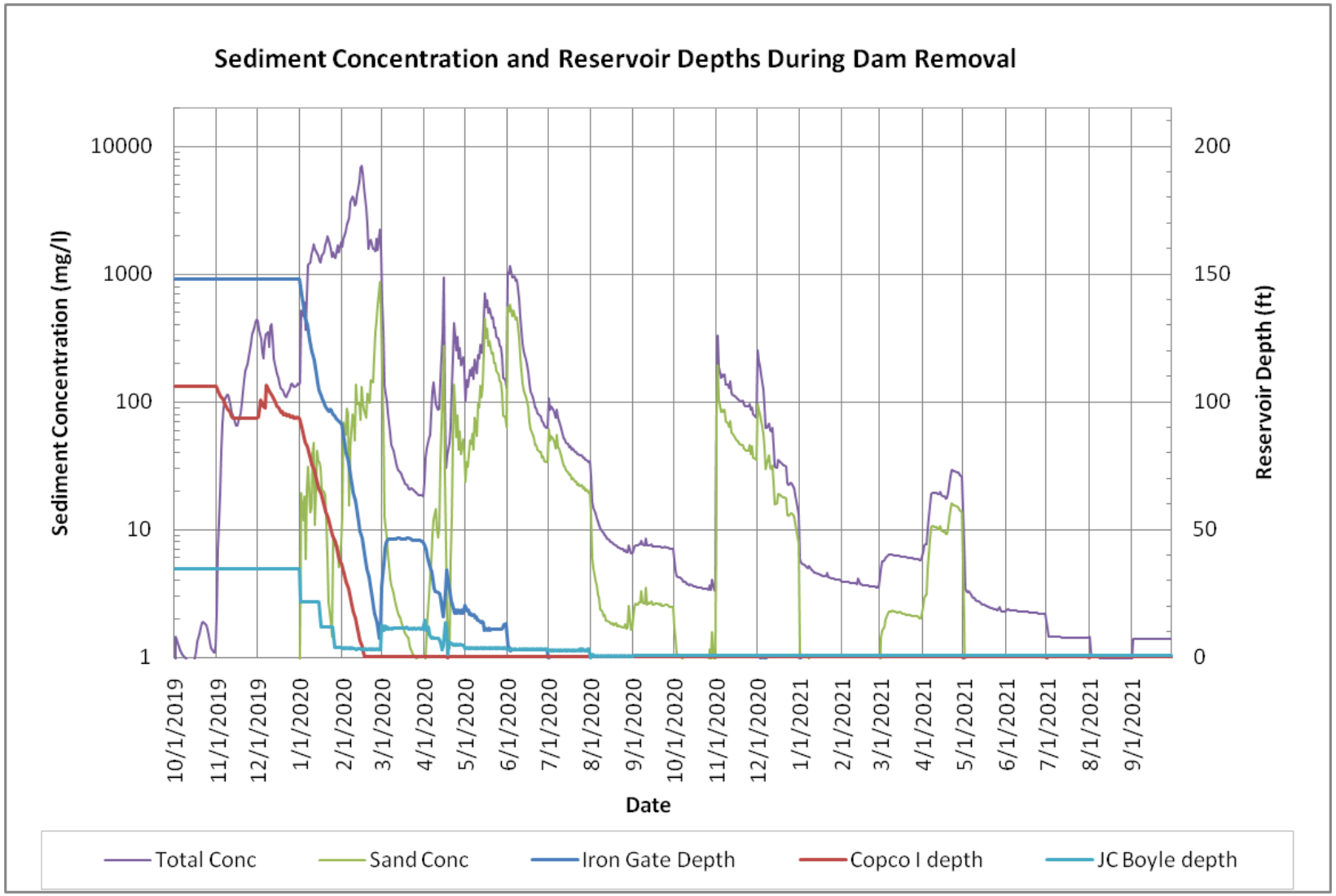


Figure 9-16. Simulated reservoir depths and sediment concentration below Iron Gate Dam for WY 1984 (Wet year) for Scenario 8.

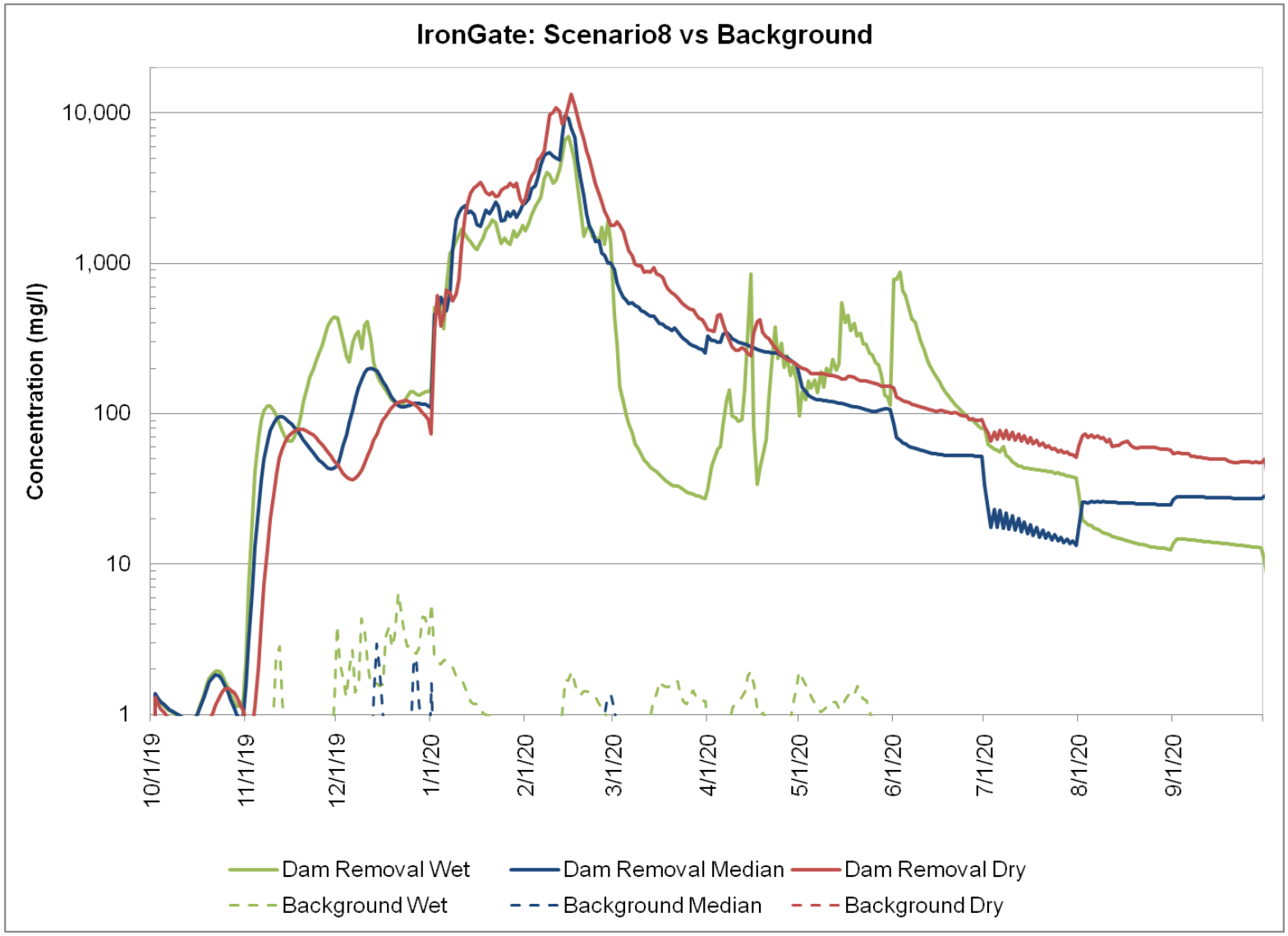


Figure 9-17. Sediment concentrations at the Iron Gate gage for Scenario 8 and for background conditions for dry, median and wet years.

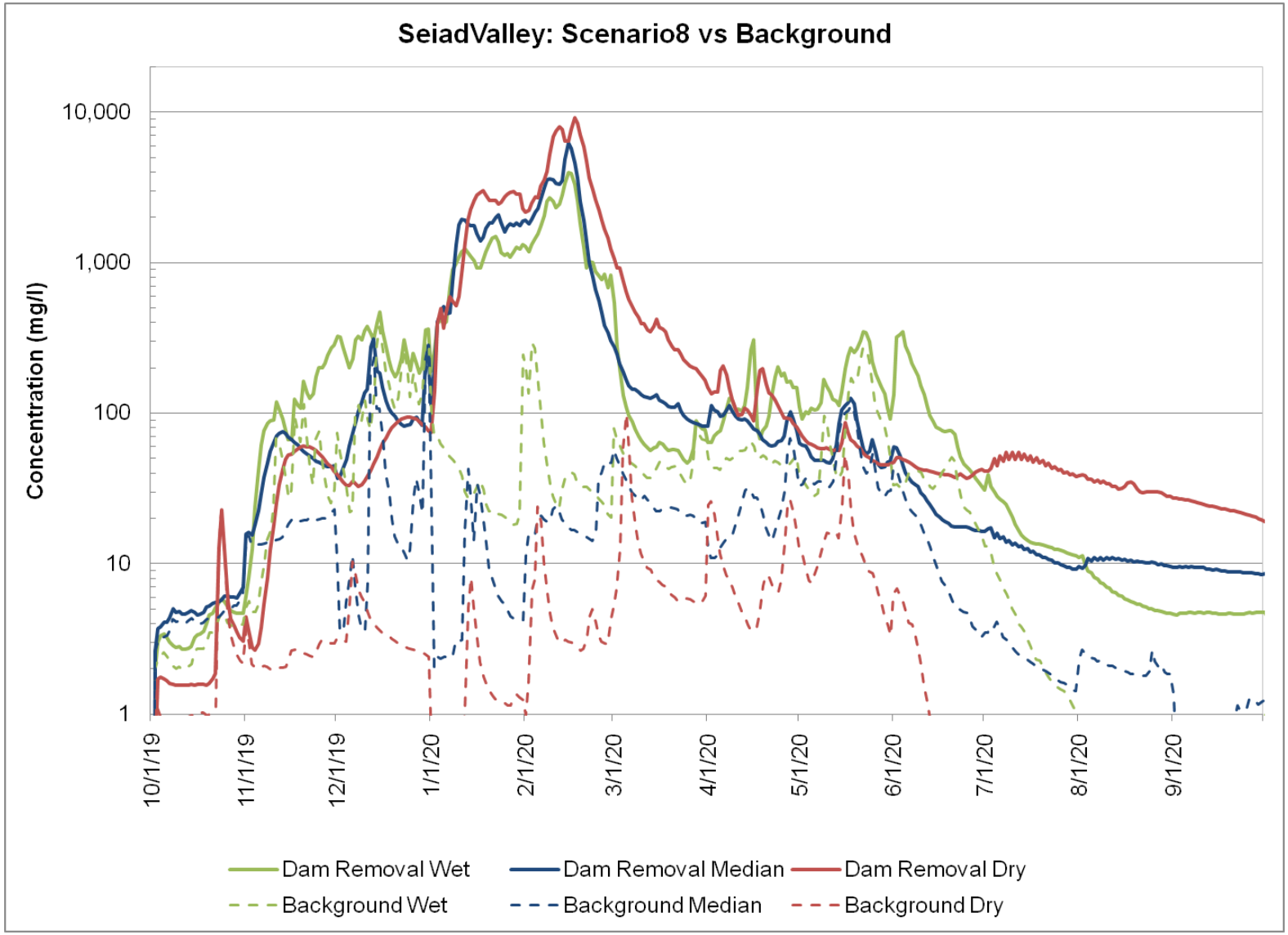


Figure 9-18. Sediment concentrations at Seiad Valley for Scenario 8 and for background conditions for dry, median and wet years.

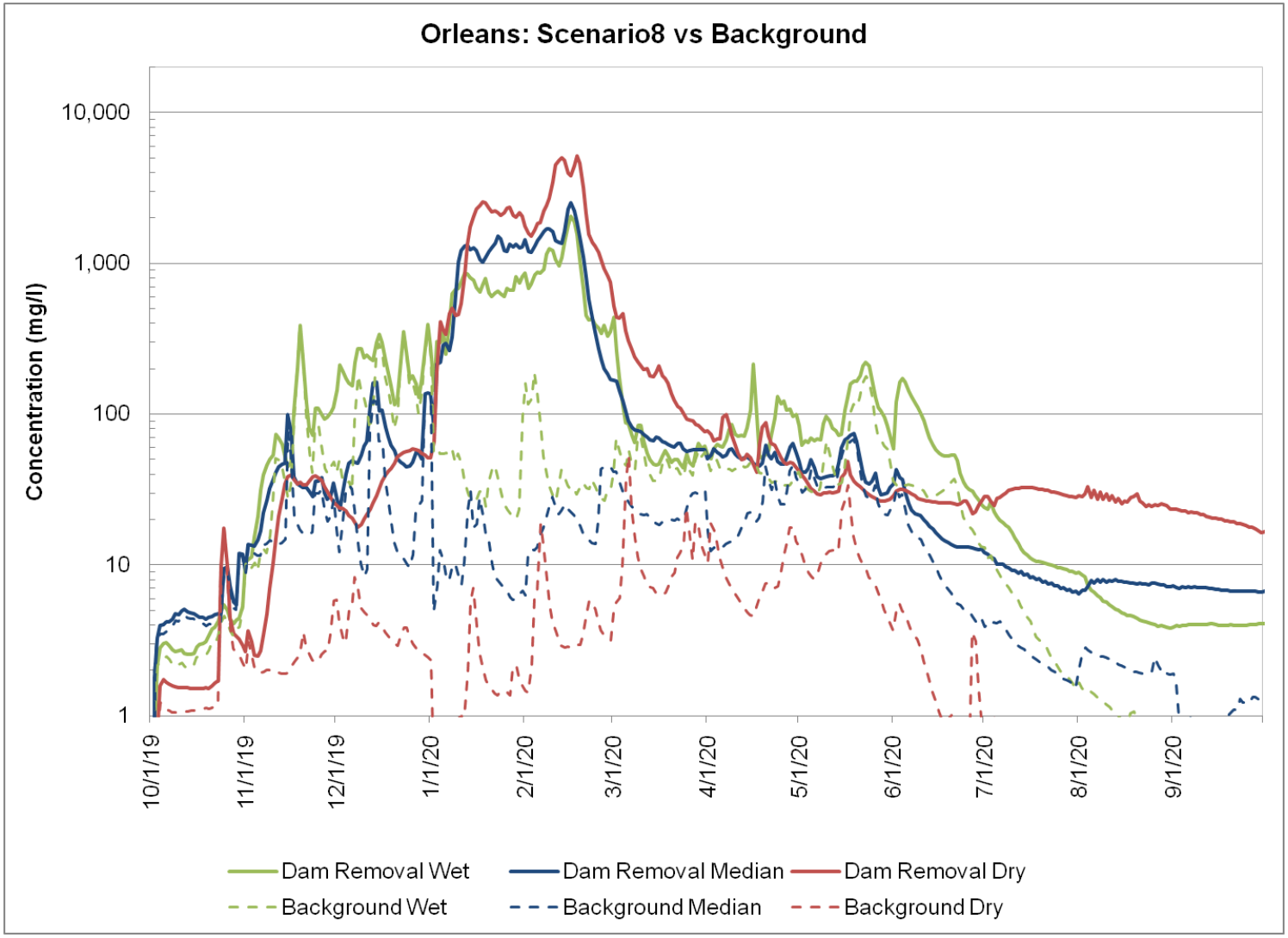


Figure 9-19. Sediment concentrations at Orleans for Scenario 8 and for background conditions for dry, median, and wet years.

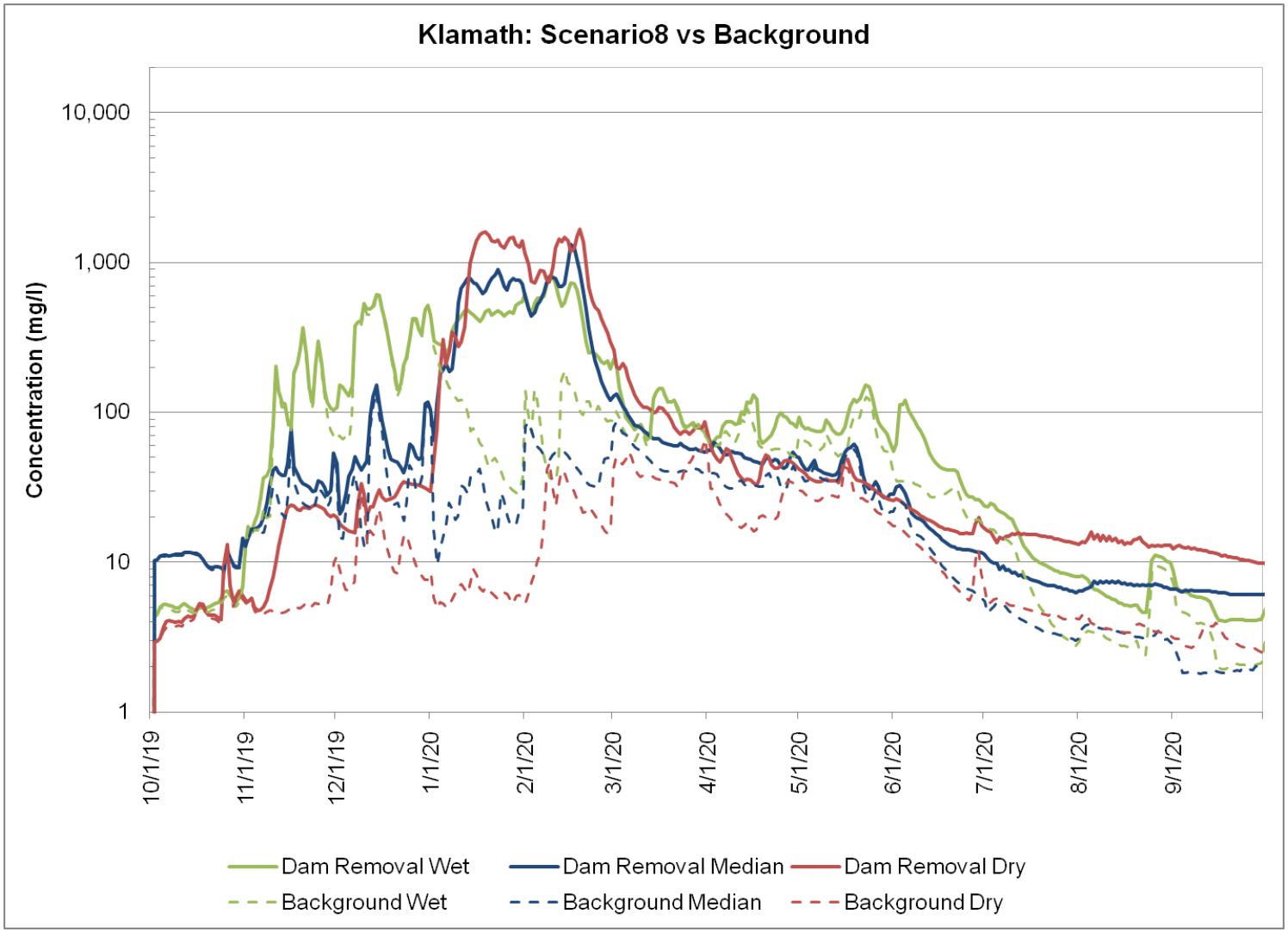


Figure 9-20. Sediment concentrations at the Klamath gage for Scenario 8 and for background conditions for dry, median, and wet years.

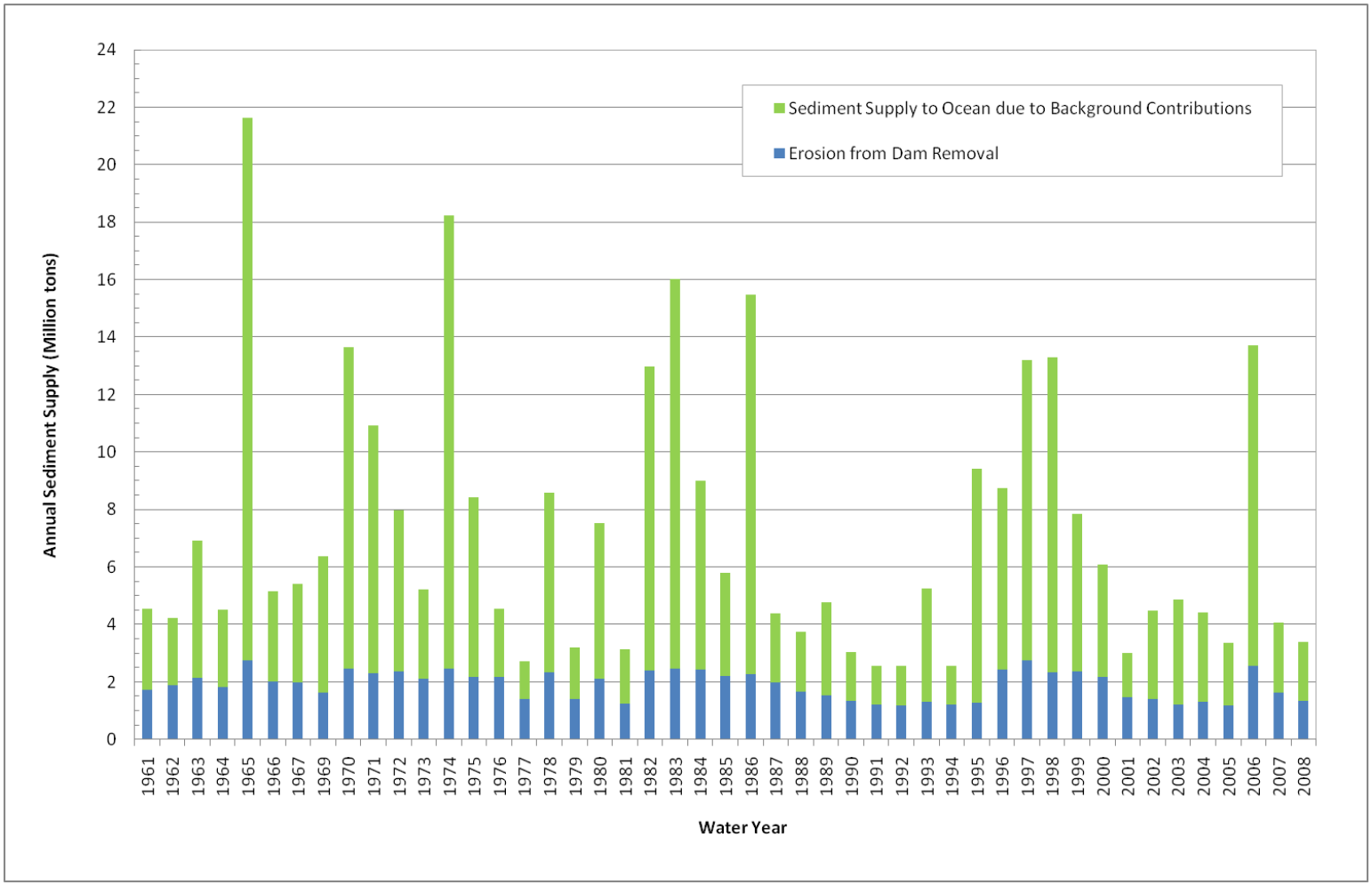


Figure 9-21. Sediment delivery to the ocean under Scenario 8 and with dams in place (No Action) for the year of dam removal. Note: these results are only valid for the year of dam removal. No significant increase in sediment loads is predicted for years following dam removal.

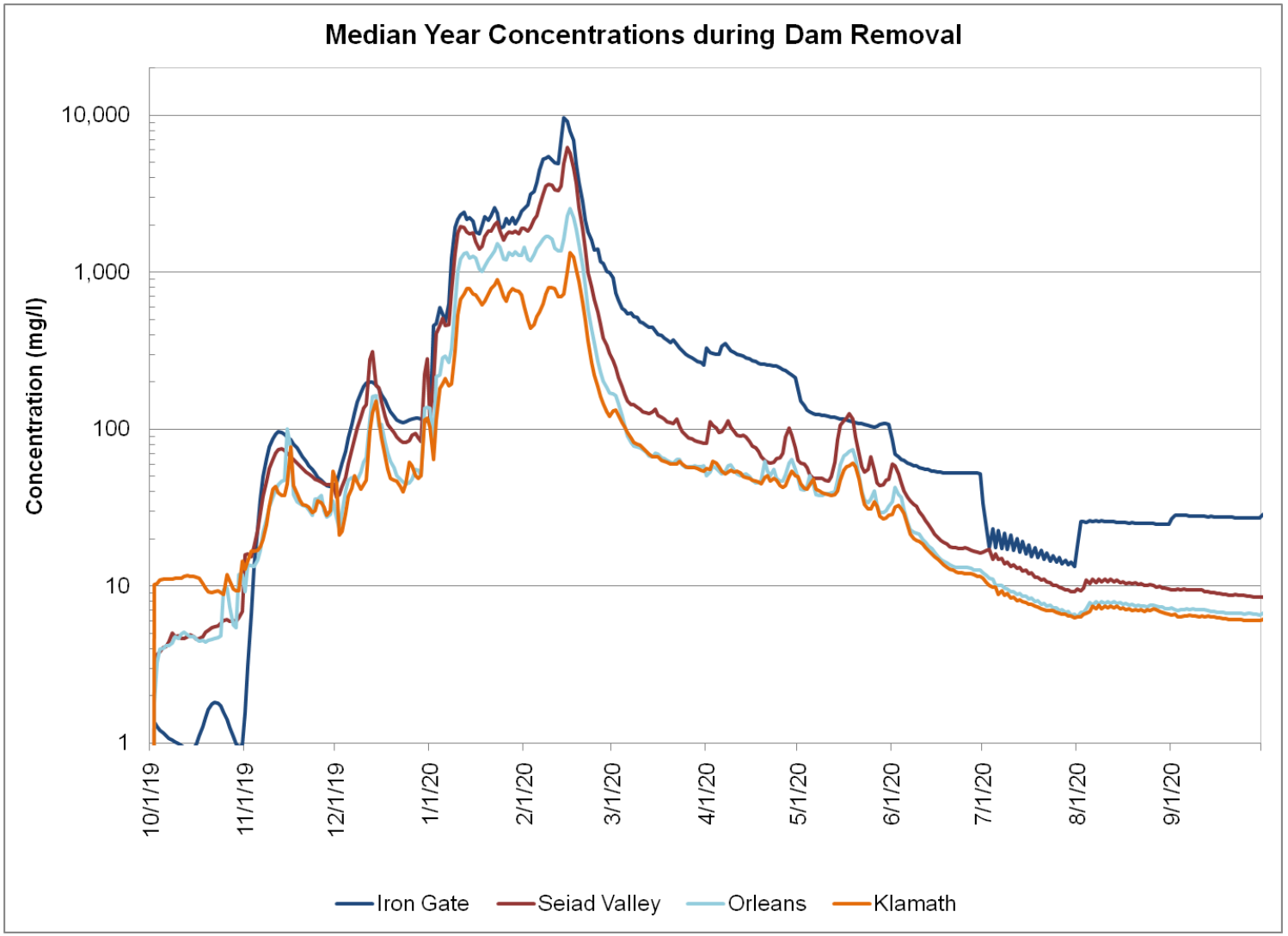


Figure 9-22. Sediment concentrations at stream gage locations for Scenario 8 for median year (1976).

