Model Development and Estimation of Short-term Impacts of Dam Removal on Dissolved Oxygen in the Klamath River

Prepared for
U.S. Department of the Interior
Klamath Dam Removal Water Quality Sub Team
Klamath River Secretarial Determination

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The findings and conclusions in this report represent a collaborative effort between USBR, USFWS, USGS, and Stillwater Sciences in support of the Klamath River Secretarial Determination process. The final report has not been formally disseminated by the agencies involved and should not be construed to present any agency determination or policy.

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Addendum

1 INTRODUCTION

This report summarizes modeling approaches, assumptions and results of a modeling evaluation of short-term variations in dissolved oxygen (DO) due to sediment releases associated with the removal of one or more of four dams in the Klamath Hydroelectric Project (Figure 1; FERC Project No. 2082). Estimates of the volume of sediment retained by these dams include 10.0 million m^3 (13.1 million yd^3) (Greimann et al. 2011), 11.1 million m^3 (14.5 million yd^3) (Eilers and Gubala 2003), and 11.1 million m^3 to 15.6 million m^3 (14.5 to 20.4 million yd^3) (GEC 2006), with a high proportion of fine sediments, organic matter, and nutrients (Shannon & Wilson, Inc. 2006). Sediment transport modeling of the impacts of dam removal on suspended sediment in the lower Klamath River indicates high short-term concentrations of suspended material (i.e., peak values of 9,000–13,600 mg/L) may occur immediately downstream of Iron Gate Dam for 2–3 months following reservoir drawdown under the Proposed Action (Greimann et al. 2011, Stillwater Sciences 2008). Using