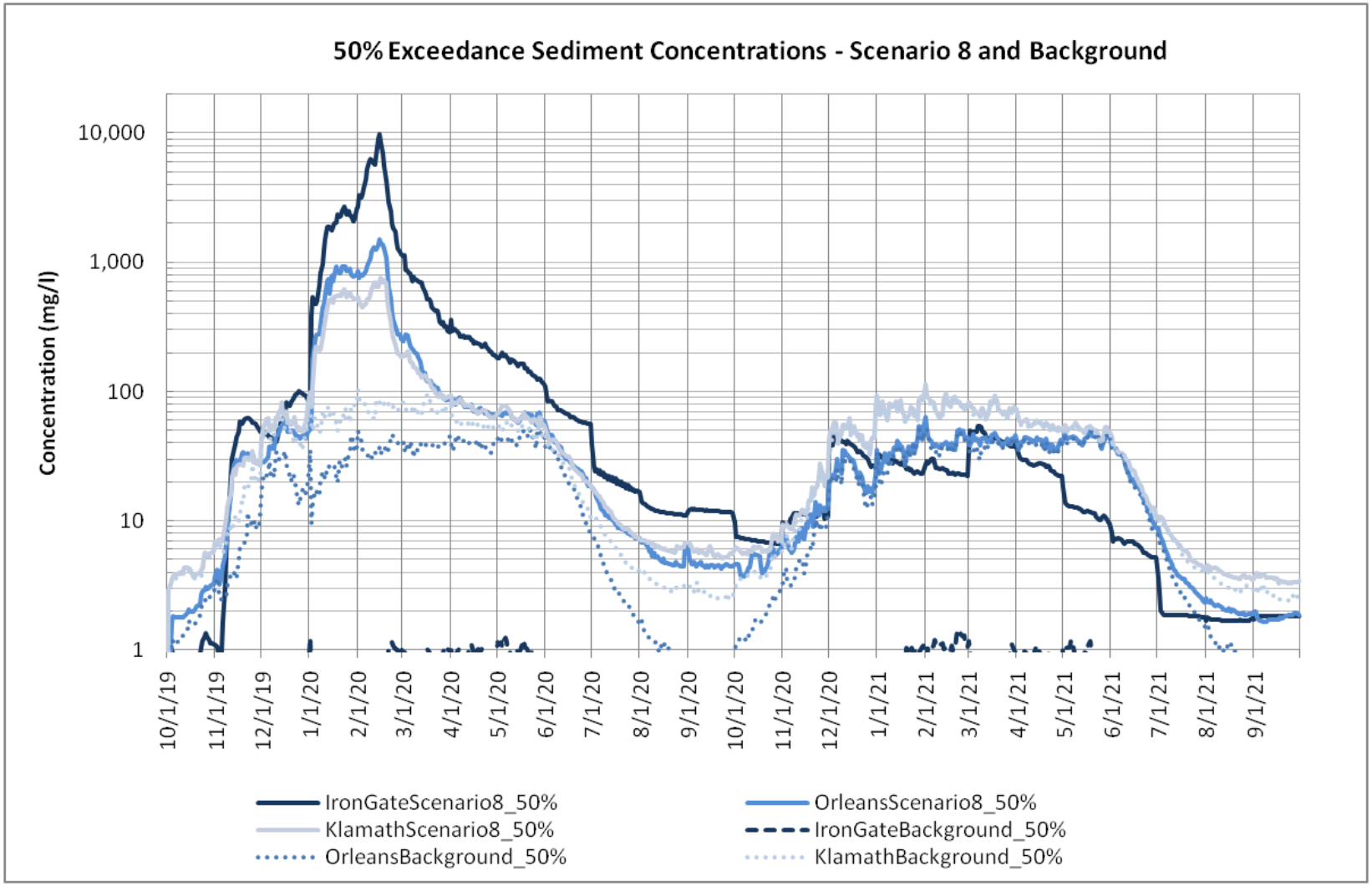


Figure 9-23. Sediment concentrations at a 50% exceedance level for below Iron Gate, at Orleans and at Klamath USGS gages.

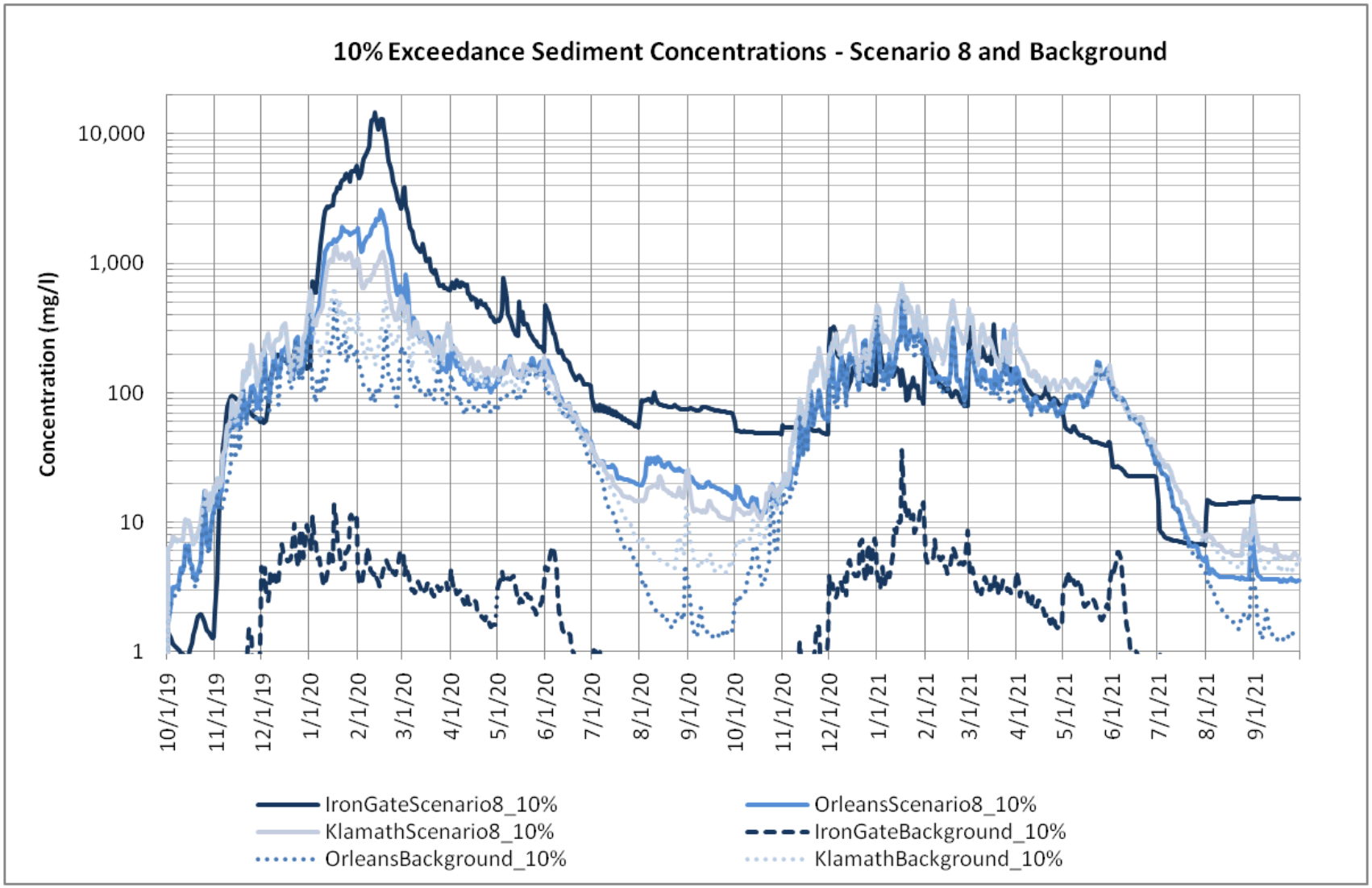


Figure 9-24. Sediment concentrations at a 10% exceedance level for below Iron Gate, at Orleans and at Klamath USGS gages.

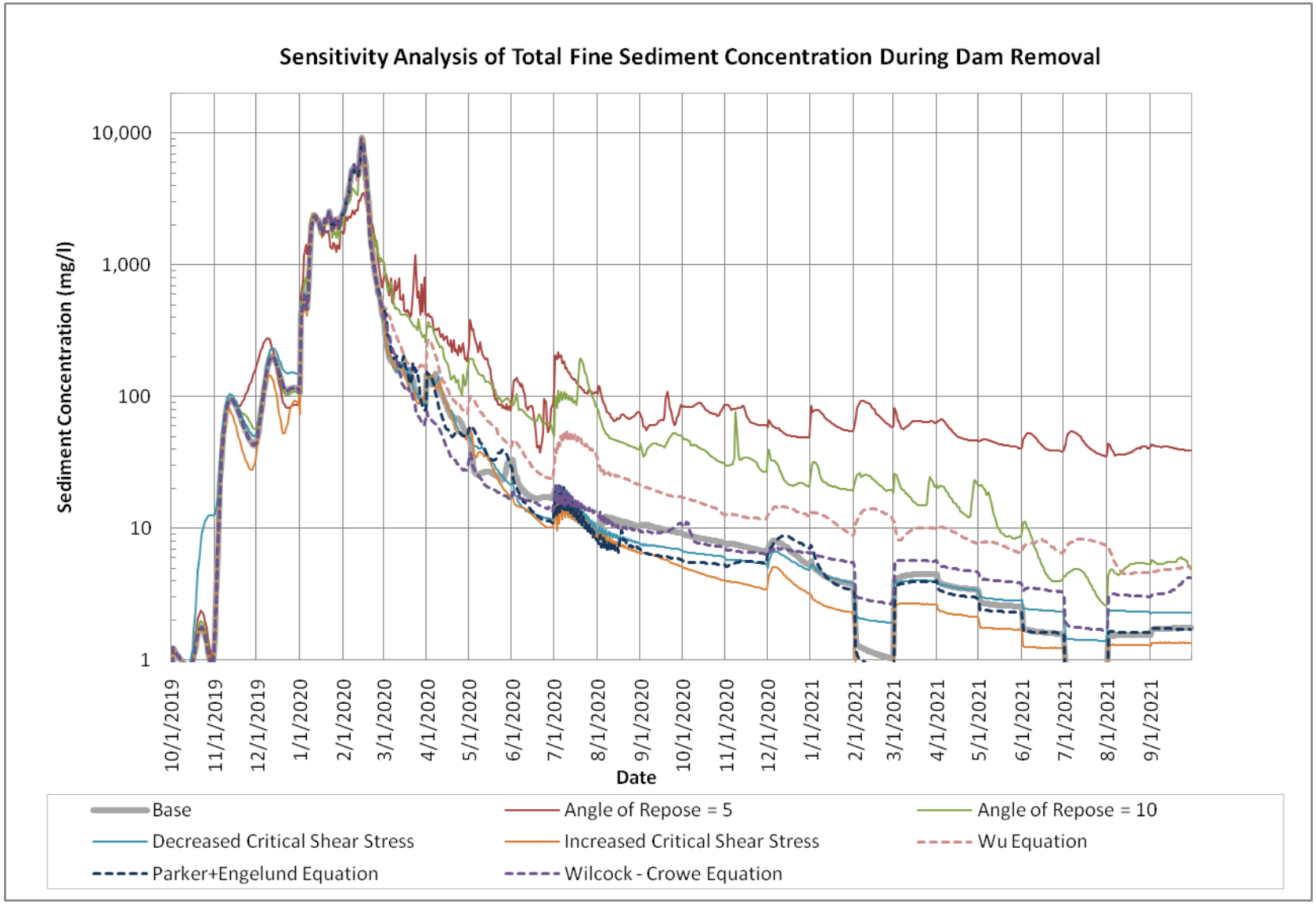


Figure 9-25. Sensitivity of Fine Sediment Concentration to Various Sediment Transport Parameters.

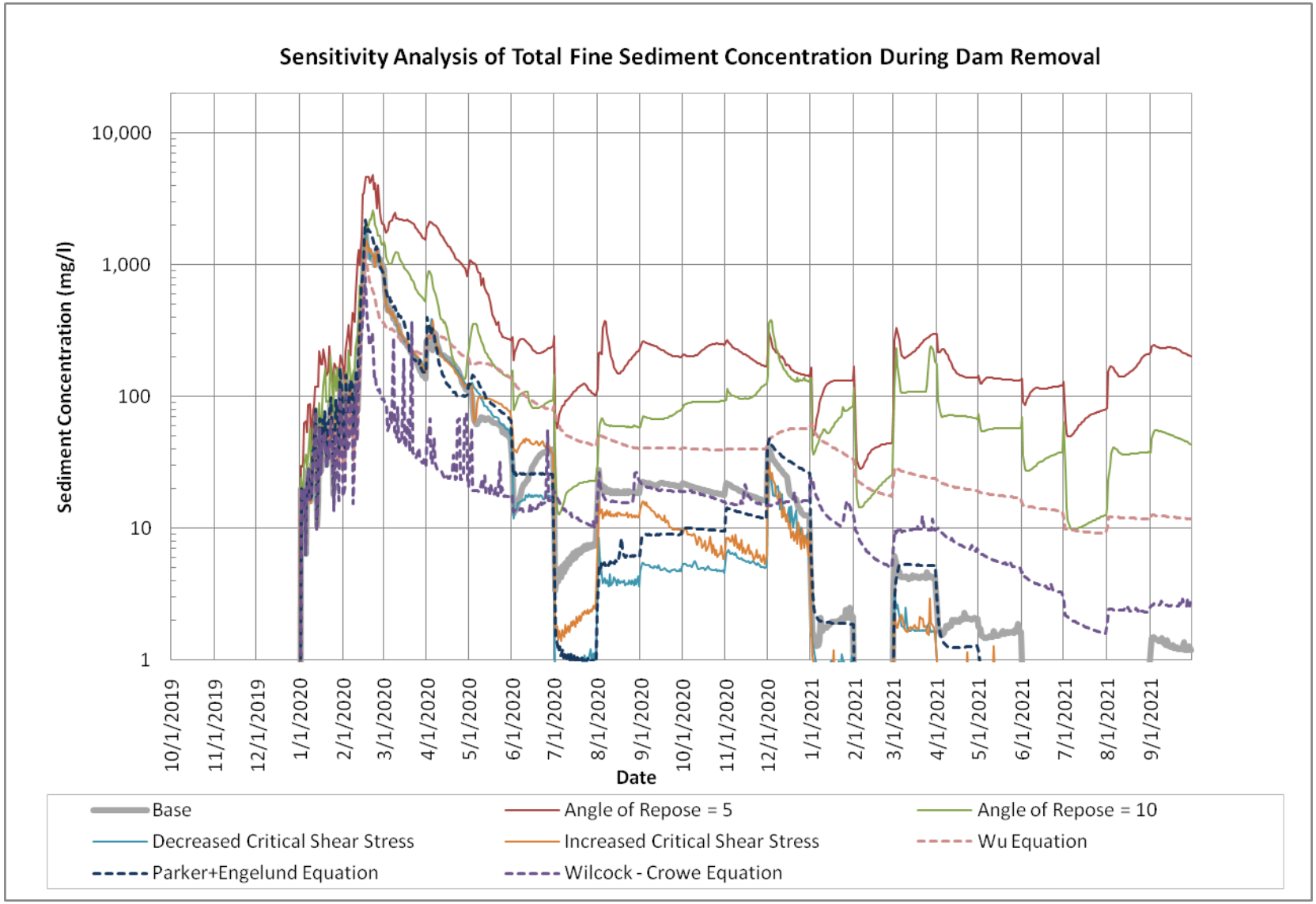


Figure 9-26. Sensitivity of Sand Concentration to Various Sediment Transport Parameters.

9.2.1.4. Erosion and Deposition after Dam Removal

The volume of erosion for dry, median, and wet years for each reservoir is given in Figure 9-27. There is between 5.4 and 8.6 million yd^3 of sediment eroded from behind the dams (41 and 66 %). Stated more loosely, approximately one to two thirds of the material will be removed depending on if it is a dry or wet year, respectively. Most of the erosion will occur during the drawdown process. During drawdown, direct hydraulic forces on the soft sediment will cause some of the erosion. There will also be slumping of sediment toward the river channel as the downslope force of sediment self-weight and the force of the draining water exceeds the shear strength of the sediment. However, as the excess water drains from the sediment, the sediment shear strength will quickly increase. The pore water pressure will decrease as the water drains from the sediment and the cohesion will increase as the sediment consolidates.

Initial stable slope estimates conservatively indicate that the stable slope of the reservoir sediment would be 10H:1V or about 6º (Shannon and Wilson, 2006). However, PanGeo (2008) estimated the stable slope would be 3H:1V. Laboratory measurements of the sediment drill cores estimate that the friction angle is between 27 and 32 degrees (2H:1V). However, because the sediments were so soft, it was difficult to obtain accurate measurement of the shear strengths. It is likely that the true value is close to the PanGeo (2008) estimate. The sediment located in the upper 1 foot will be soft, unconsolidated, and weak material that may wash away during drawdown or flow towards the river channel relatively quickly. The water content is above the liquid limit in many cases. The sediment located beneath this upper layer is expected to be relatively more consolidated but still very soft. The initial slumping process is expected to occur during the drawdown period under all scenarios. However, after drawdown, most of the sediment remaining on the terraces will be stable. The stable depth assuming an infinite slope was calculated in Section 5.6.3. Practically all the sediment on terraces of with slopes of 0.1 or less will be stable after drawdown. At a slope of 0.2, it is expected that the sediment will slump toward the river channel if the depth is greater than 3 or 4 feet. These unstable areas will include some sediment in Copco on the steeper slopes, but it will be localized to small areas.

After the initial slumping and draining of excess water from the sediment, the sediment will begin to dry as the result of evaporation. The remaining reservoir sediment volume will reduce by approximately two thirds and the depth of the sediment will decrease by about a third. Cracks will appear and the sediment will harden significantly. The drying process is expected to occur in the spring or early summer depending upon the balance of rain and evaporation rates. The resistance to erosion will increase markedly during this period and the sediment will progress from highly erodible to very resistant to erosion. Because of the cracking, some erosion will continue as gully formation occurs during rainstorms. However, the reservoir area will be mulched and seeded and this will limit

significant surface erosion. It is not likely that there is any significant erosion of reservoir material after the drawdown period and the mulch has been applied. The revegetation plan is described in Reclamation (2011b).

The reach averaged erosion and deposition depths from J.C. Boyle to Iron Gate dams are shown in Figure 9-28 and Figure 9-29 for a dry and wet year, respectively. The entire reach was split into subreaches identified by the reservoirs and the reaches between the reservoirs. There is significant erosion of the reservoir sediment during the drawdown period from January 1, 2020 to March 1, 2020, after which the river bed in the reservoir reaches is expected to remain stable. The reaches between the reservoirs show very little change, with only some minor deposition occurring in the reach between Iron Gate to Copco 2 dams.

The bed profile downstream of Iron Gate Dam before dam removal and in the two years following dam removal is shown in Figure 9-30. After dam removal, some minor deposition is shown in the reach from Bogus Creek to Cottonwood Creek in the first year, but no additional deposition is indicated after the first year following dam removal. The reach averaged deposition downstream of Iron Gate Dam following dam removal is shown in Figure 9-31 for a median year of dam removal. There is no significant deposition in the reach from Iron Gate Dam to Bogus Creek. From Willow Creek to Bogus Creek, there is about 1.5 feet of deposition and from Cottonwood to Willow creeks there is less than 1 foot of deposition. Downstream of Cottonwood Creek, there is less than 0.25 feet of deposition but is considered not significant. The results for a dry start year (Figure 9-32) and wet start year (Figure 9-33) are very similar.

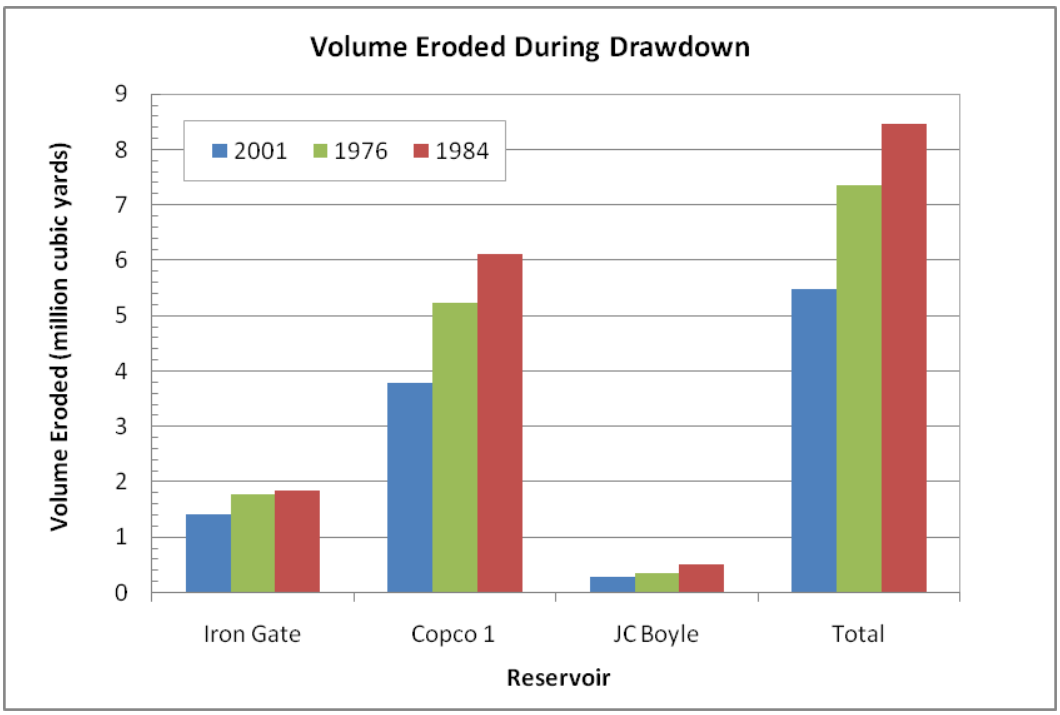


Figure 9-27. Volume of sediment erosion for preferred drawdown scenario.

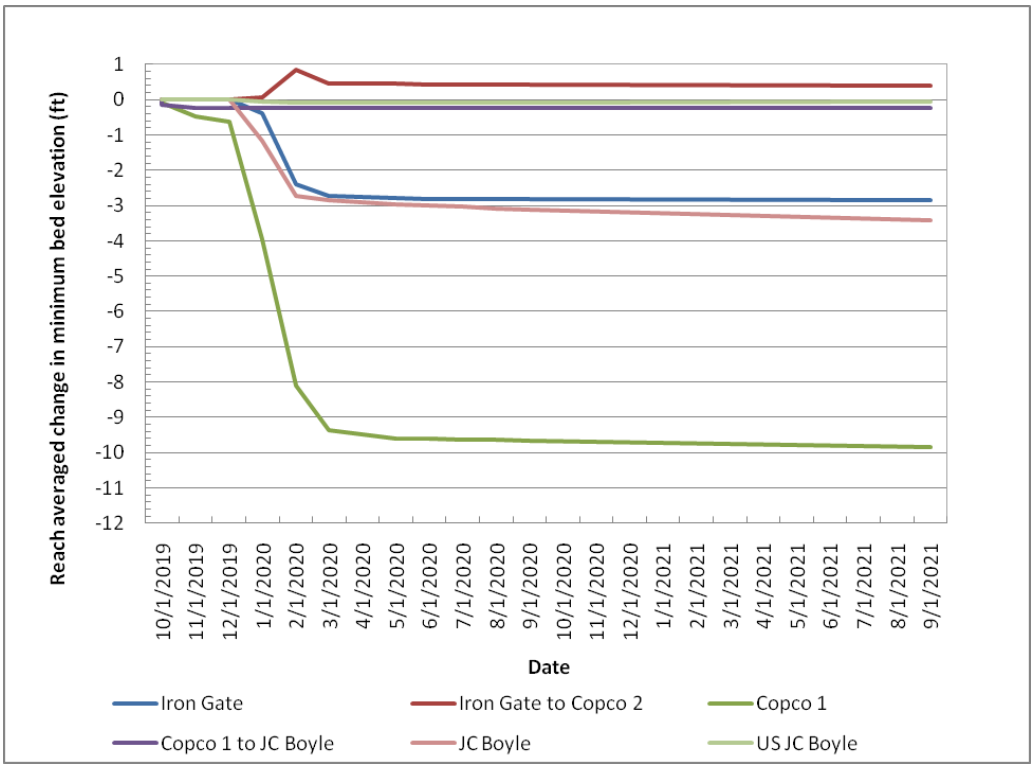


Figure 9-28. Reach averaged erosion for dry year (2001) for reaches from J.C. Boyle to Iron Gate Dam.

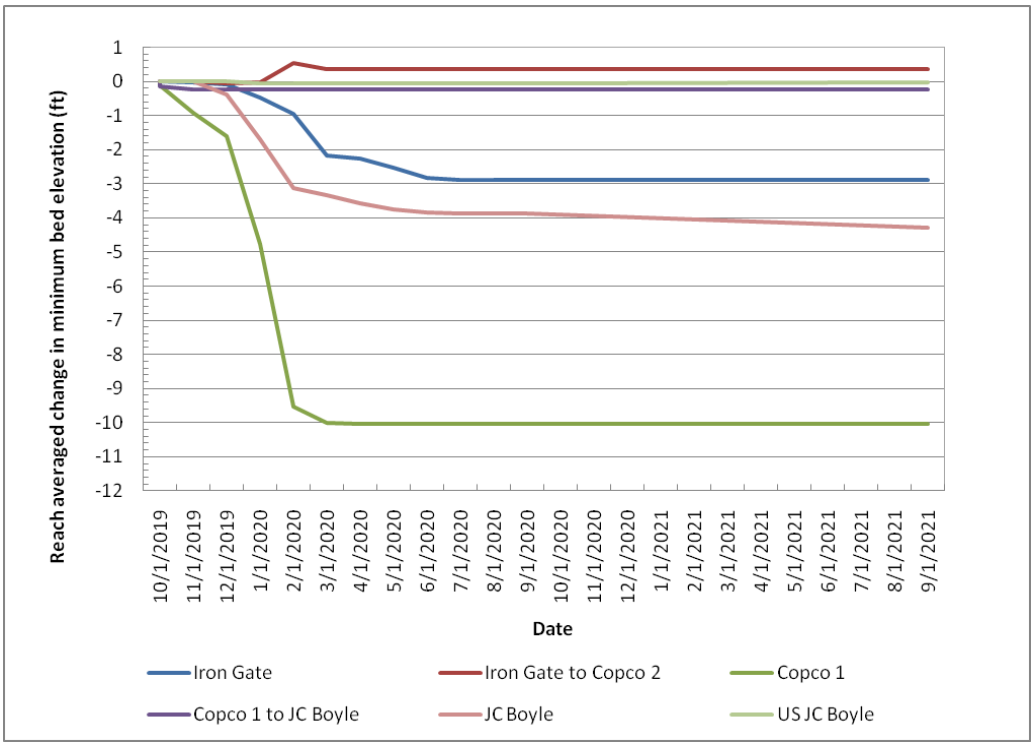


Figure 9-29. Reach averaged erosion for wet year (1984) for reaches from J.C. Boyle to Iron Gate Dam.

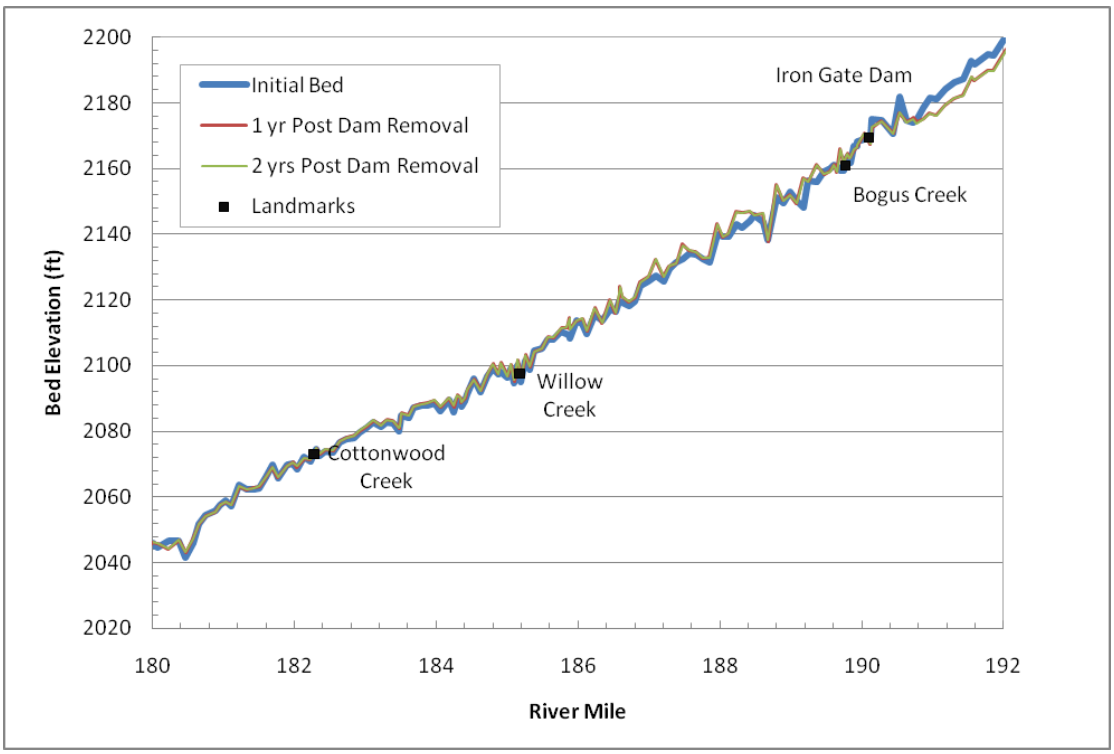


Figure 9-30. Bed profile downstream of Iron Gate Dam to Cottonwood Creek for two years following dam removal.

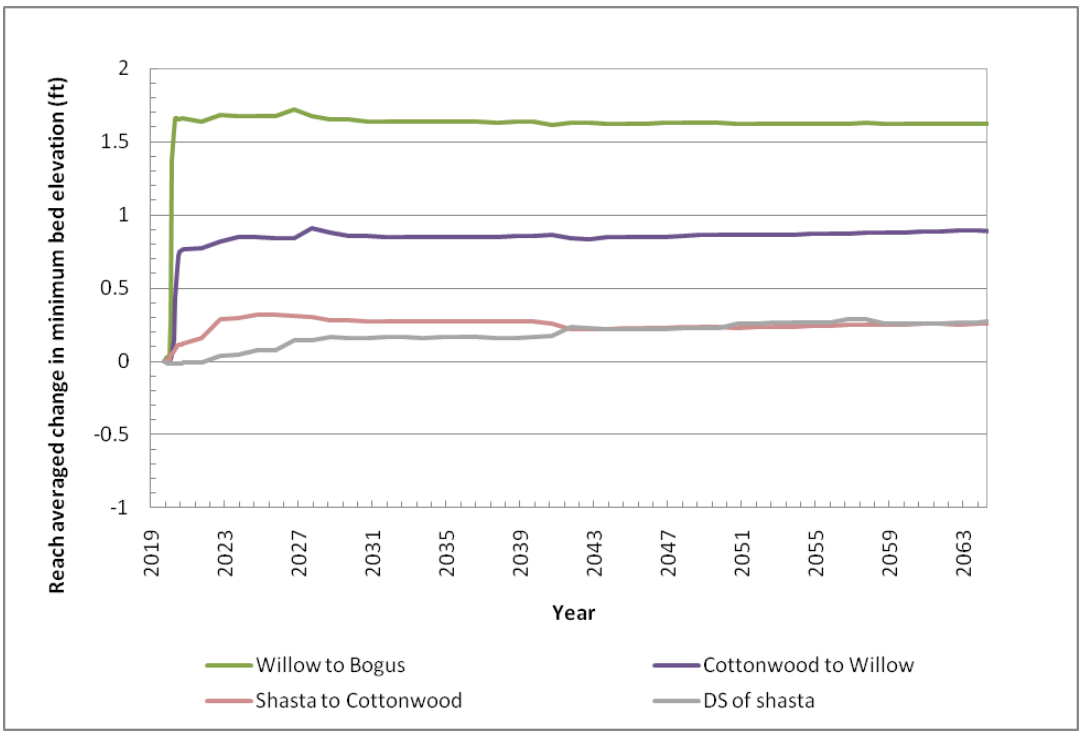


Figure 9-31. Reach averaged deposition from Iron Gate Dam to Shasta River for Scenario 8. Median start year.

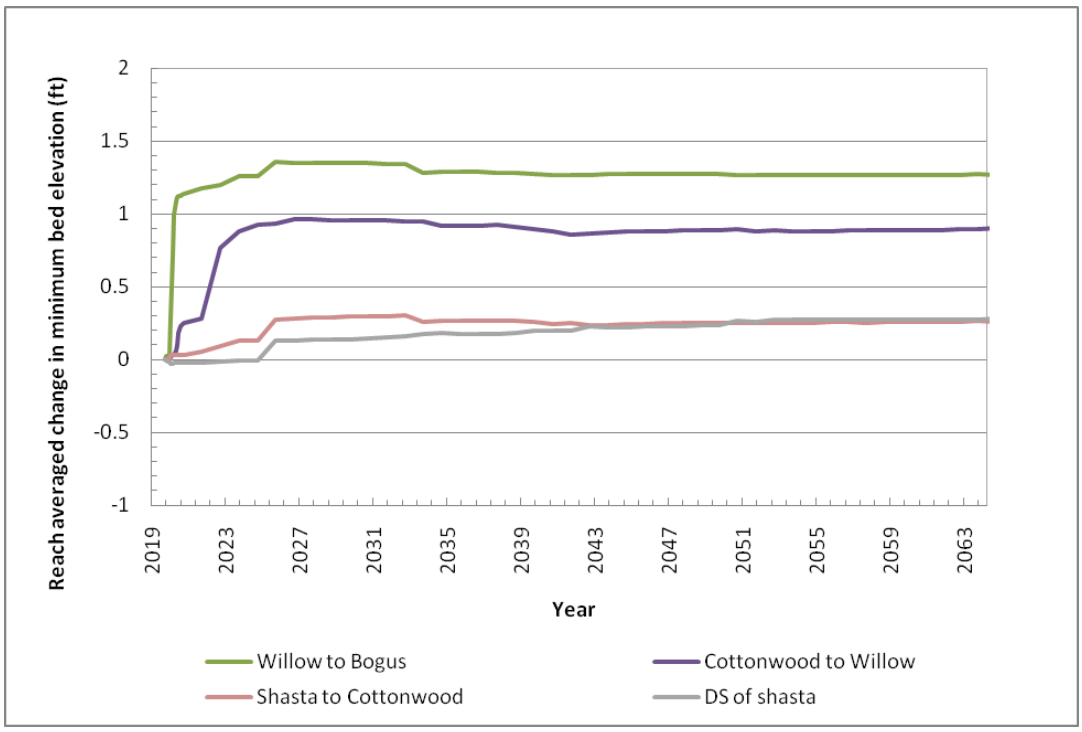


Figure 9-32. Reach averaged deposition from Iron Gate Dam to Shasta River for Scenario 8. Dry Start Year.

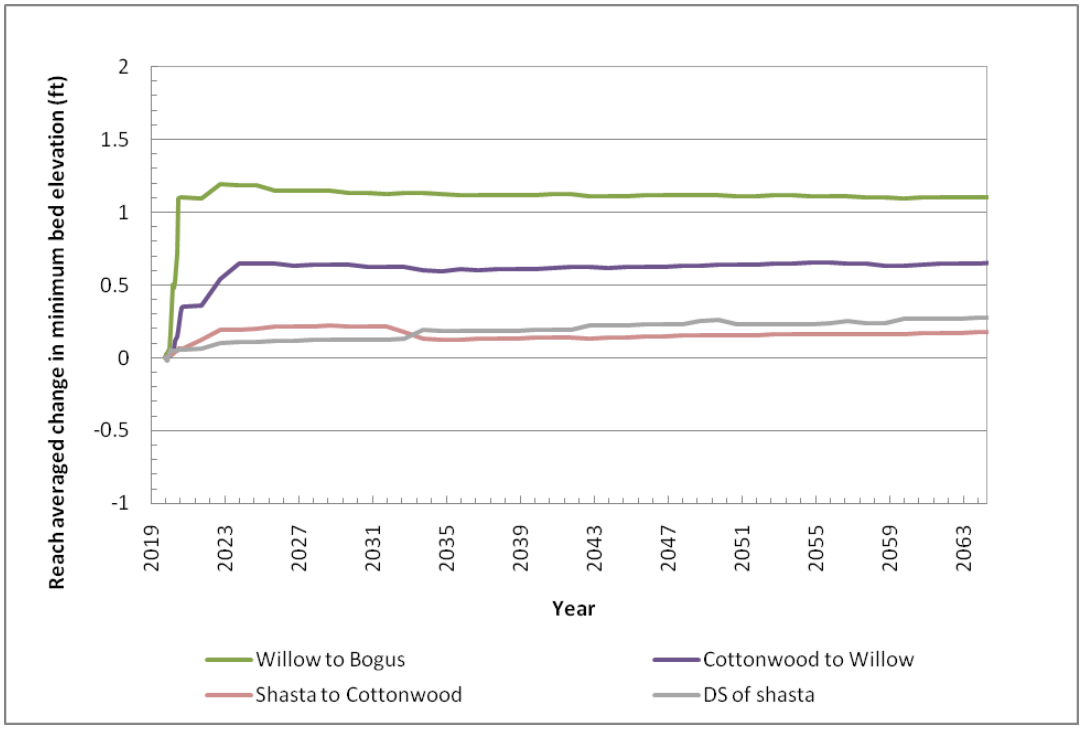


Figure 9-33. Reach averaged deposition from Iron Gate Dam to Shasta River for Scenario 8. Wet Start Year.

9.2.1.5. Bed Material after Dam Removal

SRH-1D was used to analyze the bed material fractions after dam removal. The reach average size gradation of the material in the active layer was analyzed to determine the fraction of fines (silts, clays, and organics), sand, gravel, and cobble. The active layer in the model was defined as the upper 1 foot of material in the bed. Therefore, it contains material below the visible surface. Most of the bed material data collected in the Klamath River used pebble count methods which only sample the material visible on the surface and cannot effectively sample the sand sized material. Therefore, very little sand size material was reported in these studies. Holmquist-Johnson and Milhous (2010) reported substrate data which was collected by removing the armor layer and taking bulk samples of the sediment beneath it. They reported sand contents ranging from 5% to 22 % in the substrate material at six different locations from Iron Gate Dam to the Pacific Ocean. The results reported form the active layer gradations of SRH-1D are most appropriately compared to a combination of the bulk substrate sample and the pebble count sample. We expect that if the simulated results of the sand content are in the range of 10% to 20% that this is an approximately a background level of sand within the bed under natural sediment supply conditions. Modeling the fraction of fines contained within the bed is difficult because it depends upon many factors. One of the main uncertainties is determining the sheltering effects that larger material has on the smaller material.

The fraction of fines, sand, gravel, and cobble in the bed for the J.C. Boyle Reservoir reach is shown in Figure 9-34 for wet, median, and dry hydrologic scenarios. Within the first month following drawdown, the bed is dominated by cobble and gravel sized sediment. The fraction of sand remaining in the bed will be dependent upon the hydrologic scenario. Immediately upon drawdown, there may be up to 30% to 40% sand remaining in the bed. There is also some silt, clay, and organics expected to remain in the bed, but in fairly low amounts depending upon their ability to adhere to larger particles. Under wet conditions, some of this sand and fine material will be flushed from the bed and by the second year, there is expected to be approximately 20% sand or less. Under median or dry conditions, the higher sand contents may remain until a high flow mobilizes the bed and flushes the sands from the bed. Regardless of the scenario, it is expected that by 2025, the bed is near equilibrium conditions with a small fraction of sand in the bed consistent with the reaches upstream and downstream.

Figure 9-35 shows the fraction of fines, sand, gravel, and cobble in the Copco Reservoir reach. Similar to the J.C. Boyle Reservoir reach, the bed is dominated by cobble and gravel sized sediment within the first month after drawdown. The sand is flushed from the bed quicker at Copco Reservoir than J.C. Boyle Reservoir, mostly likely because the upper part of J.C. Boyle Reservoir has a lesser slope than the slope through Copco Reservoir. For the Wet and Median Year, there is very little change after Year 1. The bed attains an equilibrium gradation typical of the upstream and downstream reaches within the first year. For the Dry Year, the response is slower and it is expected to take at least at median type of year to return the bed to equilibrium conditions. Based upon mobilization criteria presented in the Section 9.2.3 for the

lower reaches, a flow of approximately 6,000 cfs will be required to mobilize the bed and flush the residual fines from the bed. It is expected that a similar flow will be required to obtain similar results in the Copco Reservoir reach.

Figure 9-36 shows the fraction of fines, sand, gravel, and cobble in the Iron Gate Reservoir reach. There is substantially more fine material expected at Iron Gate because it is downstream of Copco Reservoir. During a wet year scenario, the bed is restored to an equilibrium cobble and gravel bed stream with a small amount of sand after the spring runoff. For the median and dry year scenario, the bed remains over 30% sand for the first two years. By year 2025, the bed attains a near equilibrium cobble and gravel bed stream with a small amount of sand, similar to the wet year scenario.

Downstream of Iron Gate Dam, there will be a substantial increase in sand content immediately following reservoir drawdown in the Bogus Creek to Iron Gate reach (Figure 9-37). The percent of sand in the bed is expected to increase to up to 40% for the month immediately after reservoir drawdown. Under a wet scenario, it is expected that the percent sand would then decrease to below 20% by the end of spring runoff in 2020. Under a median or dry scenario, a subsequent wet year will be required to flush the sand material from the bed and return to an equilibrium level with a small amount of sand sized material in the bed.

The response of the reach from Willow Creek to Bogus Creek is expected to be similar to the reach above it (Figure 9-38). However, because the reach is longer, it may take slightly longer to flush the excess sand from the bed and move through the reach. Under a median or dry scenario, it may take 5 or 6 years to return sand content in the bed to equilibrium levels in this reach.

The reach from Cottonwood Creek to Willow Creek will respond slightly slower than the upstream reaches and the recovery to equilibrium levels may be slightly slower with the full return to equilibrium sand levels taking up to 10 years (Figure 9-39).

The bed material in the reach from Shasta River to Cottonwood Creek (Figure 9-40) will show a more gradual response and it is anticipated that it will be difficult to measure significant response. Sand contents are not expected to rise above typical levels in the Klamath River. Furthermore, downstream of the Shasta River, model results indicate there will be no significant effect of dam removal on bed material gradations.

The reach averaged D50 and D16 representative diameters for the same reaches are presented in Figure 9-41 to Figure 9-47. The same basic information is contained within these plots as the bed material percentage plots.

The fine fraction of the released sediment (silts, clays, and organics) is not expected to deposit in significant amounts in the river channel. The majority of this material will be transported to the ocean and not interact significantly with the river bed. However, there may be deposition of fine material along vegetated areas or in slack water areas. In particular, if removal occurs during a dry year, some bank lines and some of the

slack water areas will be covered with a veneer of fine material. The fine material will typically not penetrate beyond twice the D90 of the bed material (Diplas and Parker, 1991; Schälchi, 1992).

Stewart et al (2002) documented a fine sediment release on the South Fork McKenzie River, Oregon. As part of the Willamette Valley Temperature Control Project, the U.S. Army Corps of Engineers (COE) modified the intake tower of Cougar Dam on the South Fork McKenzie River, Oregon. These modifications will allow operators to release colder water during the winter, and warmer water during the summer, to improve habitat conditions for bull trout and spring Chinook salmon. In order to carry out work on the intake tower, the COE lowered Cougar Reservoir below minimum pool elevation in April 2002, thereby exposing deltaic and lake bottom sediments to reworking by the South Fork McKenzie and other reservoir tributaries. The reworking of these sediments resulted in a prolonged discharge of turbid water from Cougar Reservoir that was highly visible for miles downstream and even affected the turbidity of the Willamette River below the confluence of the McKenzie. Although the COE had predicted in its Environmental Impact Statement (EIS) that turbidity would increase during the drawdown (predicted levels of 30 NTUs and spikes of 100 NTUs), they underestimated the magnitude, timing, and duration of the problem. Between April 1st and May 25th turbidity levels at the South Fork gauging station below the dam averaged 68 NTUs with spikes of up to 379 NTUs. The length of the high turbidity was approximately 2 months. The existing bed material downstream had a D50 of approximately 20 to 50 mm which is slightly smaller than the Klamath River bed material downstream of Iron Gate.

Stewart et al. (2010) stated that there was a relative enrichment in fines in the alluvial reaches below Cougar Reservoir as compared with the reaches above the reservoir. Upstream reaches and mainstem McKenzie sites have clay fractions representing 2.5% of the <2mm sample by weight as opposed to 9.5% in the South Fork below the dam. This increase in fines was not detectable below the confluence of the South Fork and the mainstem McKenzie River, which is located approximately 4 miles downstream. Because no in-situ sampling of gravels was conducted prior to the reservoir release in the spring of 2002, they were unable to discern whether this fines enrichment pre-dated the release, although high levels of fine sediment stored in channels downstream of dams is relatively uncommon.

Based upon the results of Stewart et al. (2010), if removal occurs in a dry year, we expect a measureable but small increase in the fine material (silts, clays, and organics) in the bed after dam removal. Stewart et al. (2010) reported an increase from 2.5% to 9% of clays within the < 2 mm size range, but this equated to less than 2% of the entire bed material sample which consistent primarily of gravels. We expect a similar type of result after dam removal on the Klamath River. The amount of fine deposition will also decrease with distance from the dam. Stewart et al. (2010) did not find any detectable increase in fine material after the confluence with a larger tributary. The tributaries downstream of Iron Gate Dam will have a similar dilution effect on the fine sediment release on the Klamath River. A longer distance of river will likely be affect on the Klamath River because of the higher sediment concentrations and duration

expected. Downstream of the Shasta River, no significant deposits of reservoir material and no significant change to the bed material are expected.

The only reservoir material that will be transported to the estuary will be the fine material (silt, clays, and organics). The fine material will not deposit in significant quantities in the estuary. There are currently high concentrations of silt and clay transported through the estuary and the sediment sampling of Reclamation (2010) documented the absence of fine material in the estuary except in the backwater and vegetated areas. If removal occurs during a low flow year, there may be small amounts of deposition in these areas, but it will be relatively small volumes of material.

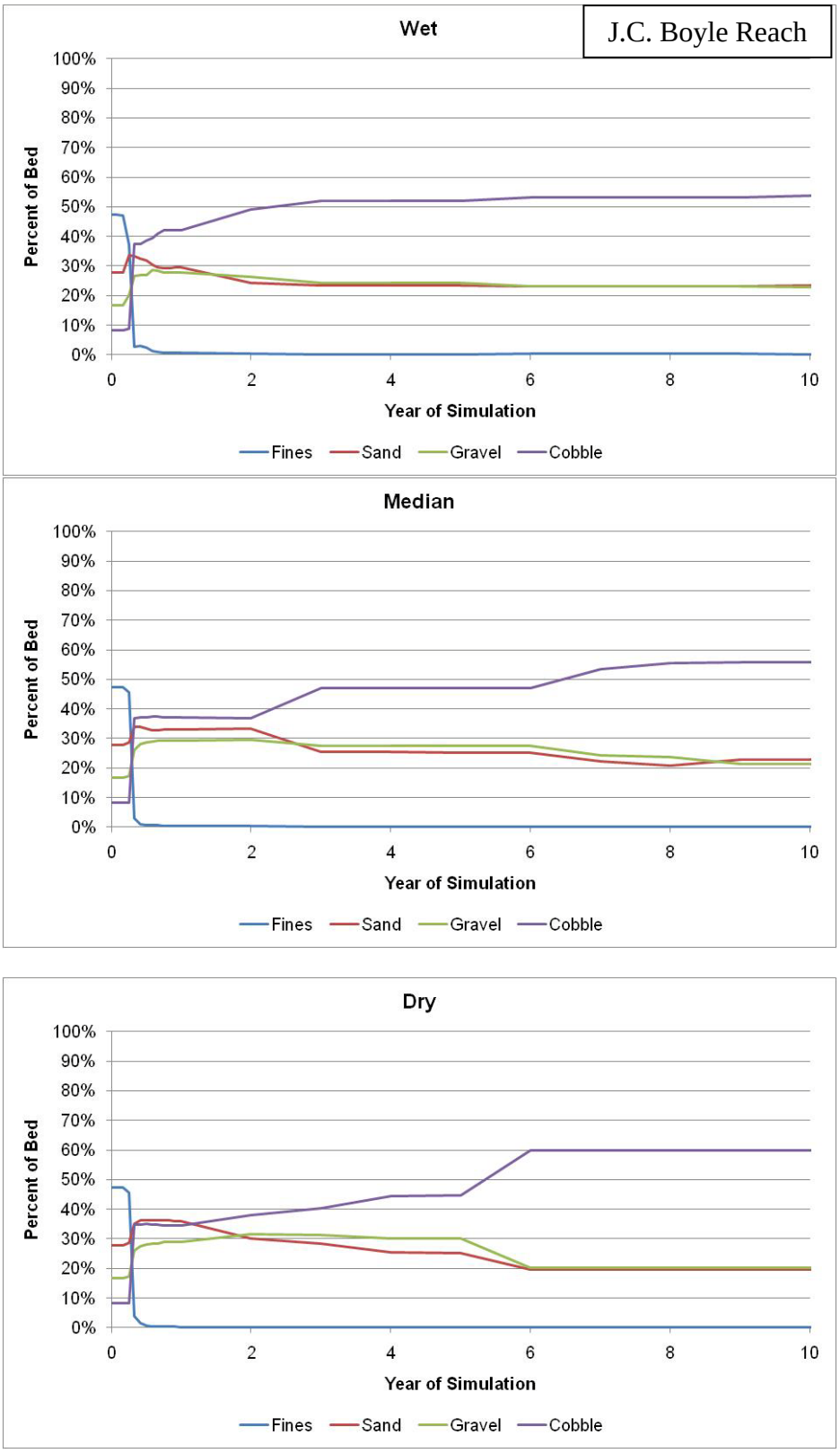


Figure 9-34. Bed material for the 10 years following dam removal for Wet, Median, and Dry Years for J.C. Boyle Reach

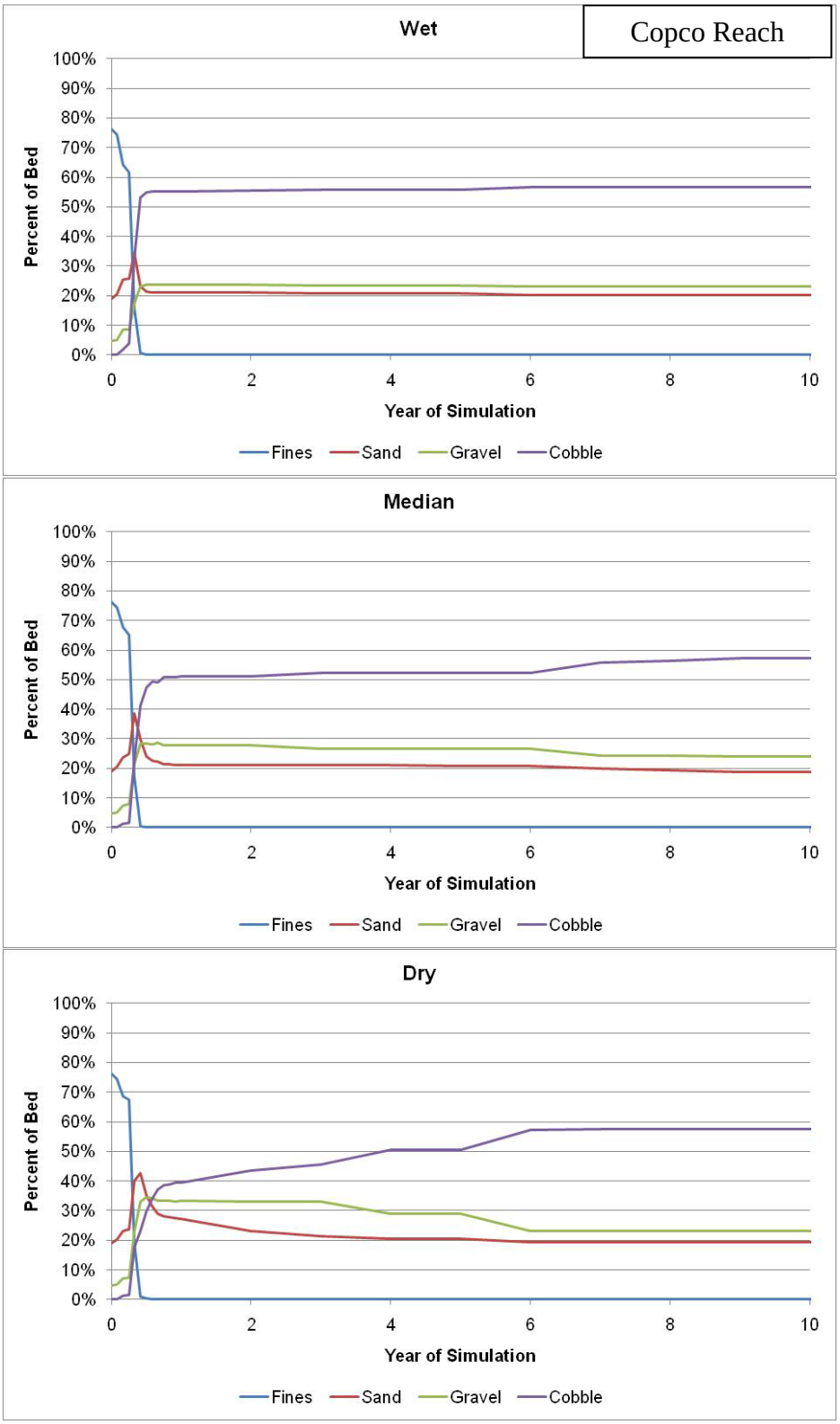


Figure 9-35. Bed material for the 10 years following dam removal for wet, median, and dry years for Copco Reach.

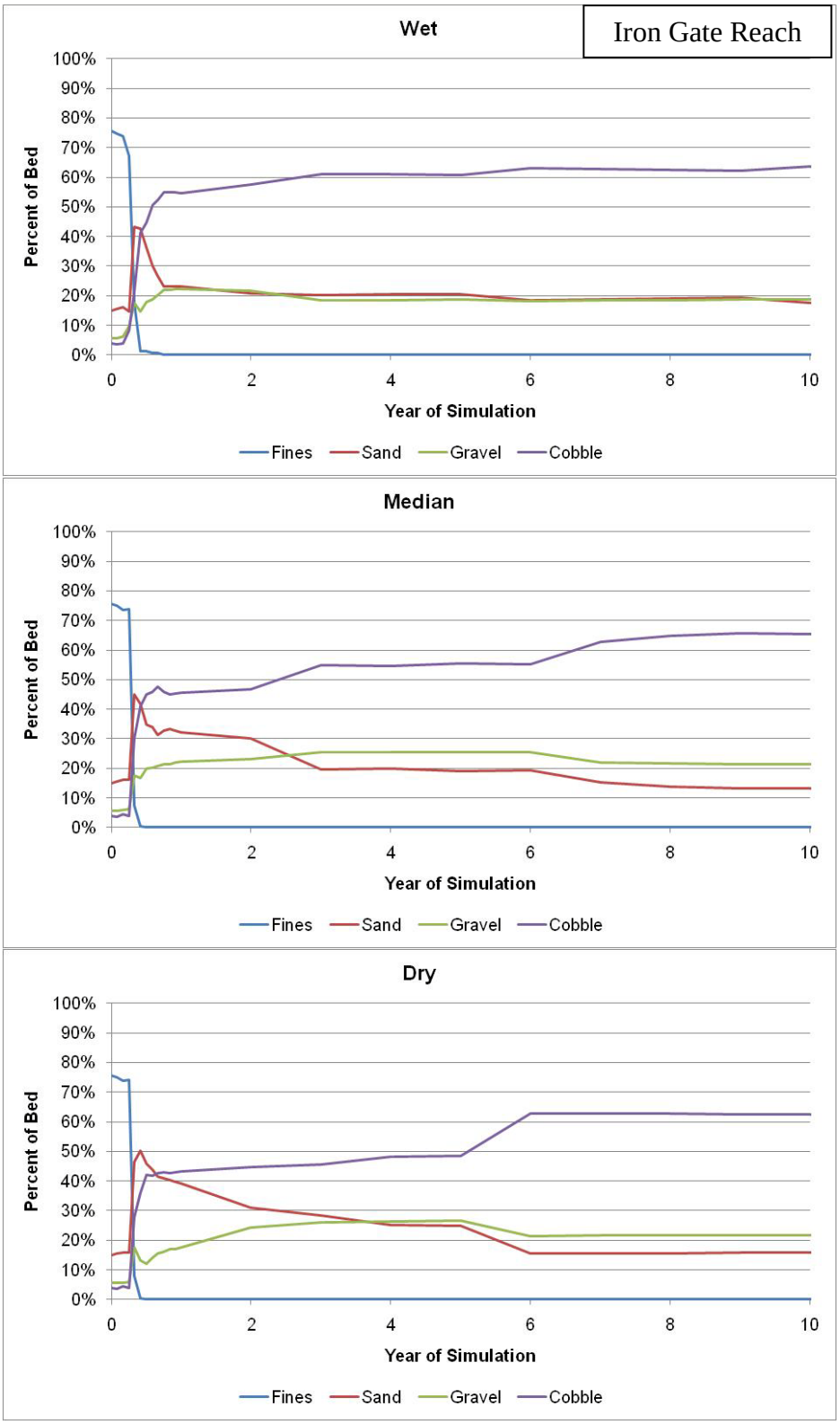


Figure 9-36. Bed material for the 10 years following dam removal for wet, median, and dry years for Iron Gate Reach.

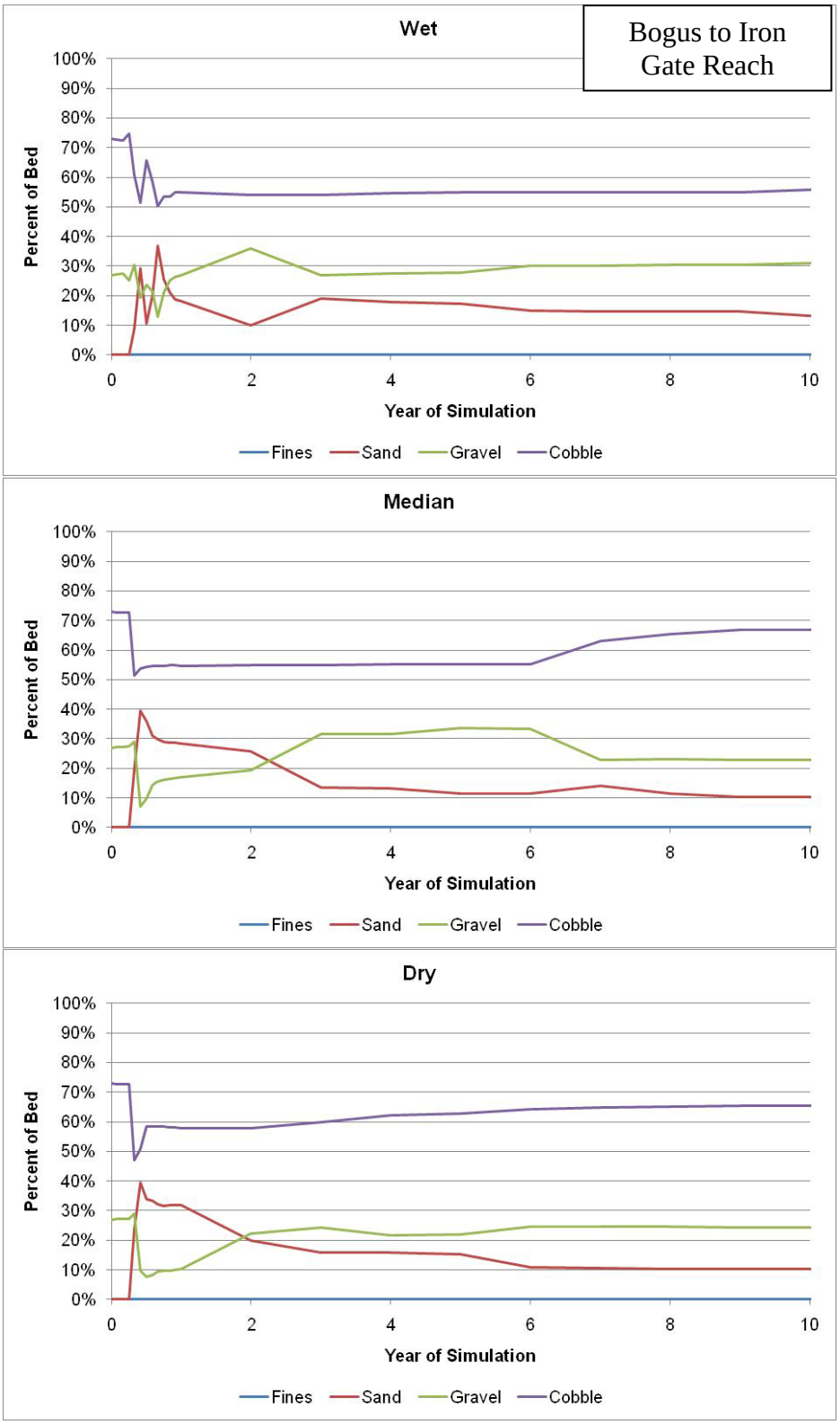


Figure 9-37. Bed material for the 10 years following dam removal for wet, median, and dry years for Bogus Creek to Iron Gate Reach.

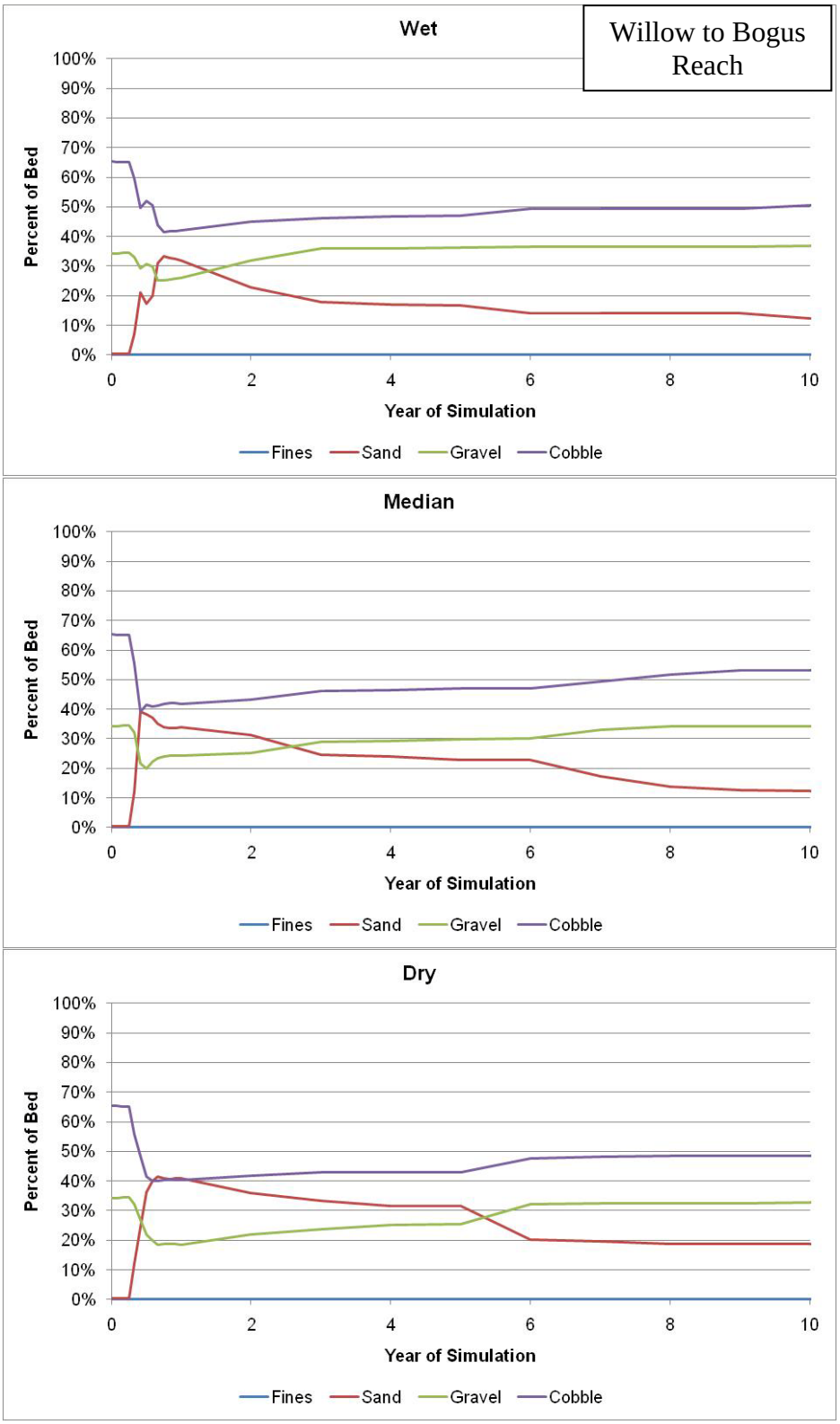


Figure 9-38. Bed material for the 10 years following dam removal for wet, median, and dry years for Willow Creek to Bogus Reach.

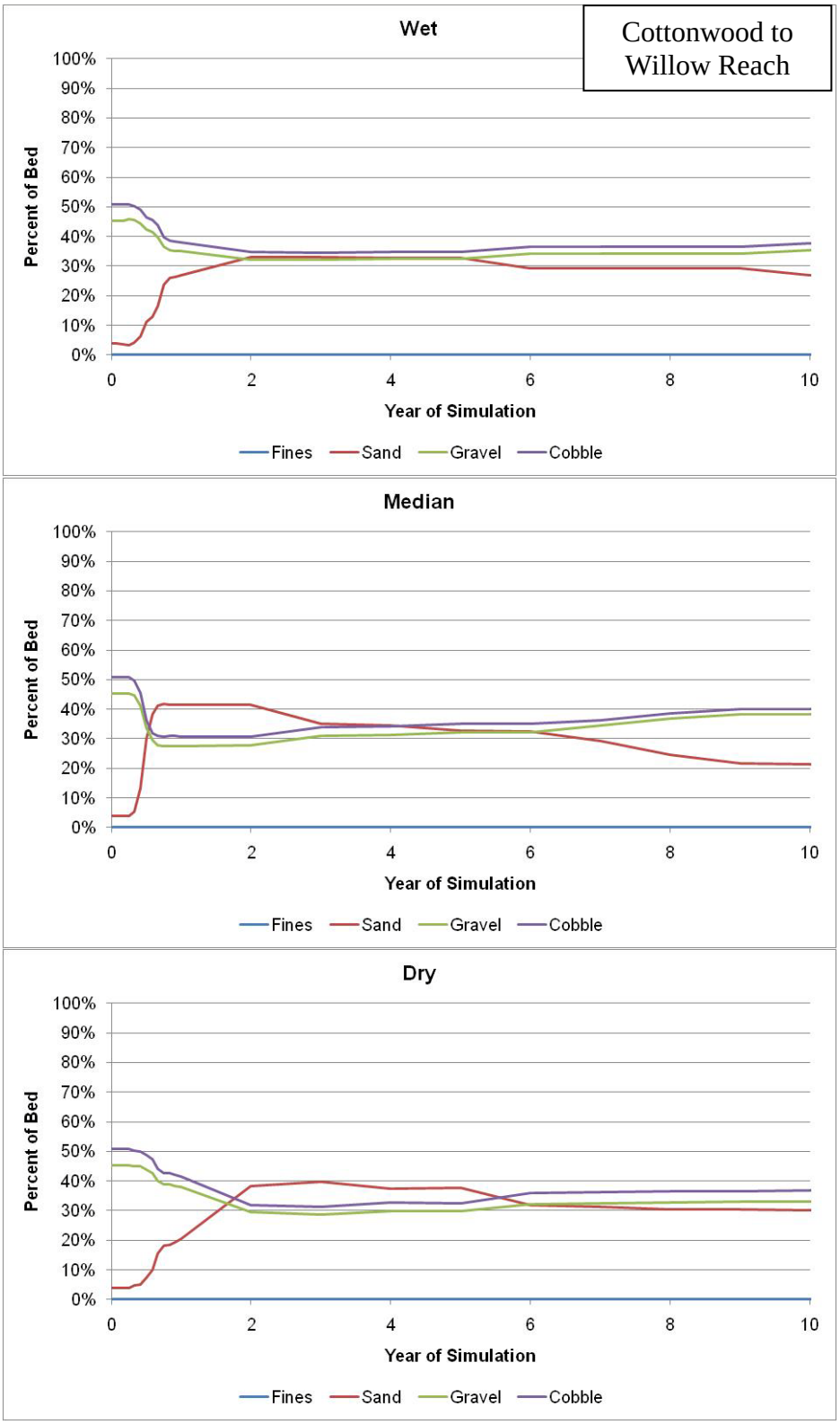


Figure 9-39. Bed material for the 10 years following dam removal for wet, median, and dry years for Cottonwood to Willow Creek Reach.

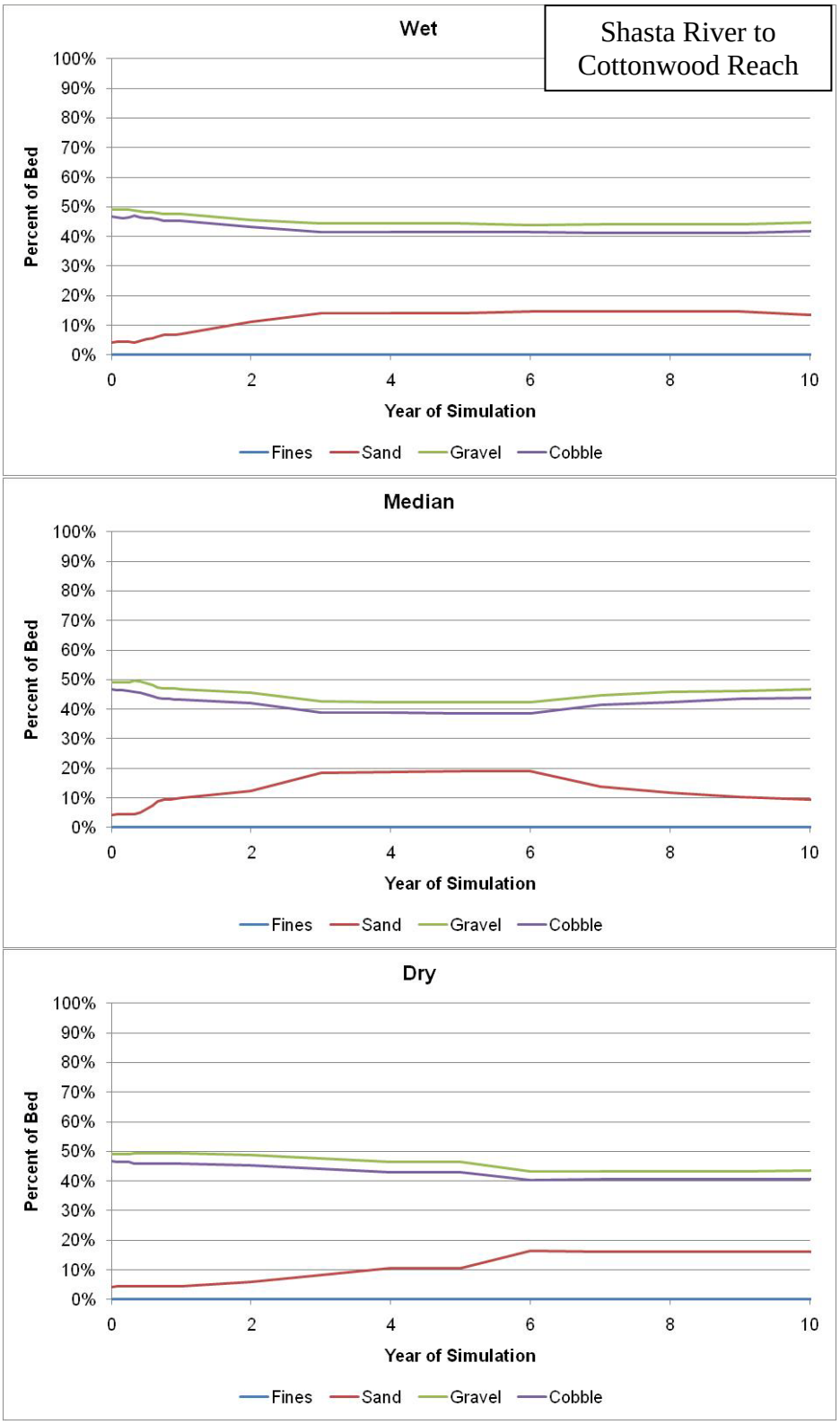


Figure 9-40. Bed material for the 10 years following dam removal for wet, median, and dry years for Shasta River to Cottonwood Creek reach.

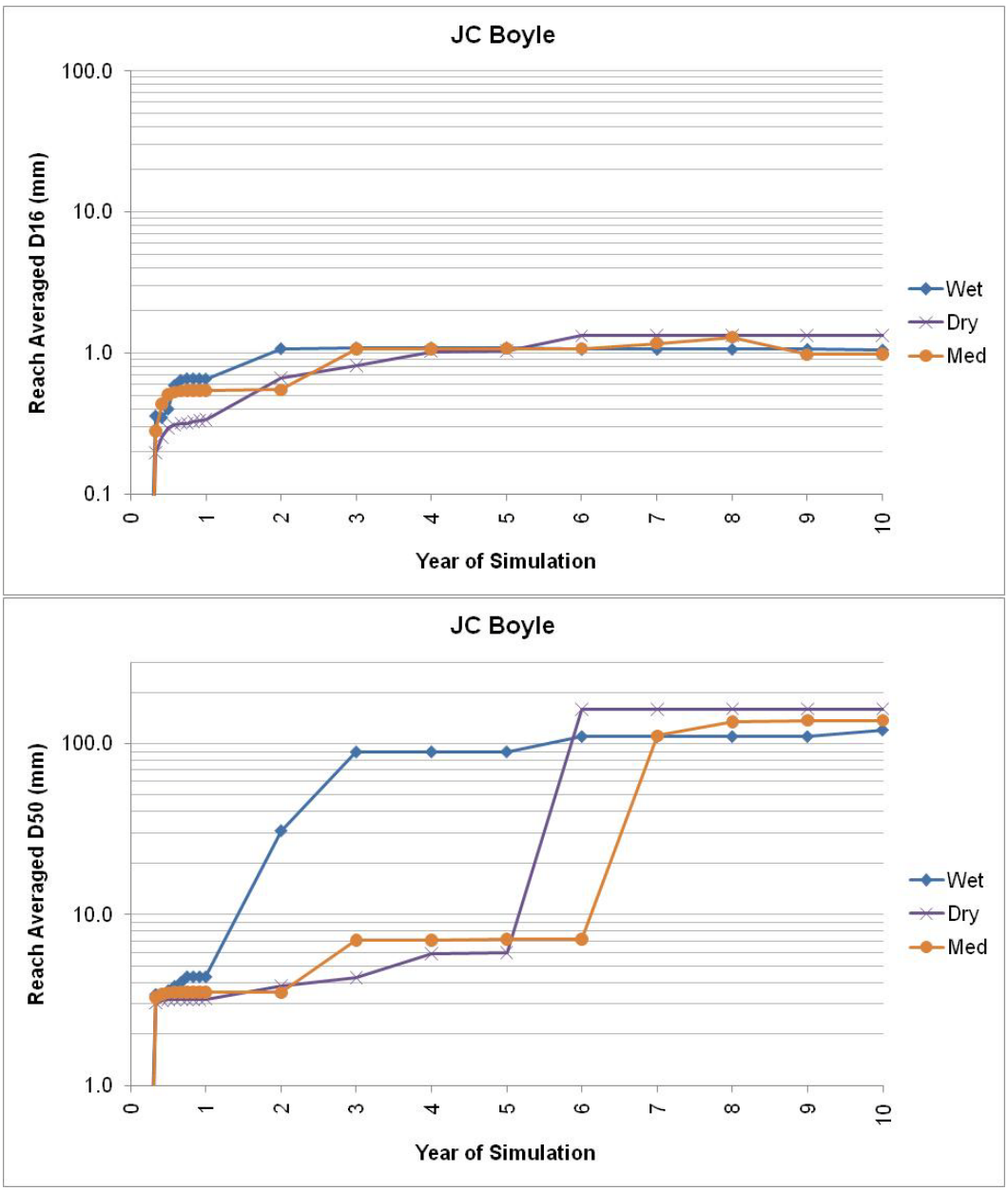


Figure 9-41. Reach averaged D16 and D50 in J.C. Boyle Reservoir reach following dam removal.

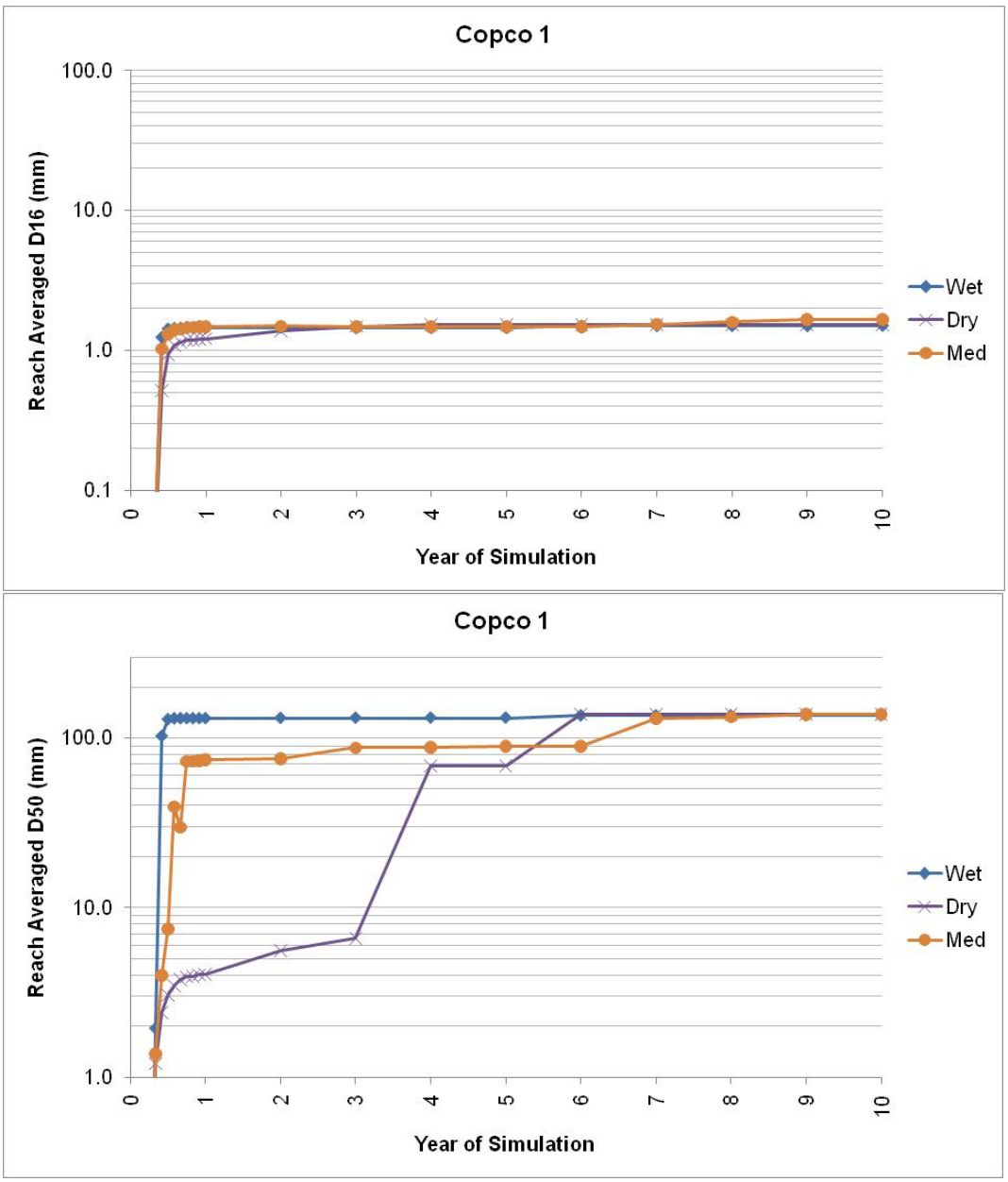


Figure 9-42. Reach averaged D16 and D50 in Copco Reservoir reach following dam removal.

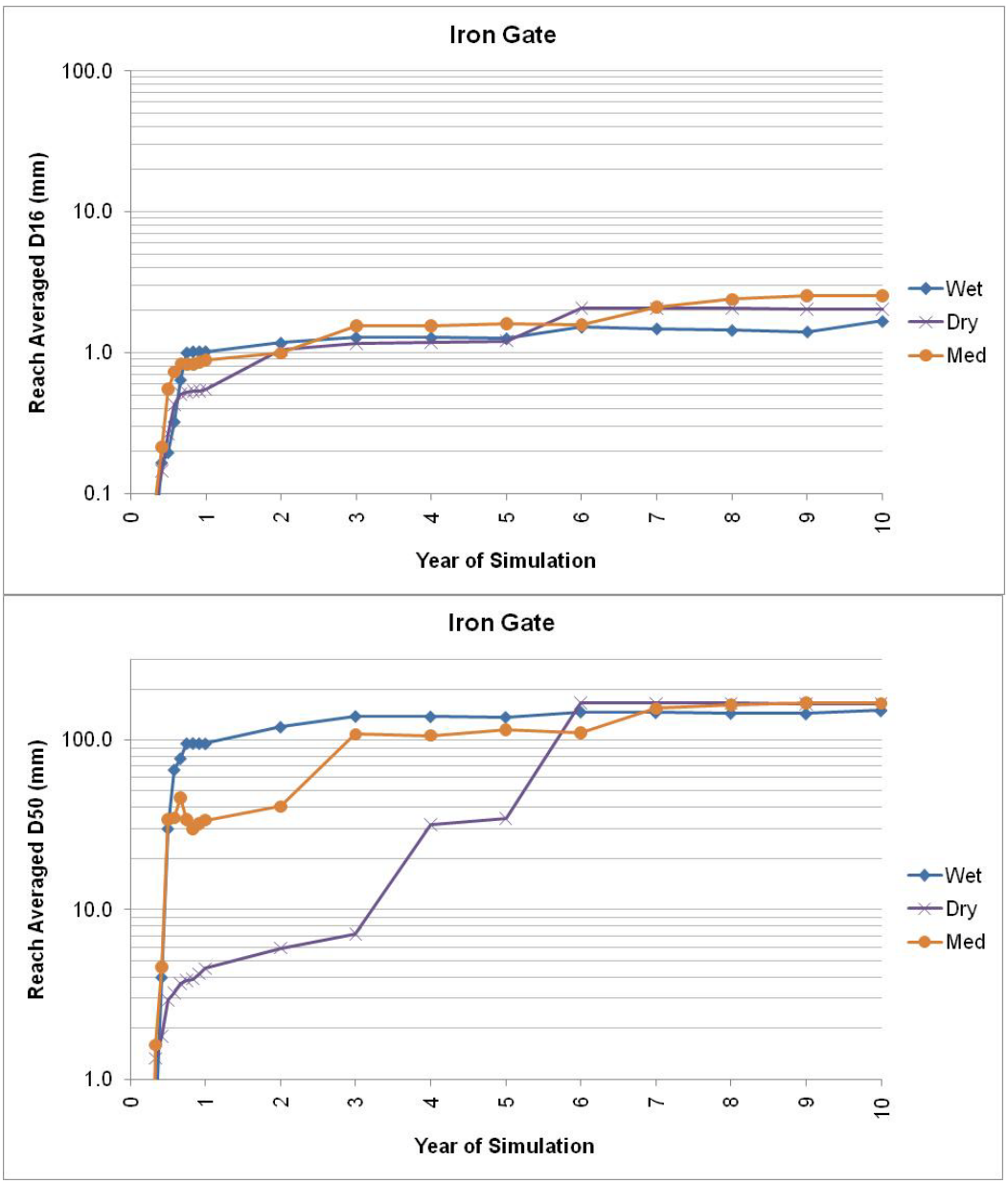


Figure 9-43. Reach averaged D16 and D50 in Iron Gate Reservoir reach following dam removal.

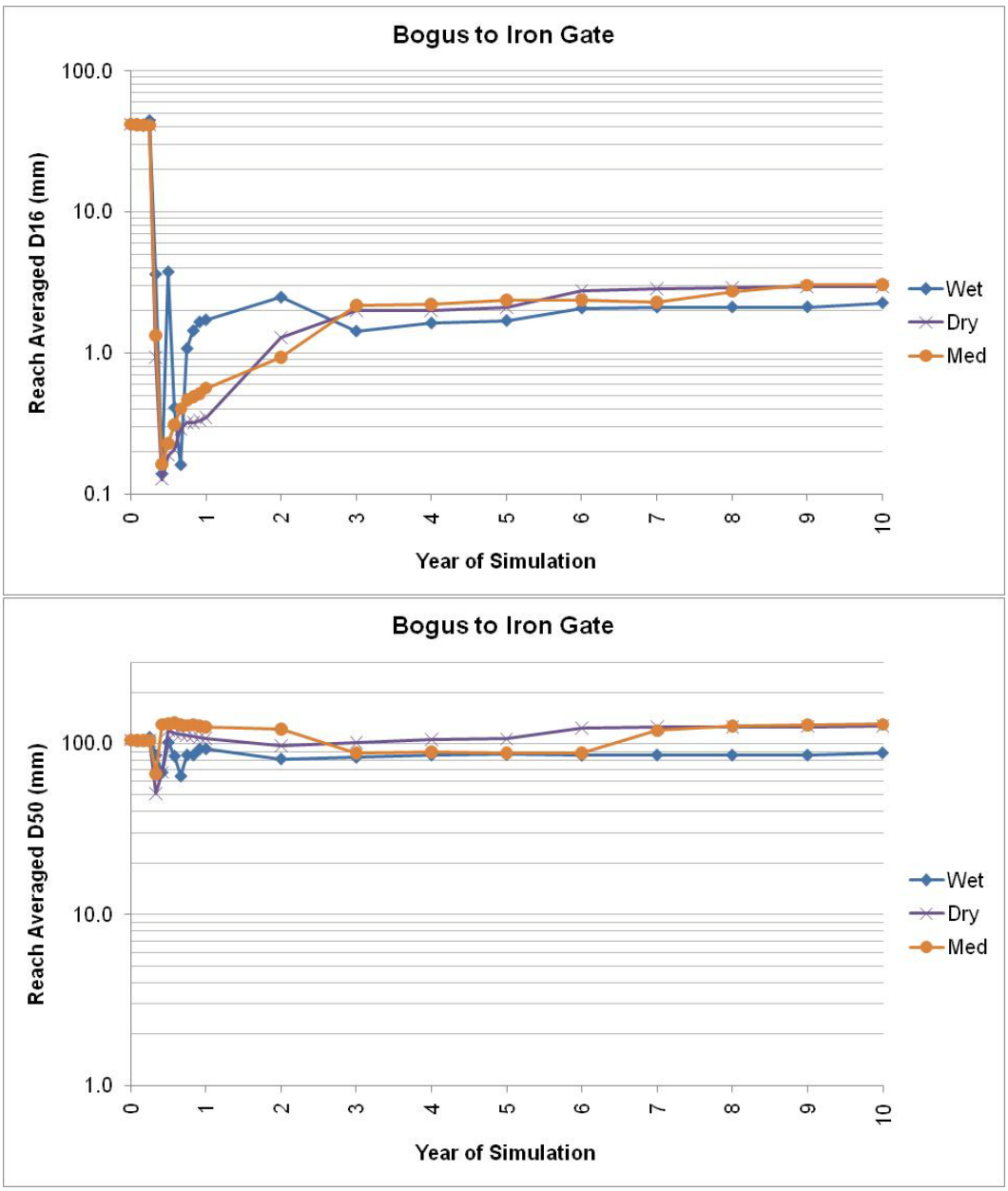


Figure 9-44. Reach averaged D16 and D50 in Bogus Creek to Iron Gate reach following dam removal.

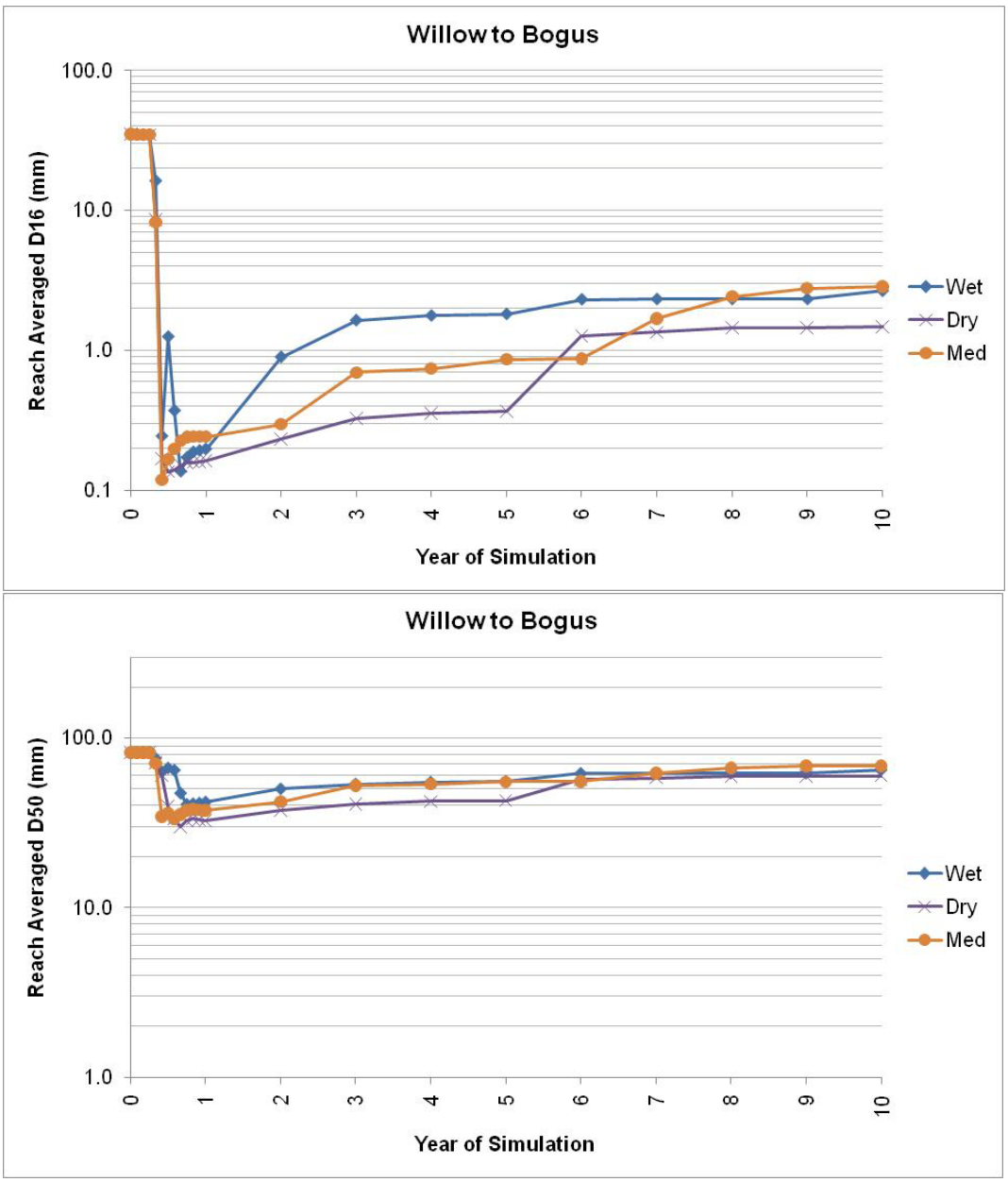


Figure 9-45. Reach averaged D16 and D50 in Willow Creek to Bogus Creek reach following dam removal.

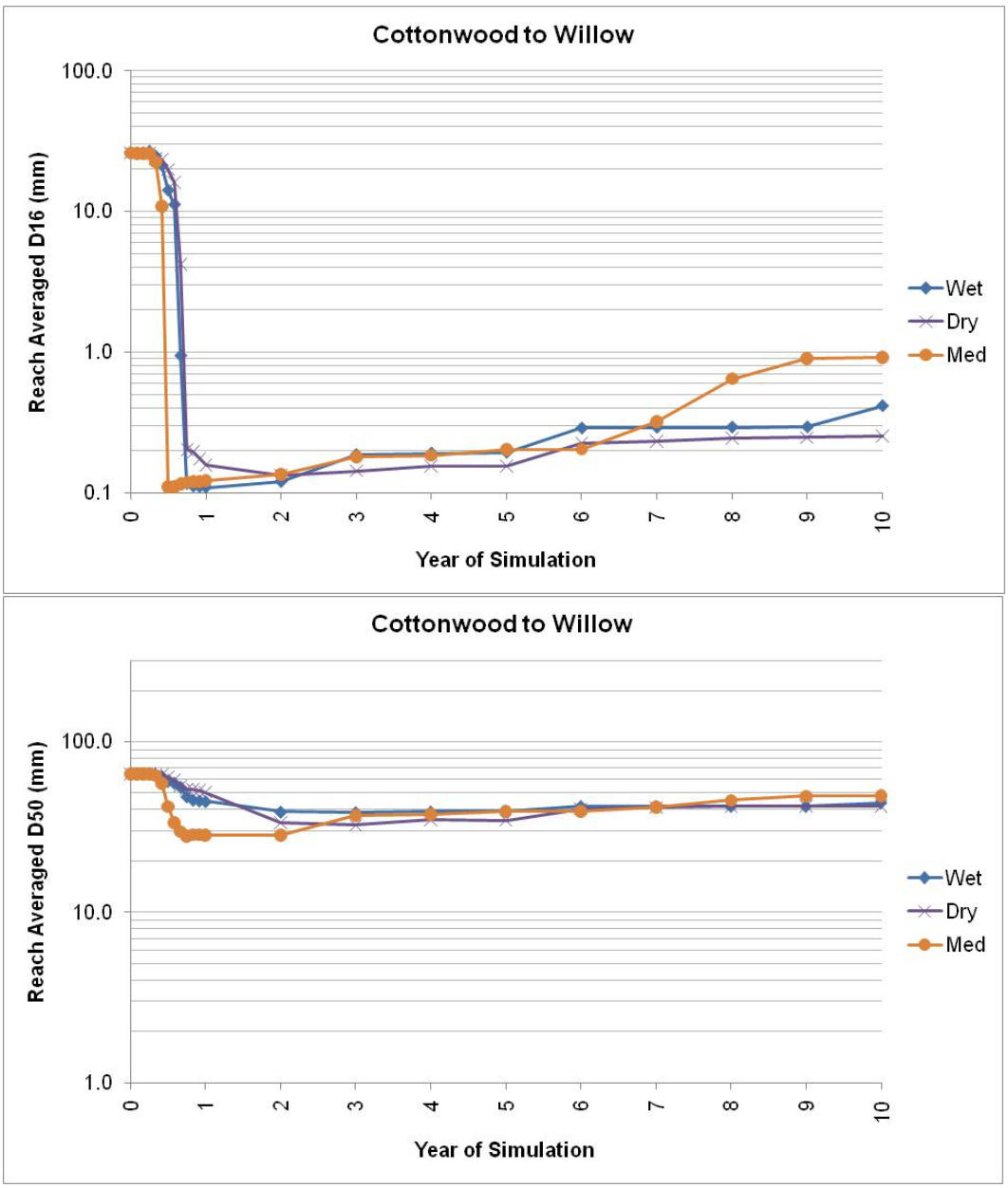


Figure 9-46. Reach averaged D16 and D50 in Cottonwood Creek to Willow Creek reach following dam removal.

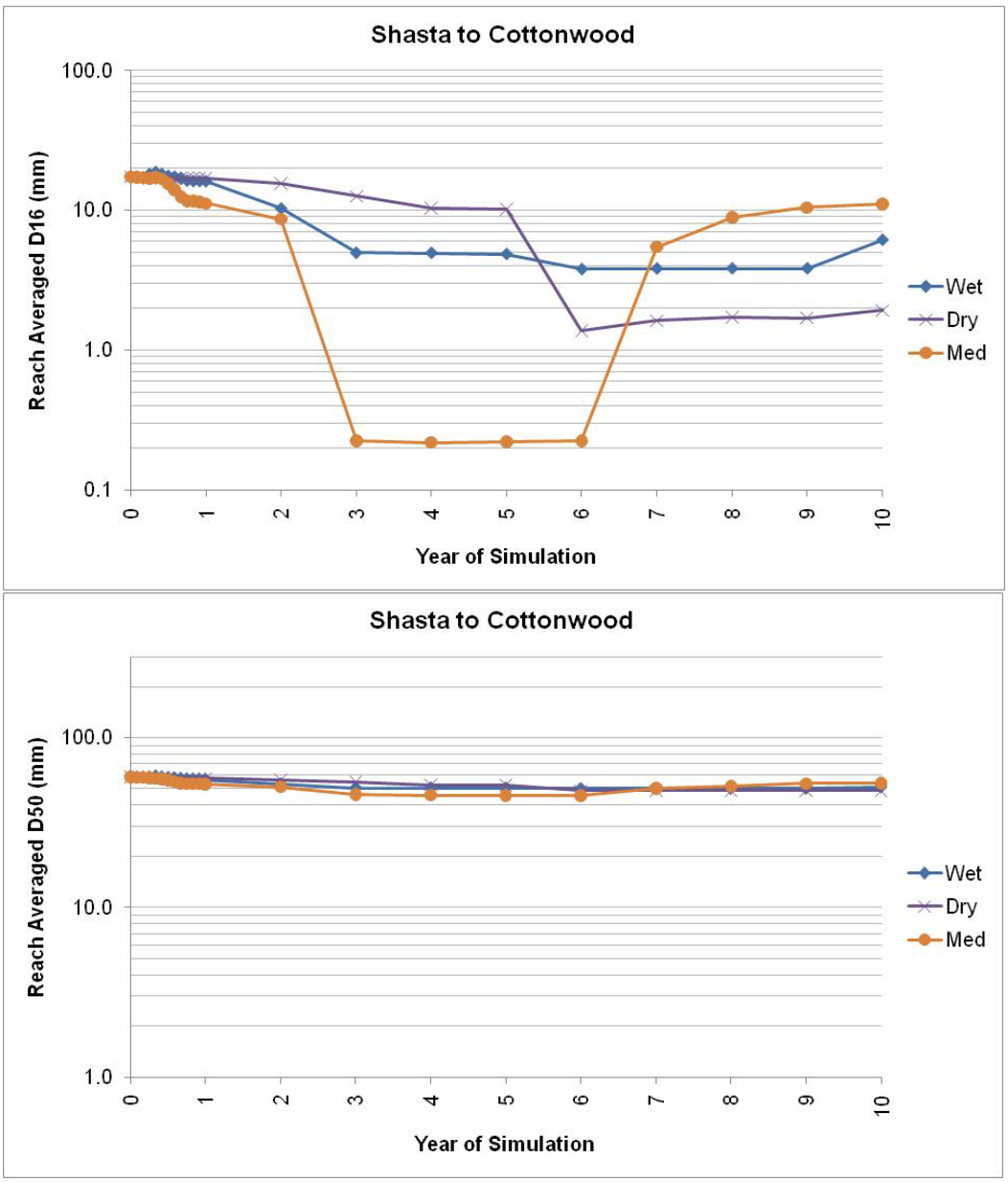


Figure 9-47. Reach averaged D16 and D50 in Shasta River to Cottonwood Creek reach following dam removal.

9.2.2. TWO-DIMENSIONAL ANALYSIS OF COPCO 1 DRAWDOWN

More detailed two-dimensional modeling of the erosion of sediment at Copco 1 was performed using a SRH-2D. This was done to verify the erosional patterns that may occur during reservoir drawdown and to verify the assumptions inherit in the 1D simulations.

SRH-2D v3 is a 2D, depth-averaged, hydraulic and sediment transport mobile-bed model for river systems and was developed at the Bureau of Reclamation. The hydraulic flow modeling module, documented by Lai (2008; 2010), is widely used; the mobile-bed sediment transport module is based on the Reclamation's latest sediment modeling methodology (Greimann et al. 2008), and is only used internally at present. The robustness and accuracy of SRH-2D have been proven with a range of Reclamation projects as well as with studies at many external institutions. Detailed technical information, selected application cases, and the SRH-2D version 2 model may be downloaded from the following Reclamation website: http://www.usbr.gov/pmts/sediment/. Sediment transport modeling details and applications may be found in a number of papers such as Greimann et al. (2008), Lai and Greimann (2007; 2008; 2010) and Lai et al. (2009), in addition to many project reports.

One of the major features of SRH-2D is the adoption of the arbitrarily shaped element method of Lai et al. (2003) for geometry representation. This allows use of the unstructured hybrid mesh for river modeling which has been shown to be flexible and led to increased accuracy and efficiency.

Major capabilities of SRH-2D are listed below:

- 2D depth-averaged solution of the dynamic wave equations for flow hydraulics.
- An implicit solution scheme for solution robustness and efficiency.
- Unstructured or structured meshes with arbitrary mesh cell shapes may be used. In most applications, a combination of quadrilateral and triangular meshes works the best.
- Steady or unsteady flows.
- All flow regimes: subcritical, supercritical, or transcritical flows.
- Unsteady, non-equilibrium, and non-uniform modeling of the sediment transport.
- Multi-size sediment transports, with bed sorting and armoring.
- Effects of gravity and secondary flows.
- Non-cohesive or cohesive sediments.

SRH-2D is a two-dimensional (2D) model, and it is particularly useful for problems where 2D effects are important. Examples include flows with in-stream structures (such as weirs, diversion dams, release gates, coffer dams, etc.), bends and point bars, perched rivers, and multi-channel systems. 2D models may also be

needed if hydraulic characteristics are important, such as: flow recirculation and eddy patterns, lateral variations, flow overtopping over banks and levees, differential flow shears on river banks, and interaction between the main channel, vegetated areas, and floodplains. Some of the scenarios listed above may be modeled in 1D, but additional empirical models are used and extra calibration must be carried out with unknown accuracy.

9.2.2.1. 2D Modeling Details

A 2D analysis begins by defining a solution domain and then generating a mesh that covers the domain. The solution domain is determined based on the objectives of the project and most often it is constrained by available data. In this study, the solution domain includes the entire reservoir, as shown in Figure 9-48.

Figure 9-48. Solution domain used by the SRH-2D modeling.

A mesh is generated using the Surface Water Modeling System software (SMS). The following website link provides more information for the software: http://www.aquaveo.com. Additionally, the SRH-2D manual (Lai, 2008) and the theoretical discussion in Lai (2010) may be consulted for an in-depth discussion. The mesh consists of mixed quadrilaterals and triangles. A total of 10,504 mesh cells are used; an overall view of the mesh is displayed in Figure 9-49, while two close-up views of part of the mesh are in Figure 9-50.

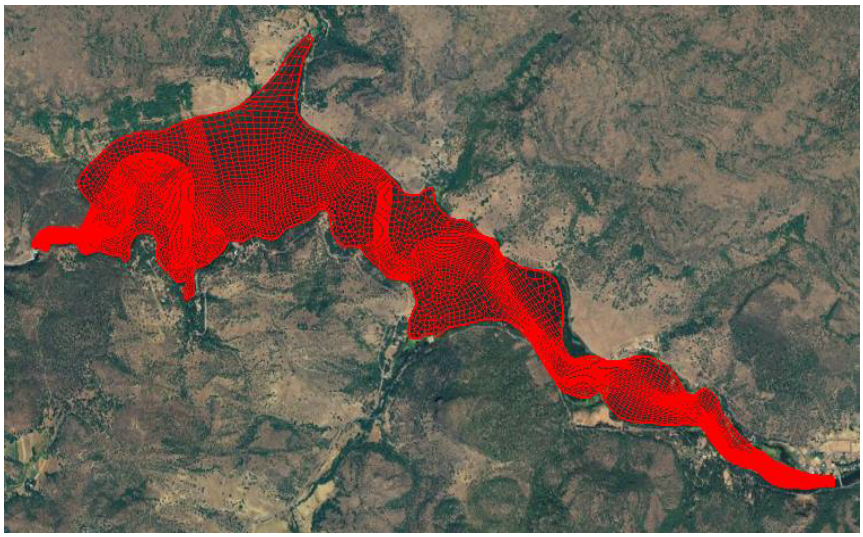
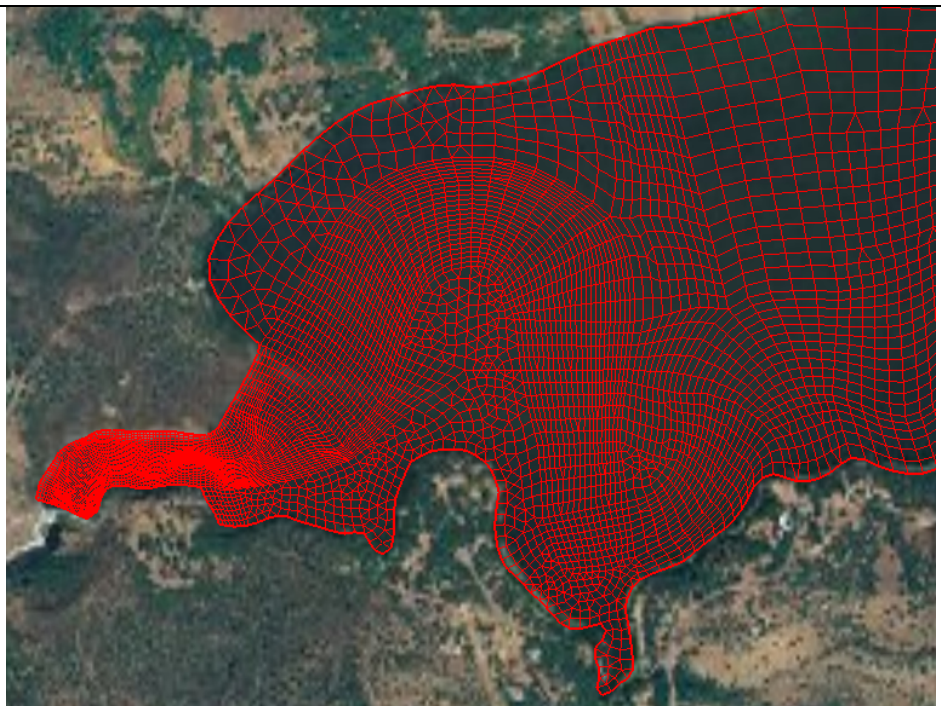
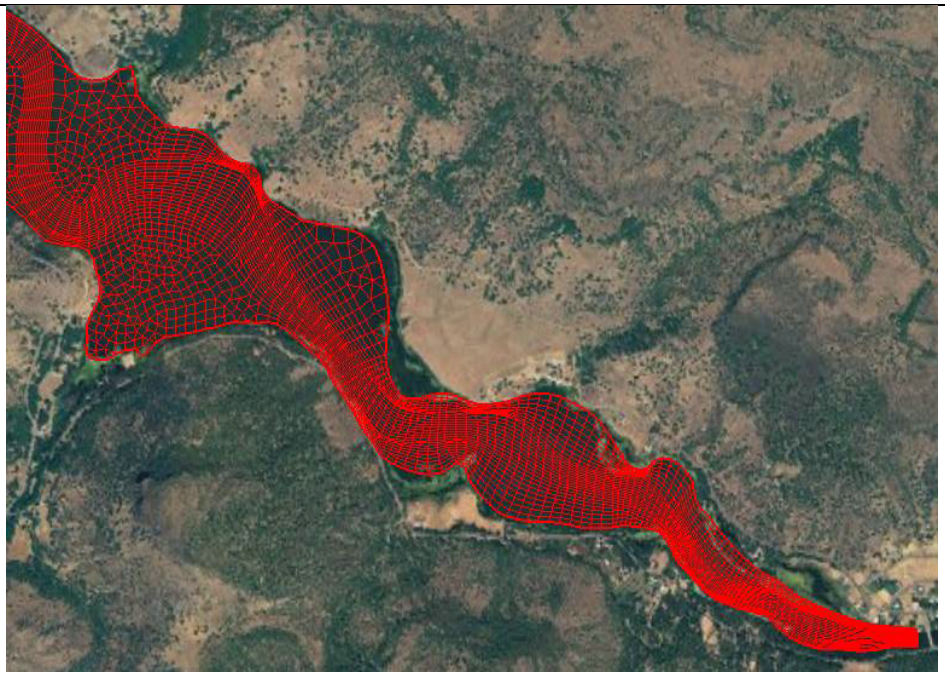


Figure 9-49. An overall view of the entire mesh.



(a) View of the mesh near the dam



(b) View of the mesh near the upstream boundary

Figure 9-50. A zoomed-in view of the mesh.

Topographic and bathymetric data are based on the survey data in the form of a digital elevation model (DEM). The DEM data were imported into SMS and interpolated to the mesh to represent the bed elevation. This bed elevation was used as the initial reservoir bed before drawdown. The contours of the initial bed elevation represented by the mesh are shown in Figure 9-51.

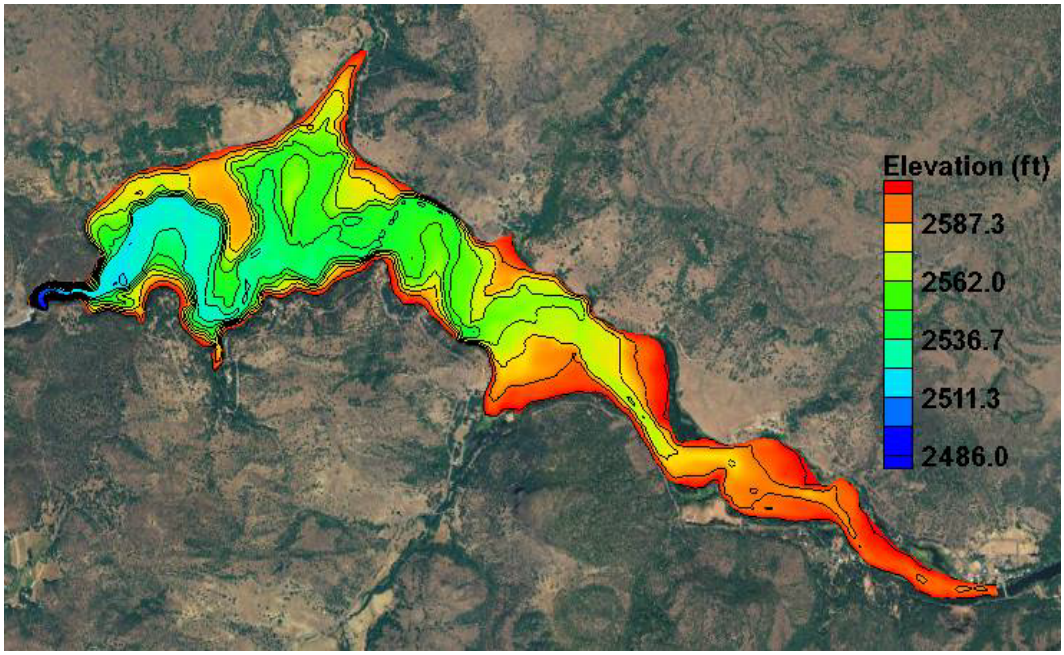


Figure 9-51. Bed contours represented by the mesh based on the survey data DEM and it is used as the initial bed elevation for the modeling.

Flow resistance is calculated with the Manning's roughness equation in which the Manning's coefficient (*n*) is used as one of the model inputs. In this study, a uniform Manning's coefficient of 0.03 is used.

The bed gradation distribution over the solution domain is also needed for the sediment transport analysis. In this study, all relevant data are based on available survey data discussed above. The solution domain is divided into an upstream and a downstream zone (Figure 9-52). Two bed layers are assumed in each zone. The top bed layer has uniform bed gradation (composition) specified in each zone, while the gradation of the bottom layer is the same over the entire solution domain. The cumulative distributions of the bed gradation for the top layer of the two zones, as well as the bottom layer, are plotted in Figure 9-53. The thickness of the top bed layer is based on the available survey data and it is shown in Figure 9-54.

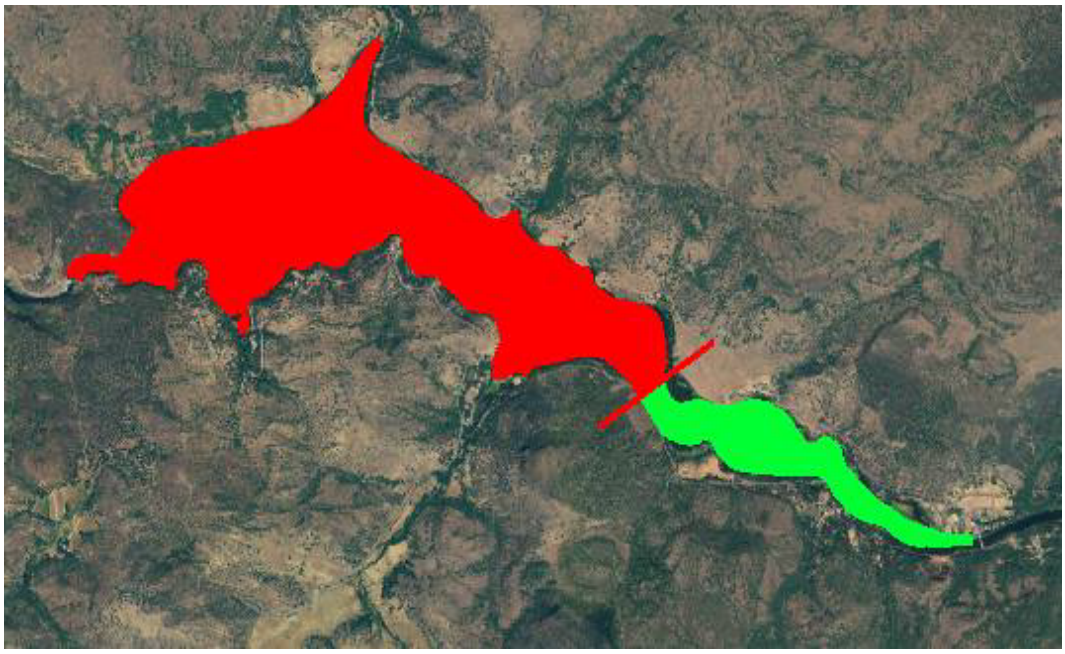


Figure 9-52. Two bed gradation zones, upstream and downstream zones, used to specify the bed sediment properties.

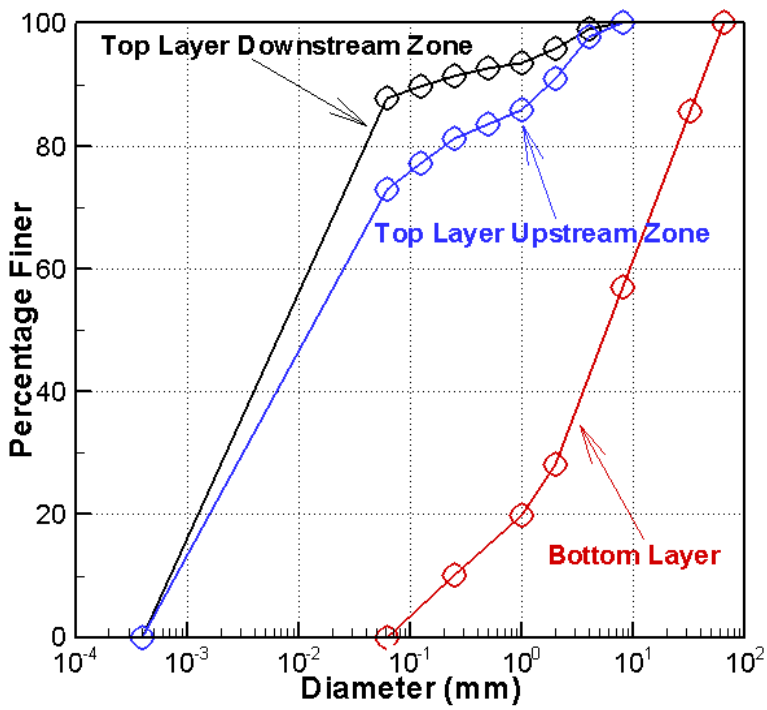


Figure 9-53. Cumulative distribution of the bed sediments for both the top and bottom layers of the Copco 1 Reservoir.

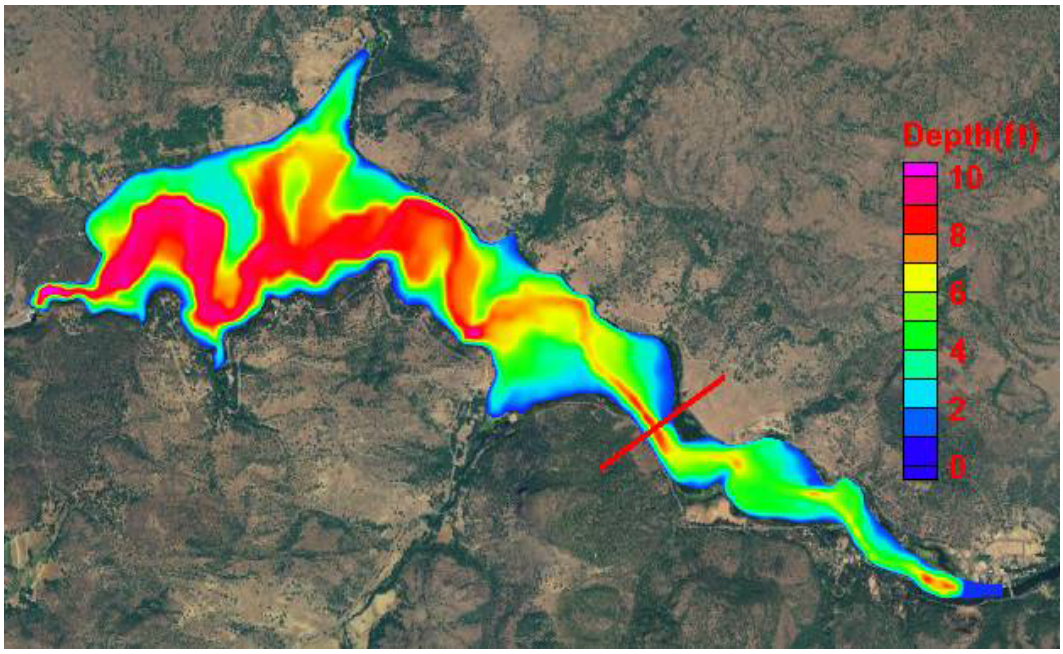


Figure 9-54. Distribution of thickness (ft) of the top bed layer.

9.2.2.2. 2D Modeling Scenarios and Boundary Conditions

Three hydrological scenarios are used for the drawdown simulation, and they represent the flow hydrograph for the Dry Year (2004), Average Year (1968), and Wet Year (1999). Simulation of each scenario starts at November 15 for a duration of six months. The flow discharges into the Copco 1 Reservoir for the three scenarios are shown in Figure 9-55. For the current modeling, the sediment input into the reservoir is assumed to be zero. This assumption is justified as majority of the sediment supply is in the form of the wash load that simply passes through the reservoir. Therefore, the total sediment released downstream may be estimated by simply adding the known sediment supply rate at Copco 1 Dam and the predicted sediment release by the present model together.

Initially, the reservoir is assumed to be filled with water at an elevation of 2,603 feet. Drawdown starts on November 15 through release of water at the exit gate. The release is at a maximum drawdown rate of 3.0 ft/day, subject to the constraint of the gate capacity as shown in Figure 9-56 for the discharge capacity curve. The drawdown discharge required to achieve the 3.0 ft/day rate is determined using the reservoir storage capacity curve as shown in Figure 9-57.

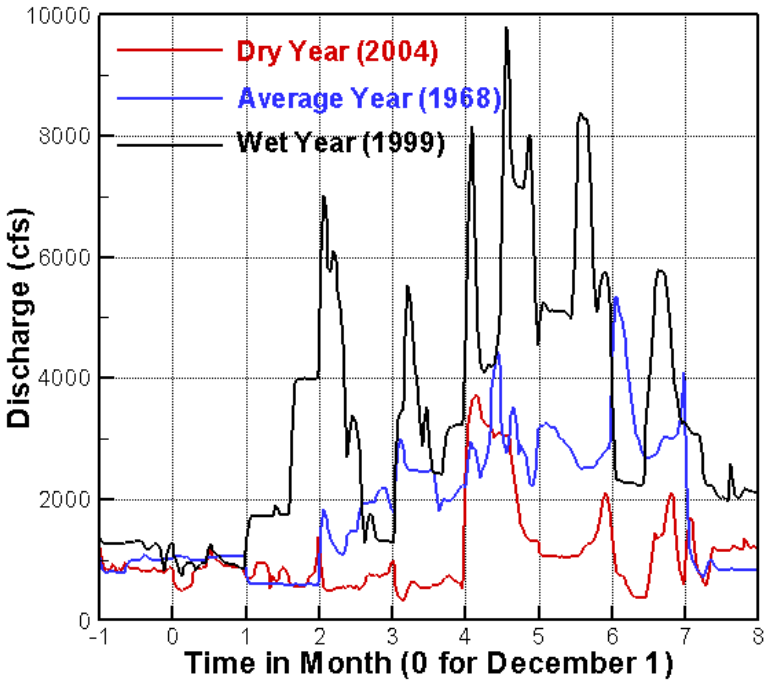


Figure 9-55. Flow discharges of three hydrological scenarios: Dry (2004), Average (1869) and Wet (1999) years for the Copco 1 Reservoir (-1 for November, 0 for December, etc.).

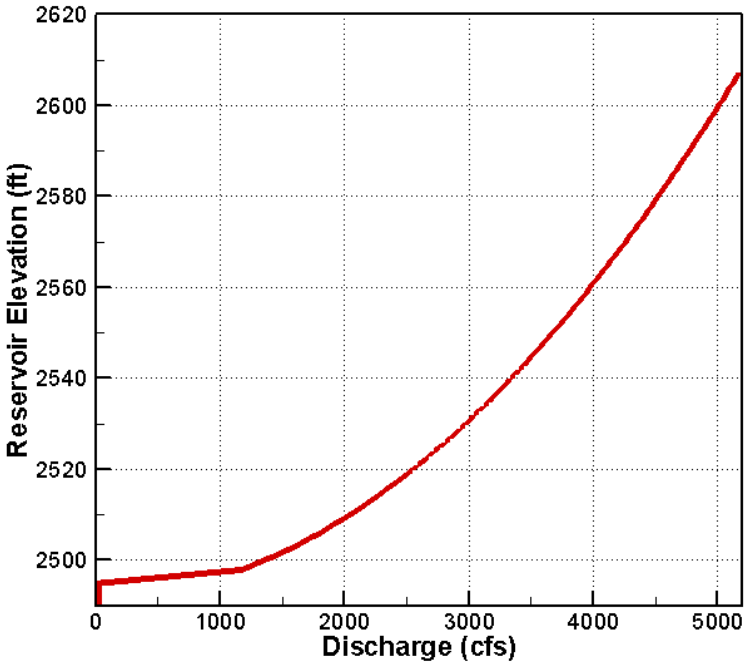


Figure 9-56. The discharge capacity curve of the gate at the exit for drawdown.

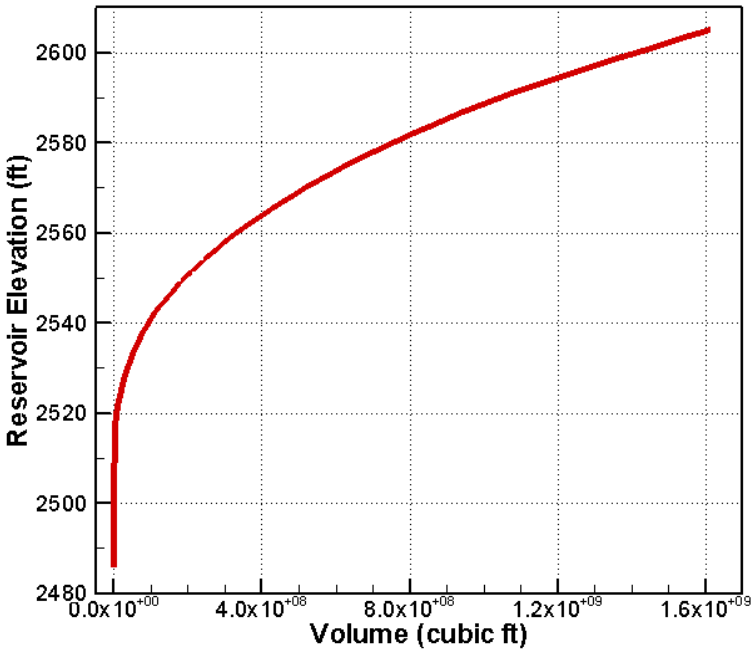


Figure 9-57. The storage capacity curve of the Copco 1 Reservoir.

A total of seven sediment size classes are used to represent the sediment and the partition is tabulated in Table 9-2. Note that size class 1 is reserved to model the cohesive material in the reservoir, while the remaining sediments are non-cohesive.

Table 9-2. Size ranges of each sediment size class

Sediment Size Class	Size Range (mm)
1	Cohesive
2	.0625 to .125
3	.125 to .5
4	.5 to 2
5	2 to 8
6	8 to 32
7	32 to 128

Each sediment size class (k) obeys the following mass conservation equation:

$$\frac{\partial hC}{\partial t} + \frac{\partial \cos(\alpha) V_t hC}{\partial x} + \frac{\partial \sin(\alpha) V_t hC}{\partial y} = S_E \qquad (1)$$

where C is the depth-averaged sediment concentration, h is water depth, t is time, x and y are two horizontal Cartesian coordinates, respectively, V_t is the depth-averaged total flow velocity, α is the angle of sediment transport direction relative to the x-axis, and S_E is the sediment exchange term between the total sediment load and the active layer. Specific models for a number of variables in the above equation will not be discussed, and they have been discussed by Greimann et al. (2008). Only the sediment exchange term needs some discussion. For a non-cohesive sediment size class, the exchange term is written as:

$$S_E = \frac{1}{L_{tot}}(q_{tot}^* - V_t hC) \qquad (2)$$

where L_{tot} is the adaptation length of the total load and q_{tot}^* is the equilibrium transport capacity for the total load transport rate. The Engelund-Hansen capacity equation was used for the current study. For the cohesive sediment class, sediment exchange between is affected through the following:

$$S_E = V_e\, p_k - V_d\, C \qquad (3)$$

where V_e and V_d are the rate of erosion and deposition, respectively, and p_k is the percentage of size class k on the bed.

In this study, the measured data are used for the parameters in the above equations. According to the measured data of the USDA Agricultural Research Service (Simon et al, 2010), the erosion rate may be computed by $V_e = k(\tau_b - \tau_{cri})$, with the measured k and τ_{cri} in the following range: $k(cm^3/N-s) = 0.5, 2.0, 20.0$, respectively, for the minimum, medium, and maximum values; and $\tau_{cri}(Pa) = 0.2, 0.25, 2.0$, respectively, for the minimum, medium, and maximum values. Three sets of parameters are used for each hydrological scenario modeled, and they are designated as the easy-erode, medium-erode, and hard-erode cases. The parameter values are defined as follows: easy-erode case values are $\tau_{cri} = 0.2\,Pa$ and $k = 20.0\,cm^3/N-s$; medium-erode case values are $\tau_{cri} = 0.25\,Pa$ and $k = 2.0\,cm^3/N-s$; and hard-erode case values are $\tau_{cri} = 2.0\,Pa$ and $k = 0.5\,cm^3/N-s$.

The deposition rate is based on the fall velocity of the cohesive sediment, and almost zero fall velocity is used in this study.

9.2.2.3. 2D Simulation Results and Discussion

A total of nine simulations are carried out, representing three hydrological scenarios and three reservoir bed material erodibility conditions for each

hydrological scenario (i.e., the easy-erode, medium-erode, and hard-erode case). Each simulation starts on November 15 and runs for a duration of six months, ending on May 15 of the next year.

The simulated reservoir water surface elevation variations and flows into and out of the reservoir are displayed in Figure 9-58 through Figure 9-60 for the three hydrological scenarios. The differences between the three bed erodibility cases are so small that only the results from the medium-erode case are plotted. The following conclusions can be drawn:

- With the 3 ft/day maximum drawdown rate and the capacity of the gate at Copco 1 Dam (Figure 9-56), reservoir water elevation can be lowered to below 2,000 feet under all scenarios within one month. However, only under the relatively Dry Year (2004) scenario can the reservoir water level be maintained at the drawdown condition. The reservoir will be filled with water quickly given a Wet Year (1999) scenario.

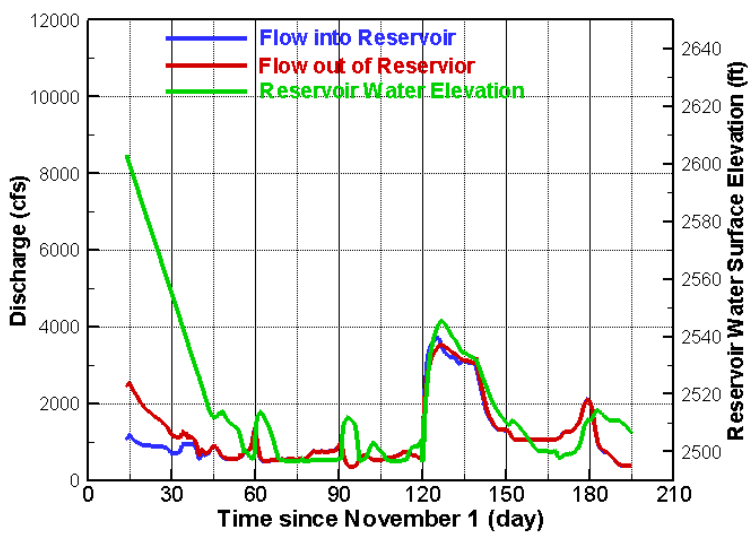


Figure 9-58. Predicted reservoir water elevation and discharge out of the reservoir for the dry year (2004) hydrology scenario and medium-erode case.

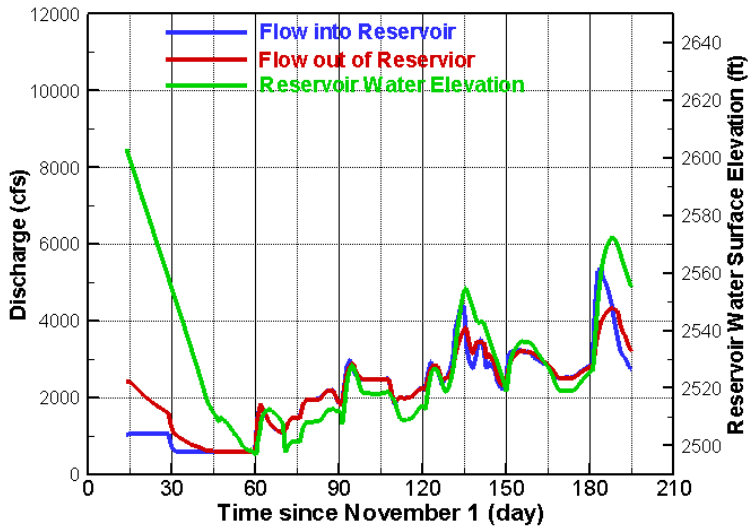


Figure 9-59. Predicted reservoir water elevation and discharge out of the reservoir for the average year (1968) hydrology scenario and medium-erode case.

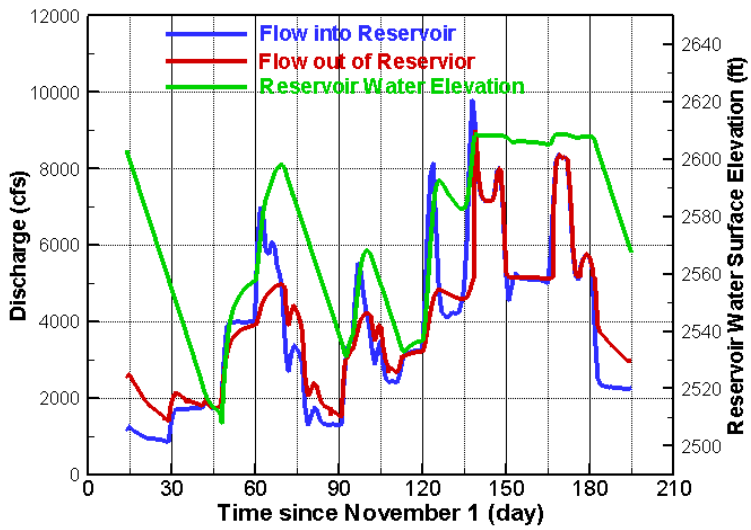


Figure 9-60.Predicted reservoir water elevation and discharge out of the reservoir for the wet year (1999) hydrology scenario and medium-erode case.

Next, the predicted sediment concentration delivered to the downstream out of the reservoir exit gate is plotted in Figure 9-61 for the three hydrological scenarios simulated. The sediment concentrations do not differ much between the dry and average year scenarios. The sediment pulse created by the drawdown has an average of about 6,000 ppm in concentration and duration of about 1.5 months for flows up to the average-year flow hydrograph. The maximum could reach more

than 7,000 ppm. For the Wet Year (1999) flow, the average of the sediment pulse is about 4,000 ppm, with the maximum of about 6,000 ppm. After January 1, the sediment concentration falls to a relatively low level of about several hundreds of ppm.

The model results are not sensitive to the range of erodibility parameters used for the reservoir bed cohesive sediment, as demonstrated in the results in Figure 9-62.

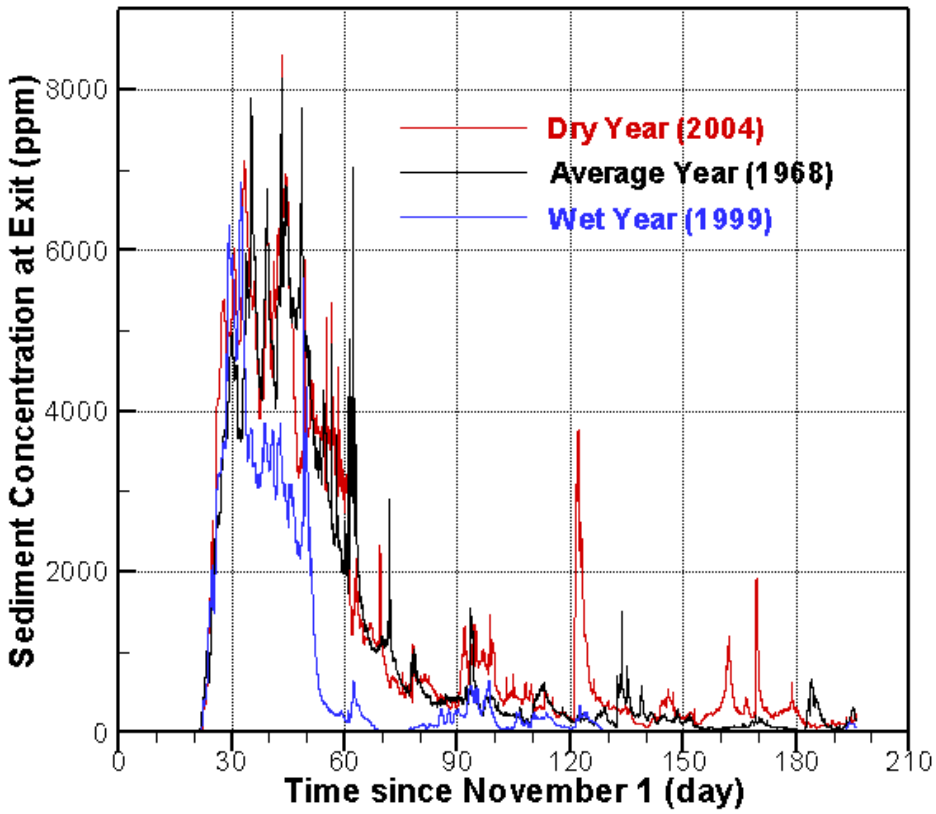


Figure 9-61. Predicted sediment concentration through the drawdown gate during the drawdown of Copco1 Reservoir under three hydrological scenarios.

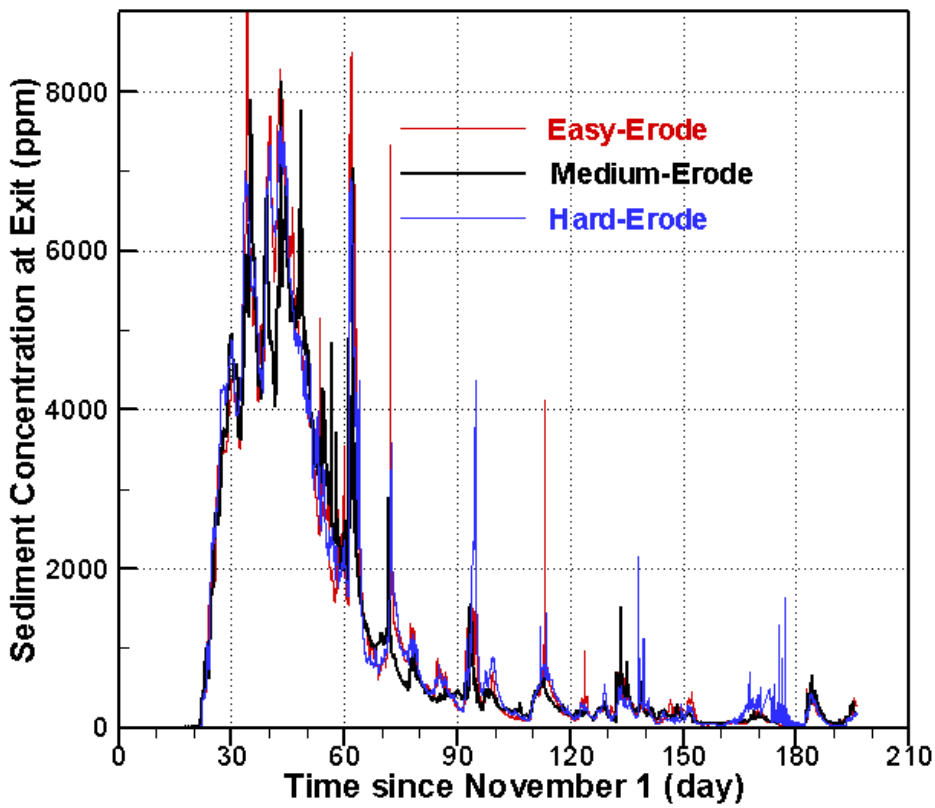


Figure 9-62. Predicted sediment concentration through the drawdown gate during the drawdown of Copco1 Reservoir under the average (1968) hydrological scenario with three bed erodibility cases.

A channel would cut through the reservoir deposit during drawdown as the example shown in Figure 9-63 for the Paonia Reservoir in Colorado. The model correctly predicts the general channel formation process during drawdown of the Copco 1 Reservoir. Two dates are selected to show the erosion, as well as the deposition, of the reservoir. The first date selected is December 29 when the reservoir pool level is approximately near its lowest level, and the second date selected is May 14 at the end of the model simulation (six months after the start of drawdown). The overall erosion pattern is displayed in Figure 9-64., Figure 9-65, and Figure 9-66 for the Dry (2004), Average (1968), and Wet (1999) flows. Furthermore, the solution domain of the Copco 1 Reservoir is divided into five zones, as marked in Figure 9-64. through Figure 9-66, for a more detailed zoom-in view of the model results. A zone-by-zone comparison of the predicted erosion and deposition patterns on December 29 and May 14 for the three hydrologic cases is shown in Figure 9-67 through Figure 9-76. The predicted eroded depth and bed elevation along the thalweg of the incised channel are compared with the initial top bed layer thickness and bed elevation in Figure 9-77 and Figure 9-78. The following conclusions can be drawn based on the model results:

- An incised channel would be formed as a result of the drawdown of the Copco 1 Reservoir. The channel alignment follows approximately the old channel.

- A major portion of the top bed layer deposit within the old channel alignment, which is the input to the model, is eroded during the drawdown period in the first one and half months. It is the case particularly for the upstream half of the solution domain (Figure 9-77). These top bed layer deposits provide most of the suspended sediment delivered to the downstream.

- It is predicted that incision does cut into the bottom bed layer for the upper half of the modeled reach (zone 4 to 6) six months later (Figure 9-77).

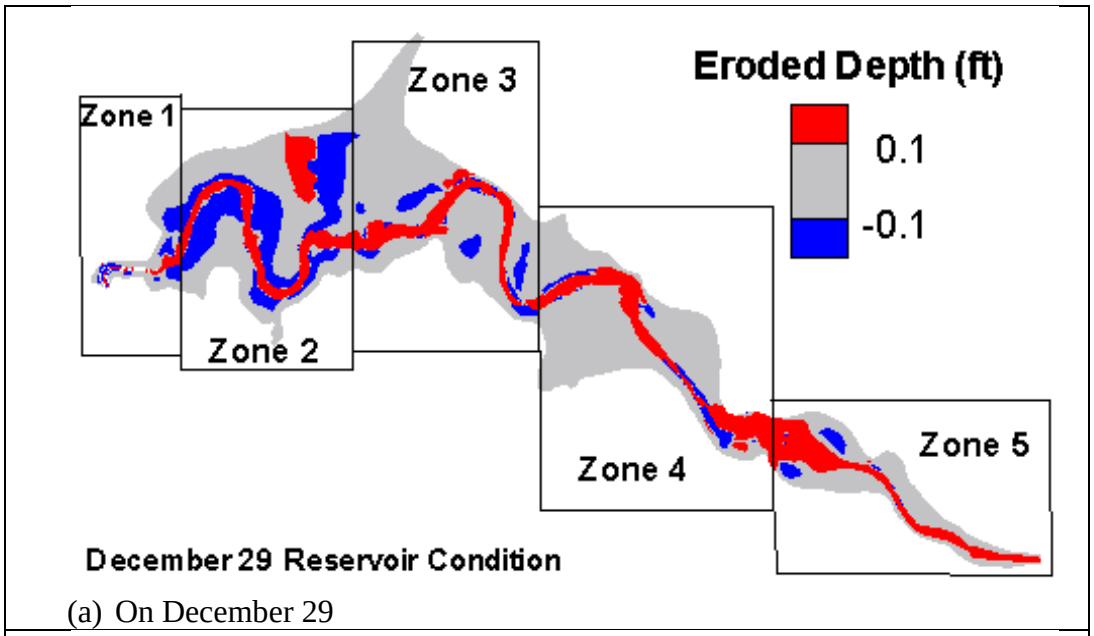
- Some deposition is predicted on the old floodplain area in the lower half of the modeled domain (zone 1 to 3), particularly in the wider area near the dam.

- For the area just upstream of the dam (e.g., zone 1 and 2), channel incision decreases with increasing flow into the reservoir; but the trend is reversed in zone 4 and 5 where incision increases with increasing flow.

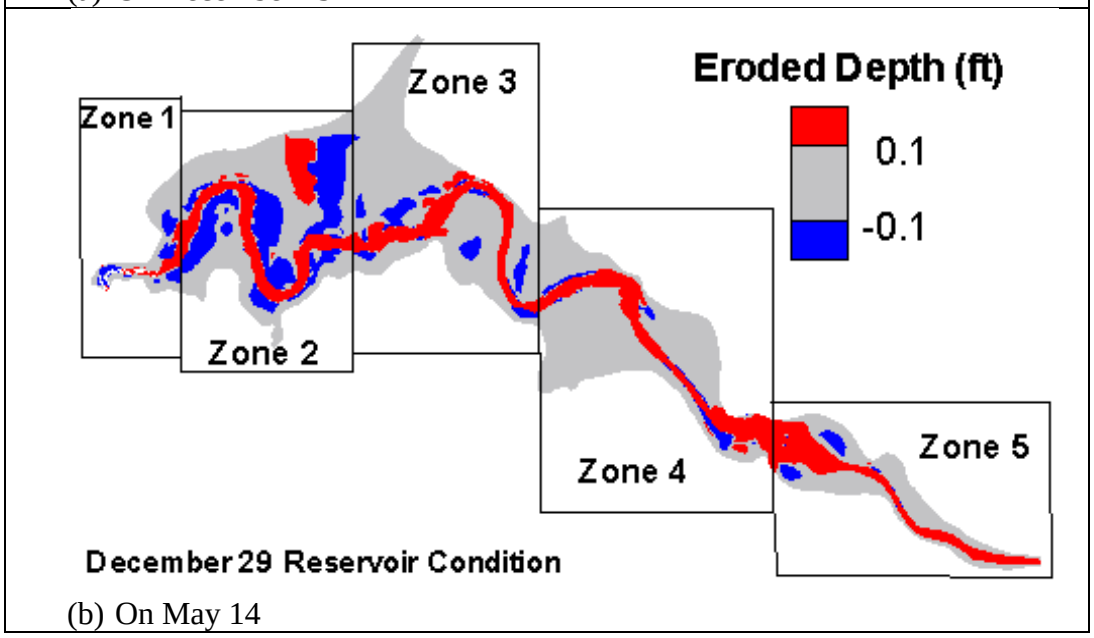
- The deposition near the drawdown gate in zone 1 may be unrealistic given that: (1) only a depth-averaged model is used, but flow is three-dimensional; and (2) flow at the gate is a type of “pressurized flow” while the model assumed an “open channel flow.” In fact, the bed near the gate is more probably erosional, not depositional. However, the inaccuracy of the erosion prediction in this area will not have much impact to the results upstream.

It is cautioned that there are uncertainties with regard to the model prediction. Major uncertainty is related to the bank erosion that is not included in the model. Therefore, the eroded material sent downstream may be underestimated. Also, the predicted channel may be narrower and deeper than what actually would happen, especially for upstream zones (e.g., zones 3 to 5).

Figure 9-63. A photo of Paonia Reservoir in Colorado after the reservoir is drawn down showing how a channel incised through a portion of the reservoir sediments .



(a) On December 29



(b) On May 14

Figure 9-64. Predicted erosion/deposition pattern on two dates during the drawdown of Copco 1 Reservoir under the Dry (2004) hydrological scenario – overall view.

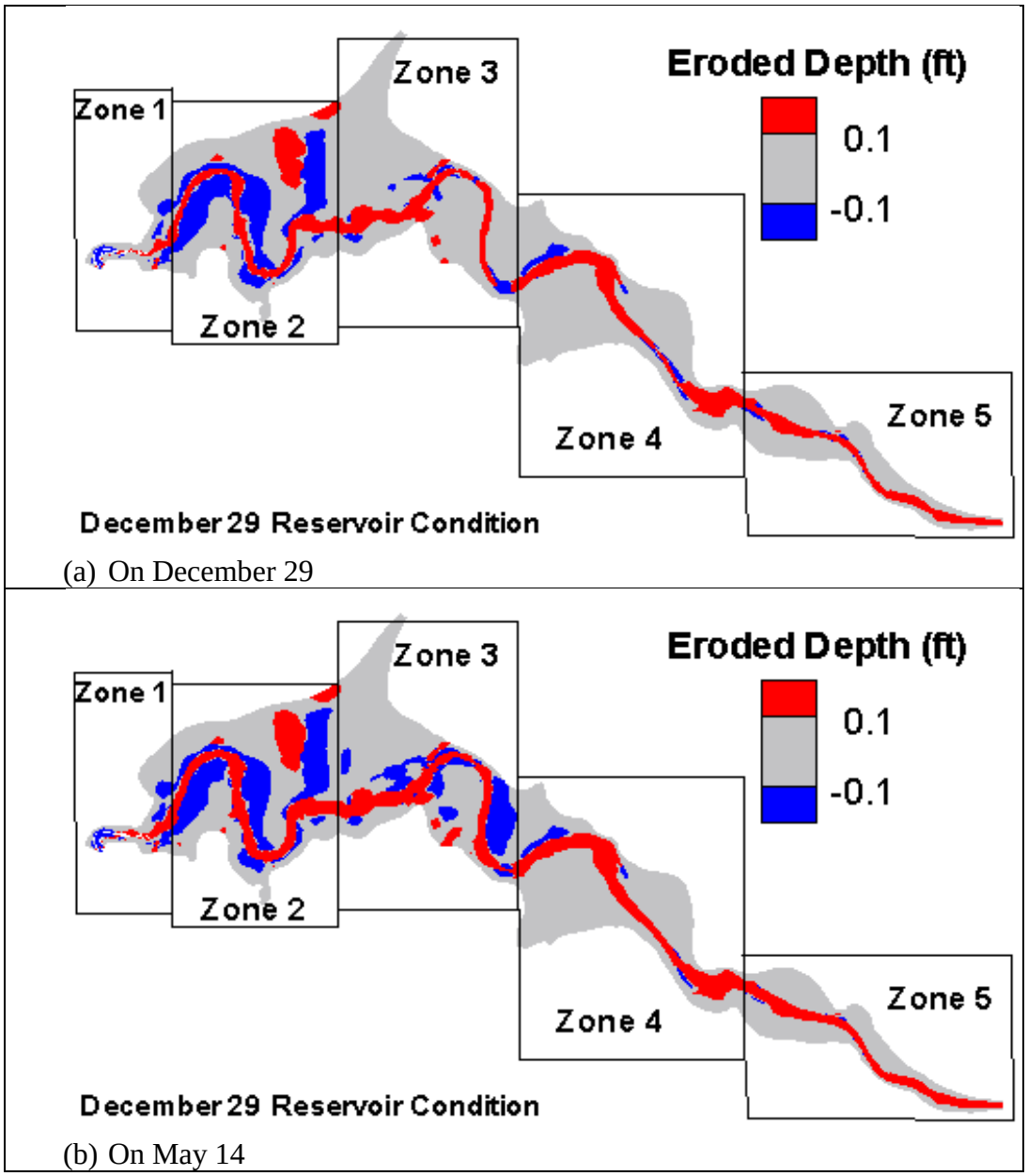
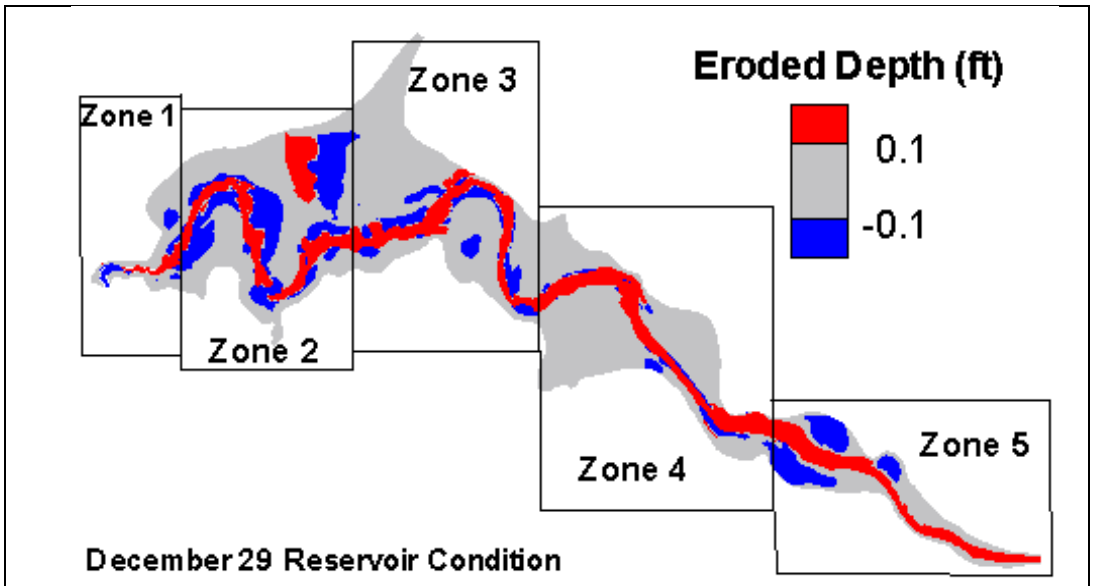
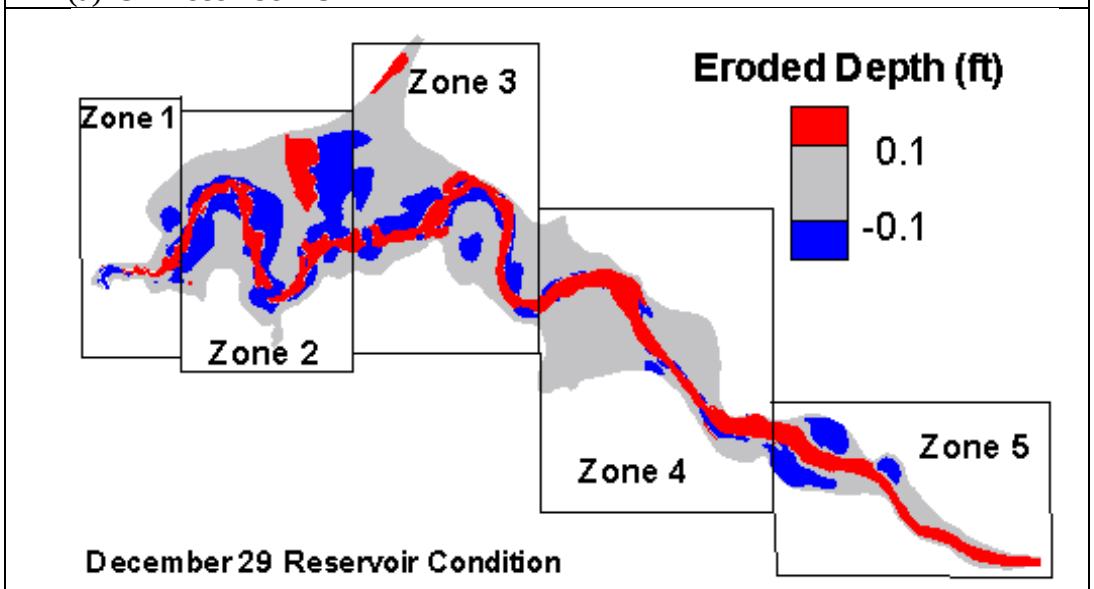


Figure 9-65. Predicted erosion/deposition pattern on two dates during the drawdown of Copco 1 Reservoir under the average (1968) hydrological scenario – overall view.

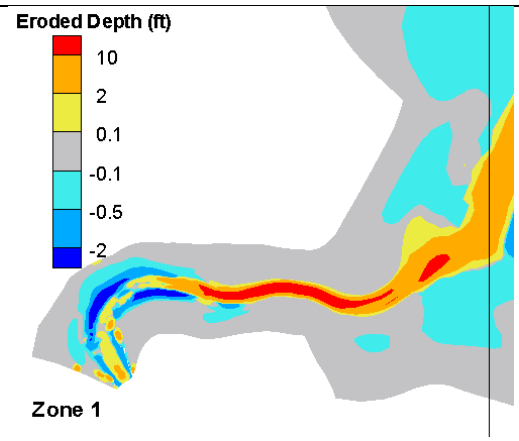


(a) On December 29

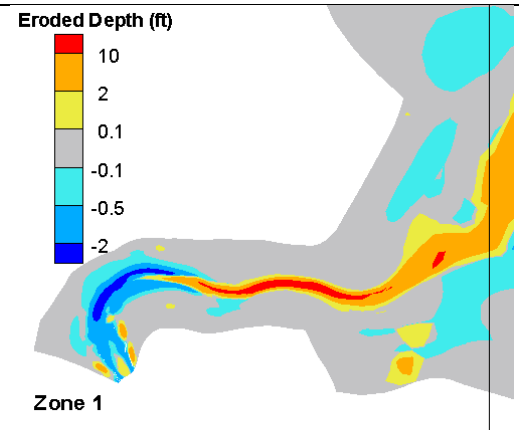


(b) On May 14

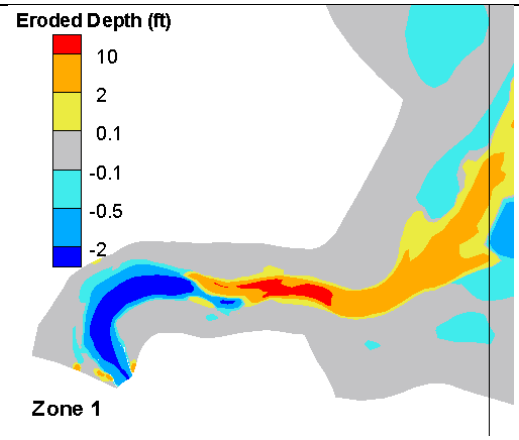
Figure 9-66. Predicted erosion/deposition pattern on two dates during the drawdown of Copco 1 Reservoir under the wet (1999) hydrological scenario – overall view.



(a) Dry Year (2004)

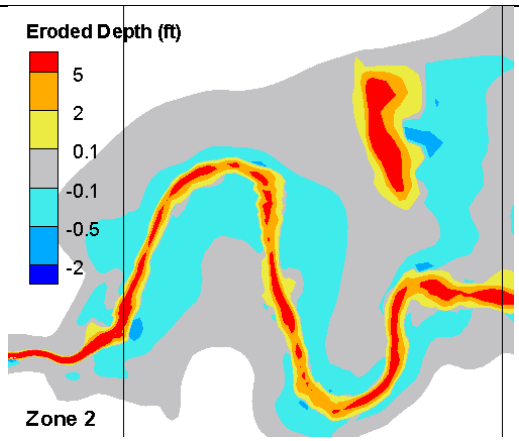


(b) Average Year (1968)

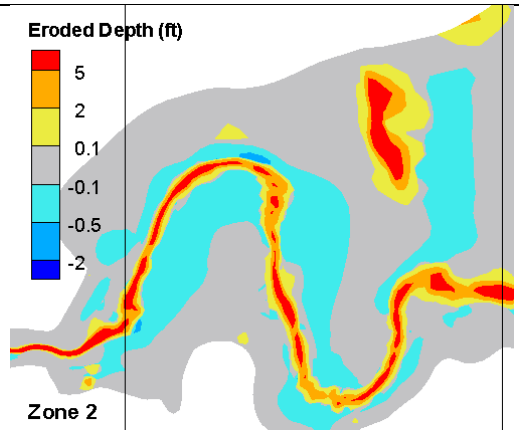


(c) Wet Year (1999)

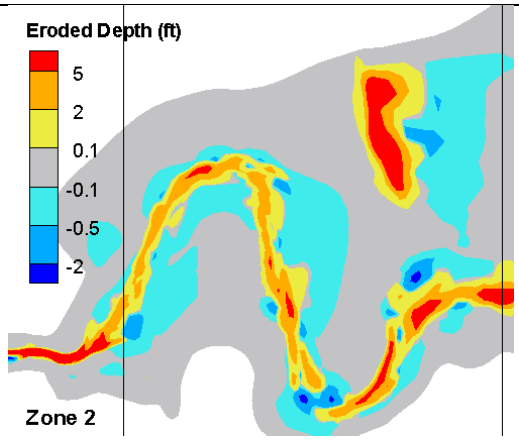
Figure 9-67. Predicted erosion/deposition pattern in zone 1 on December 29 during the drawdown of Copco 1 Reservoir under three hydrological scenarios.



(a) Dry Year (2004)

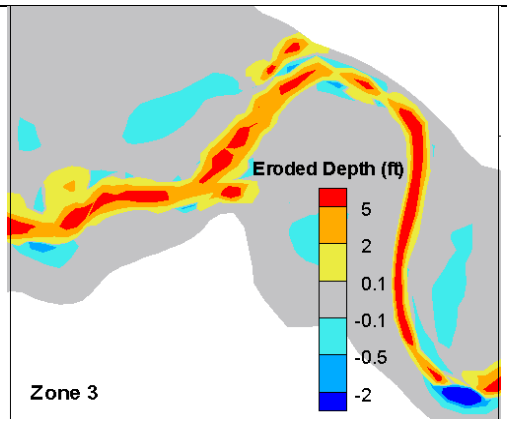


(b) Average Year (1968)

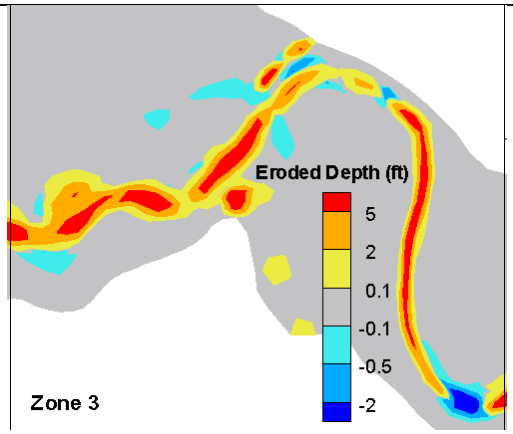


(c) Wet Year (1999)

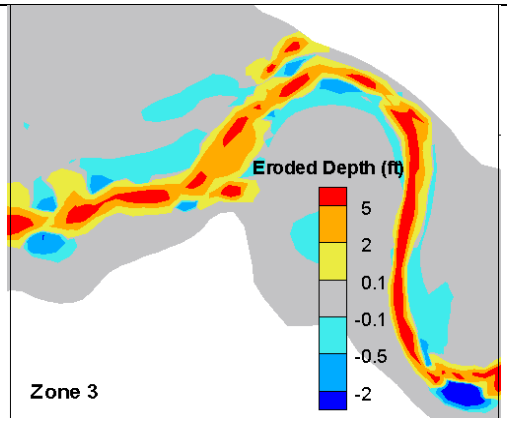
Figure 9-68. Predicted erosion/deposition pattern in zone 2 on December 29 during the drawdown of Copco 1 Reservoir under three hydrological scenarios.



(a) Dry Year (2004)

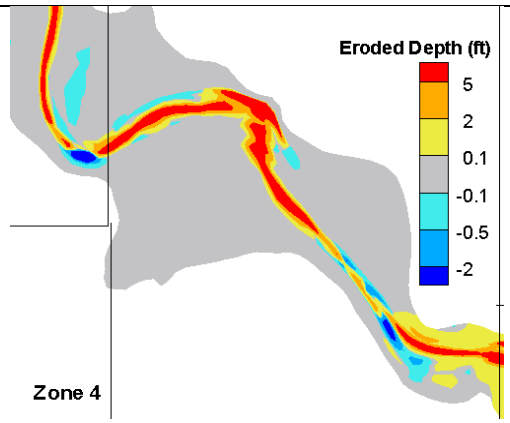


(b) Average Year (1968)

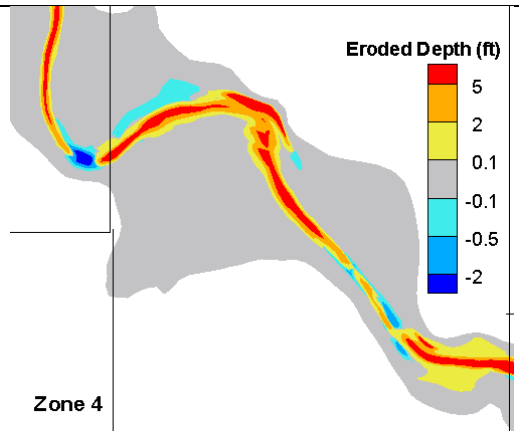


(c) Wet Year (1999)

Figure 9-69. Predicted erosion/deposition pattern in zone 3 on December 29 during the drawdown of Copco 1 Reservoir under three hydrological scenarios.



(a) Dry Year (2004)



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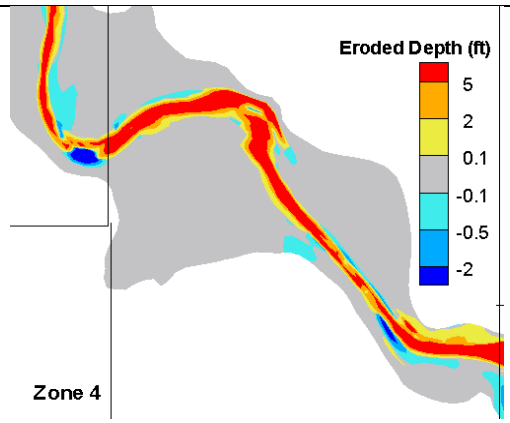
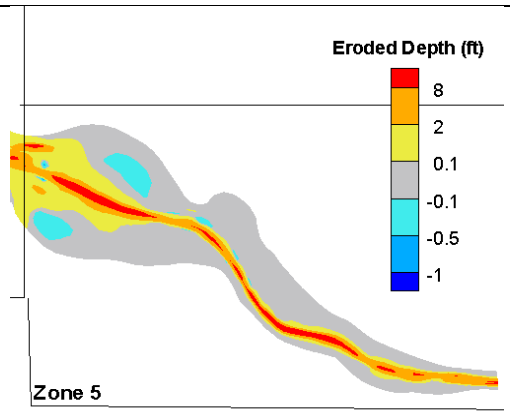
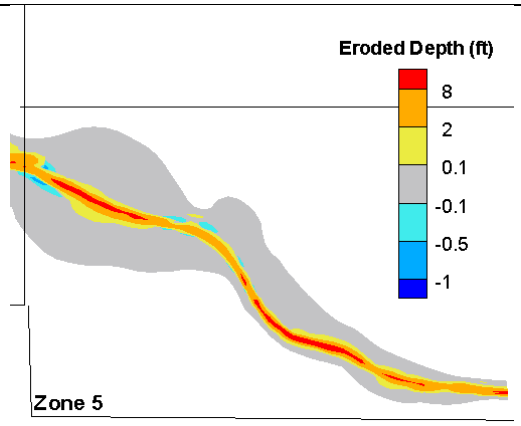


(c) Wet Year (1999)

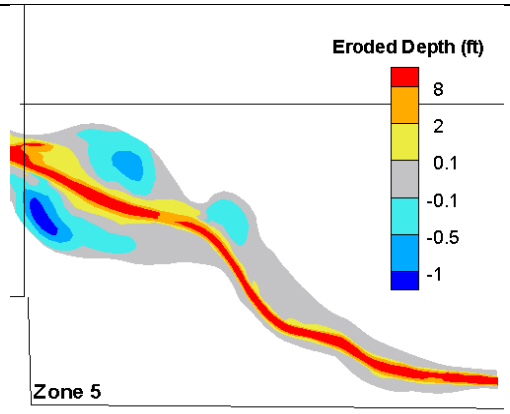
Figure 9-70. Predicted erosion/deposition pattern in zone 4 on December 29 during the drawdown of Copco 1 Reservoir under three hydrological scenarios.



(a) Dry Year (2004)

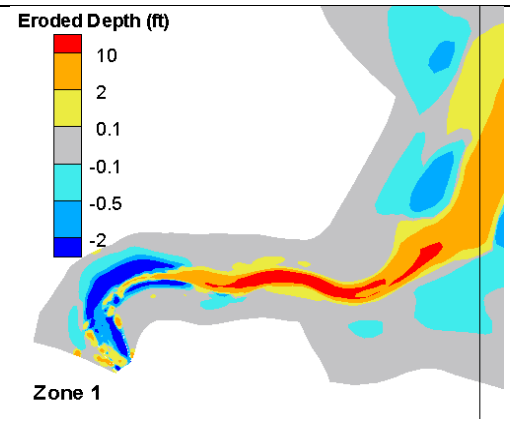


(b) Average Year (1968)

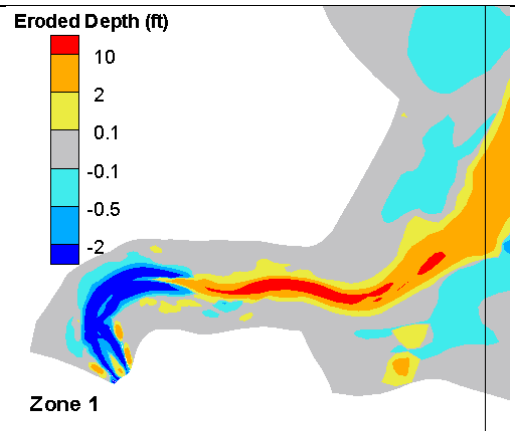


(c) Wet Year (1999)

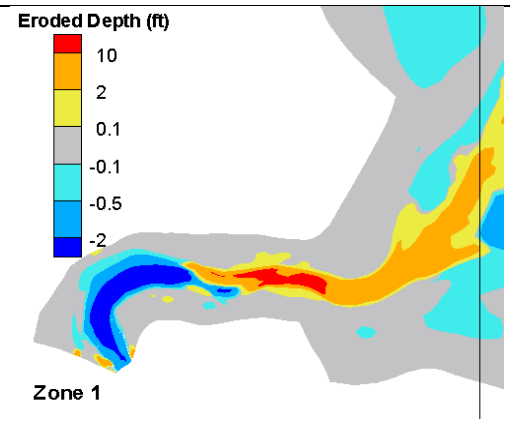
Figure 9-71. Predicted erosion/deposition pattern in zone 5 on December 29 during the drawdown of Copco 1 Reservoir under three hydrological scenarios.



(a) Dry Year (2004)

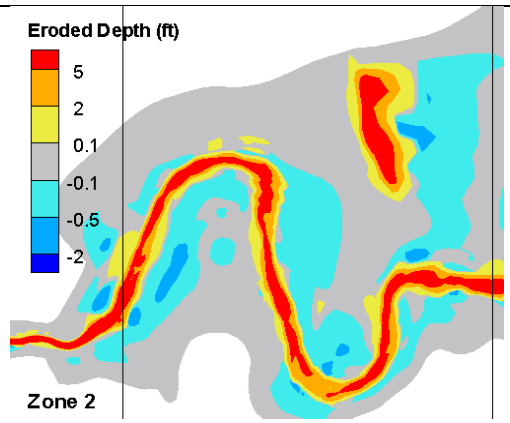


(b) Average Year (1968)

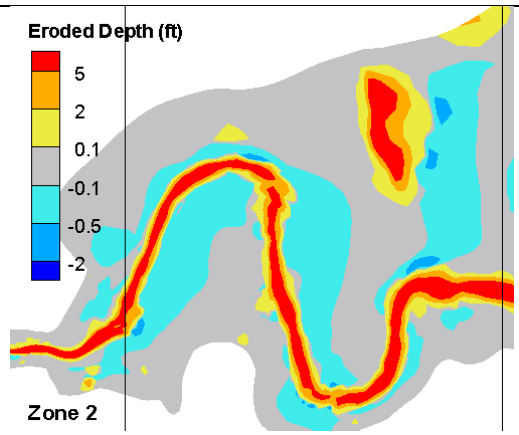


(c) Wet Year (1999)

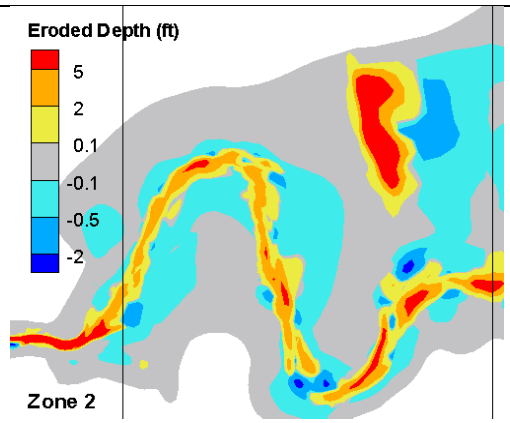
Figure 9-72. Predicted erosion/deposition pattern in zone 1 on May 14 during the drawdown of Copco 1 Reservoir under three hydrological scenarios.



(a) Dry Year (2004)

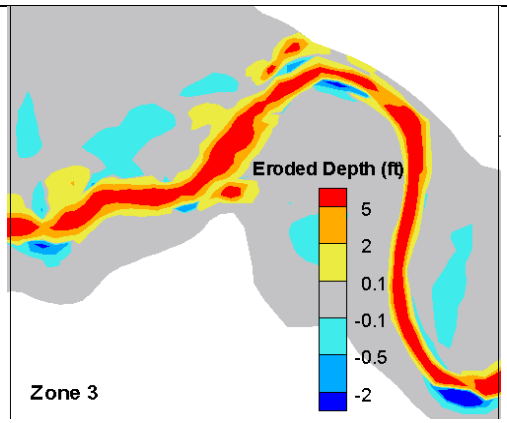


(b) Average Year (1968)

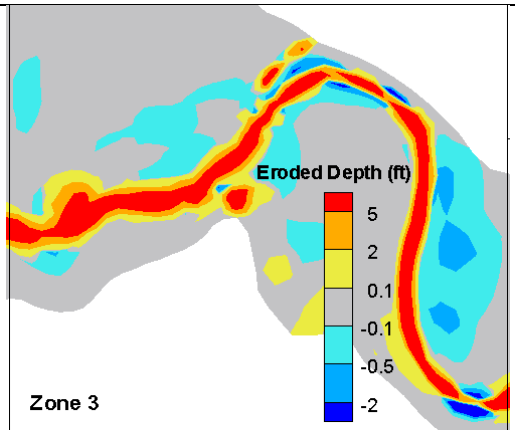


(c) Wet Year (1999)

Figure 9-73. Predicted erosion/deposition pattern in zone 2 on May 14 during the drawdown of Copco 1 Reservoir under three hydrological scenarios.



(a) Dry Year (2004)



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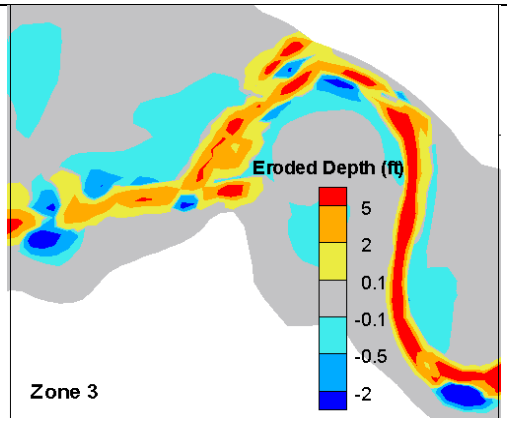
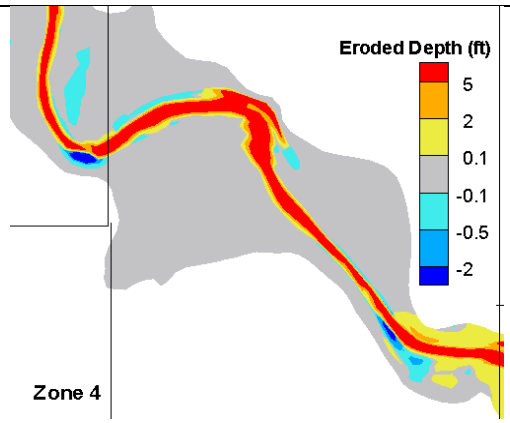
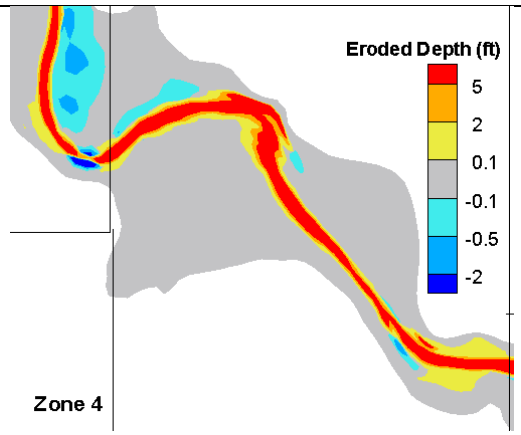


(c) Wet Year (1999)

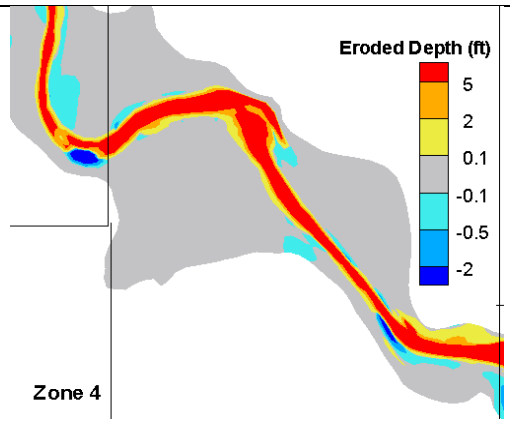
Figure 9-74. Predicted erosion/deposition pattern in zone 3 on May 14 during the drawdown of Copco 1 Reservoir under three hydrological scenarios.



(a) Dry Year (2004)

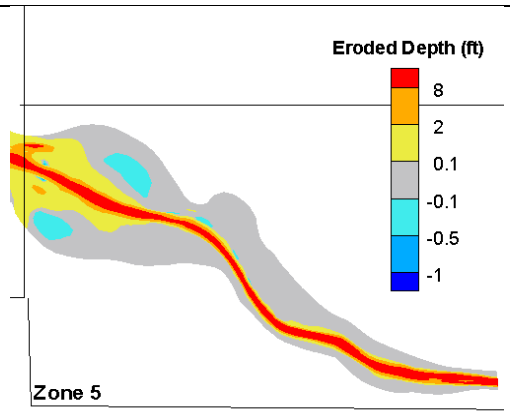


(b) Average Year (1968)

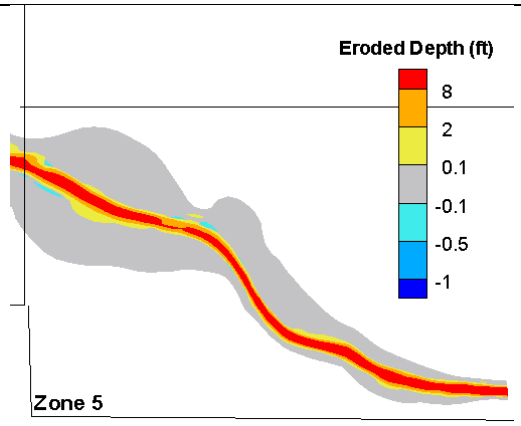


(c) Wet Year (1999)

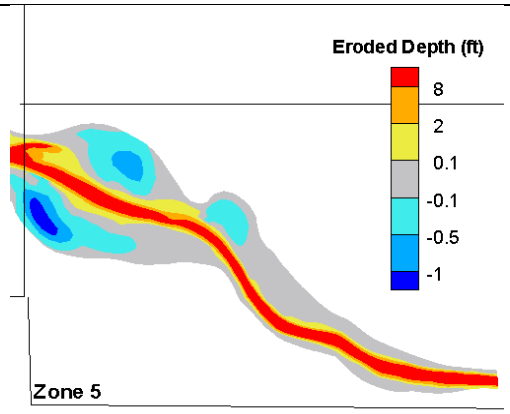
Figure 9-75. Predicted erosion/deposition pattern in zone 4 on May 14 during the drawdown of Copco 1 Reservoir under three hydrological scenarios.



(a) Dry Year (2004)



(b) Average Year (1968)



(c) Wet Year (1999).

Figure 9-76. Predicted erosion/deposition pattern in zone 5 on May 14 during the drawdown of Copco 1 Reservoir under three hydrological scenarios.

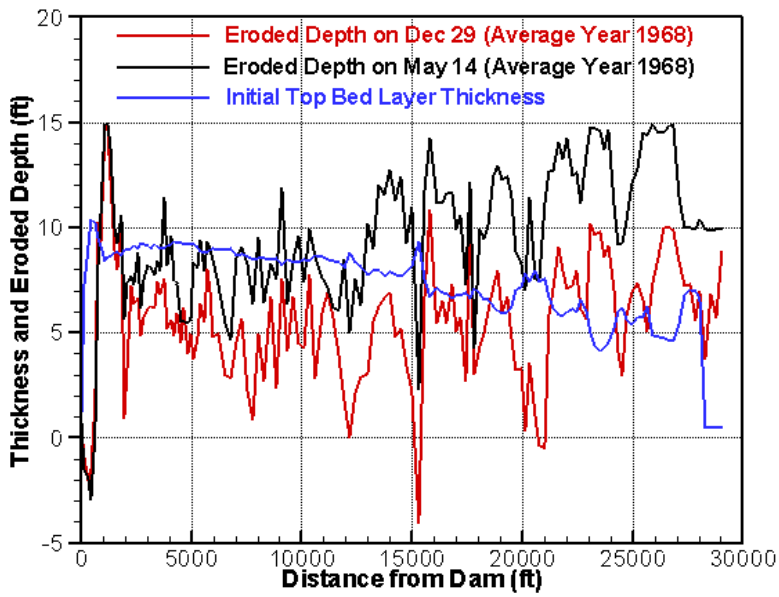


Figure 9-77. Predicted eroded depth along the thalweg of the incised channel on December 29 and May 1 (average year scenario and medium-erode case), which is compared with the initial thickness of the top bed layer deposit.

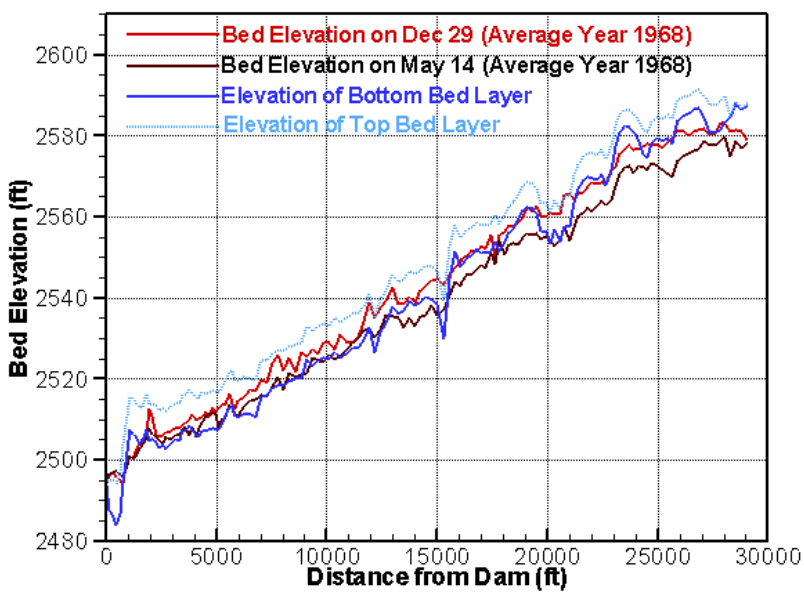


Figure 9-78. Predicted bed elevation along the thalweg of the incised channel on December 29 and May 14 (average year and medium-erode case), which is compared with the initial top and bottom bed layer elevations.

9.2.3. FUTURE BED MOBILIZATION DOWNSTREAM OF IRON GATE DAM

The bed material gradation results of the 50-year SRH-1D simulation were used to assess future bed mobility 10 years after dam removal in 2030 under the No Action and Dam Removal Alternatives. An identical analysis to that presented in Section 5.5 was performed using the predicted median particles size in year 2030 under the No Action and Dam Removal Alternatives. The only difference is that the median bed material sizes were altered based upon the 50-year simulations. The median particle sizes were given in the previous section. The resulting estimates of the initiation of bed mobilization flows and return period of those flows are given in Figure 9-79 and Figure 9-80. A range of estimates are given based upon the variation in the reference shear stress for mobilization being 0.025 to 0.035. It should be noted that when comparing alternatives, one should use the same reference shear stress in the comparison. For example, one should not use a reference shear stress of 0.025 for the No Action Alternative and a reference shear stress of 0.035 for the Dam Removal Alternative.

The comparison shows that the main effect of dam removal on bed mobilization will be from Iron Gate Dam to Cottonwood Creek (USGS RM 190 to RM 182). After Dam Removal, the median estimate of the mobilization flow will reduce from approximately 10,000 cfs to 6,000 cfs in the Bogus Creek to Willow Creek Reach (RM 189.7 to RM 185). In the Willow Creek to Cottonwood Creek reach, the median estimate of the mobilization from will reduce from about 11,000 cfs to 6,000 cfs. The return period of mobilization in this reach will decrease from 4 years to approximately 2 years. Downstream of Shasta River there will be essentially no effect of dam removal on bed mobilization.

Reduced mobilization of bed material under the No Action Alternative will generally result in more stable bed features and the existing bars will become more densely vegetated. More stable features also typically result in less complex habitat. As banks become more stable because of vegetation growth, the diversity of depth can be lost as the bars that create edge and fringe habitat become higher as the vegetation traps more sediment. This process has been documented on the adjacent Trinity River and gravel augmentation schemes are being implemented to increase bed mobilization. It is expected that the reach between Iron Gate and Cottonwood Creek will have improved habitat function under the Dam Removal Alternative than under the No Action Alternative.

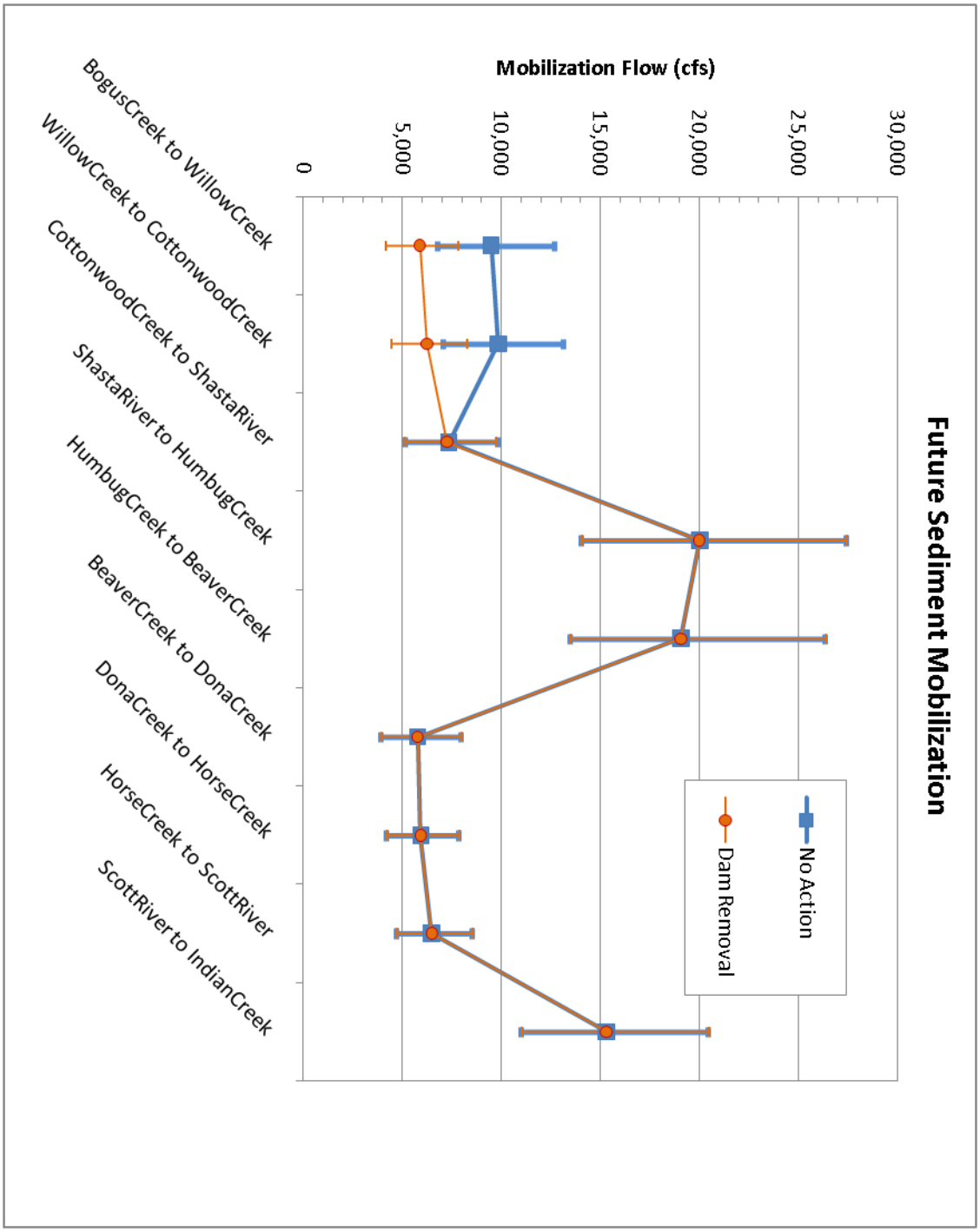


Figure 9-79. Future estimate of initiation of sediment mobilization flows under Dam Removal and No Action Alternatives.

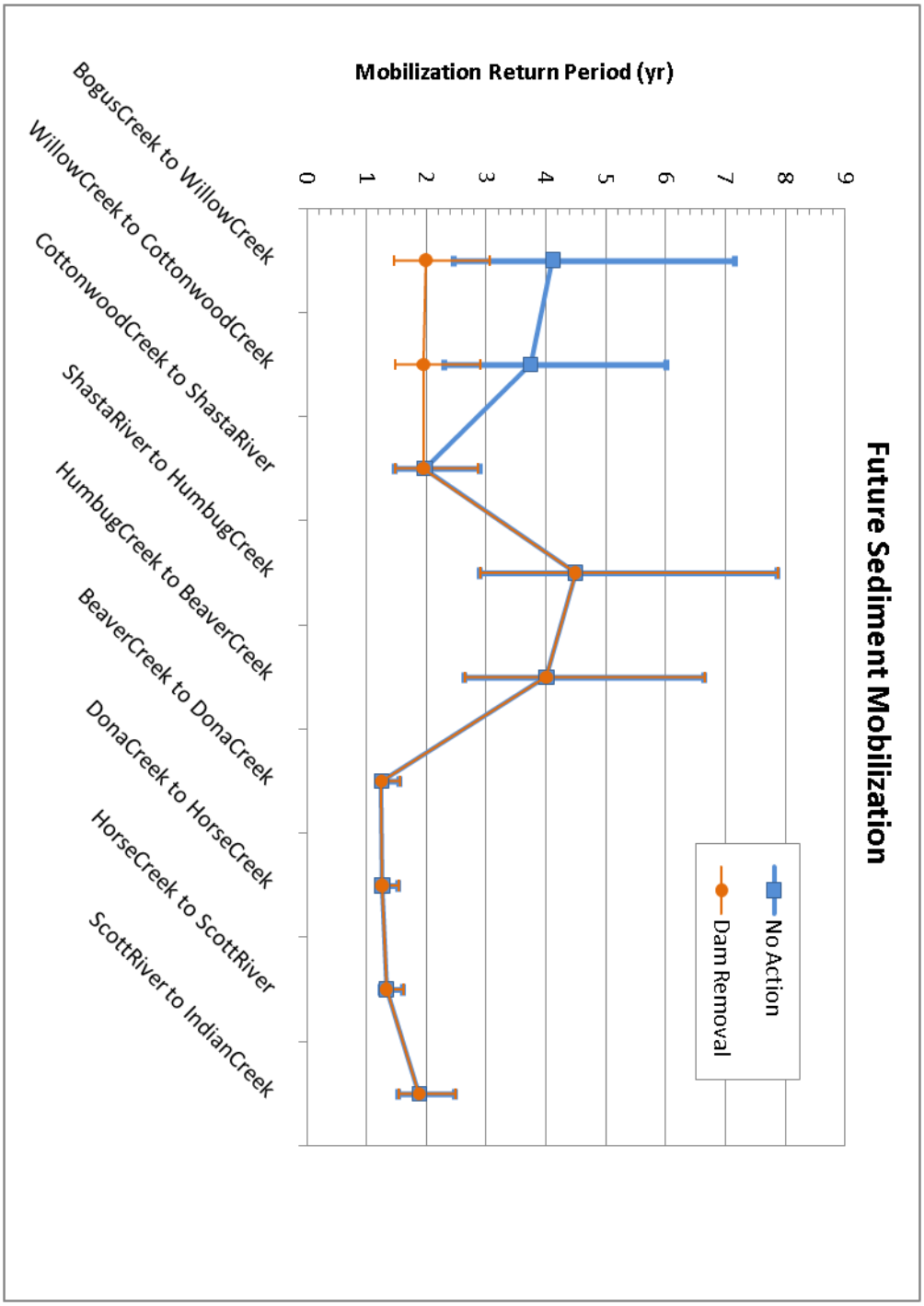


Figure 9-80. Return Period of Mobilization flow under No Action and Dam Removal Alternatives.

9.2.4. WATER QUALITY CONSIDERATIONS DURING DRAWDOWN

One consideration in the drawdown of the reservoirs is the water quality of the reservoirs at the time of drawdown. PacifiCorp (2004) states that Copco and Iron Gate reservoirs are stratified from March to Mid-November. Based upon the yearly water quality summary reports from Raymond (2007, 2008, and 2010) and Figure 3.8-5 in PacifiCorp (2004b), Copco Reservoir turns over in middle to late October and Iron Gate Reservoir in mid-November.

Table 9-3. Date of measured non-stratified conditions at Copco and Iron Gate reservoirs based upon Raymond (2008, 2009, 2010).

Year	Copco	Iron Gate
2009	Oct 13	Nov 17
2008	Oct 22	Nov 19
2007	Oct 23	Nov 28

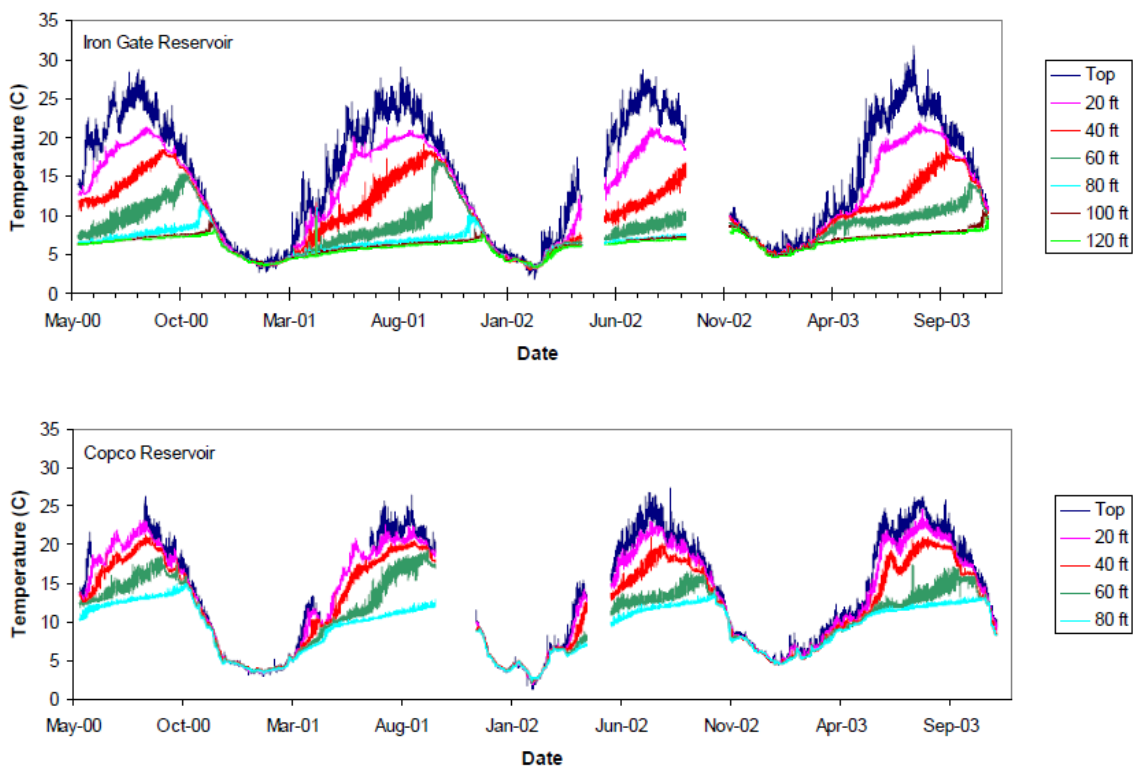


Figure 3.8-5. Hourly water temperature measurements from Copco (top) and Iron Gate (bottom) reservoirs.

Figure 9-81. Temperature profiles from PacifiCorp (Figure 3.8-5 in Water Resources Technical Appendix, PacifiCorp, 2004).

9.2.5. SUGGESTED MONITORING

The Dam Removal Alternative will require extensive monitoring of impacts to ensure that the impacts associated with removal are consistent with the expected impacts. A brief outline of the suggested monitoring objectives would be:

1. To determine the quantity and particle size distribution of sediment supplied to the downstream channel, the rate of downstream movement, and location of sediment accumulation in the channel and/or floodplain;

2. To determine the changes to the water surface elevation of a given discharge along the reach from Iron Gate Dam to Shasta River;

3. To determine the erosion and evolution of material in the reservoir region; and

4. Evaluate the condition of aquatic and riparian habitat in the Klamath River from J.C. Boyle Dam to the Ocean.

To meet these objectives the following activities are suggested:

1. Continued operation of all existing Klamath Basin stream gages to monitor flow discharge.

2. Suspended sediment measurements at the Keno, Iron Gate, Seiad Valley, Orleans and Klamath stream gages. This would begin 2 years prior to dam removal and continue at least 5 years after dam removal.

3. Bed material monitoring from upstream of J.C. Boyle to the Scott River. There would be at least one sampling trip prior to dam removal followed by every year after dam removal for 5 years. The purpose would be to monitor the content of fine material in the bed and to monitor changes to the coarse bed material.

4. Aerial Photography the year prior to dam removal and in years 1, 2, 5, and 10 after dam removal.

5. Detailed reservoir bathymetric surveys prior to dam removal followed by detailed topographic surveys in the reservoir in years 1, 2, and 5 after dam removal.

6. Channel bathymetric surveys from Iron Gate Dam to the Shasta River.

7. Monitoring of water surface elevations at several locations between Iron Gate Dam and the Shasta River.

9.2.6. SUMMARY

The sediment stored in the PacifiCorp Reservoirs is predominantly silt, clay and organic material that is 80 to 90 % water and highly erodible. Drawdown of the four PacifiCorp Dams will release approximately 1/3 to 2/3 of the approximately 15 million yd^3 of sediment that will be stored in the reservoirs by 2020. If there is a wet year, more material will be eroded and if there is a dry year, less material will be eroded from the reservoirs. The river will 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 will raise the floodplain terraces above the pre-dam conditions and the floodplains are expected to be inundated less frequently than typical floodplains. High flows will gradually widen the floodplain, but this process is expected to occur slowly over several decades.

Over 80 % of the reservoir sediment is fine sediment (silt, clays, and organics). Most of this material will be transported to the ocean during the period of drawdown which will last from January 1, 2020 to mid March, 2020. The maximum sediment concentrations during this period may be more than 10,000 mg/l downstream of Iron Gate. The tributaries entering Klamath River will significantly reduce these concentrations to less than 2,000 mg/l at the mouth of the Klamath River.

If there is a wet year, it may take longer to drain Iron Gate Reservoir because of its limited outlet capacity and there may be sediment concentrations larger than 1,000 mg/l as late as June. If there is a dry year, the sediment concentration will be higher during the drawdown period because of less dilution of sediment by the flow.

Sediment concentrations are expected to resume to background levels by the end of the summer 2020 regardless of type of hydrology present. There will be aggressive hydro seeding of the reservoir material 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.

The bed material within the reservoirs and between Iron Gate to Cottonwood Creek 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 of several days to weeks to return the bed to bed dominated by 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 which would be expected under natural conditions.

The mobility of the bed downstream of Iron Gate Dam to Cottonwood Creek will be increased by the removal of the dams. The return of the natural gravel supply

to this reach will increase the frequency of gravel mobilization from once every four years to once every other year.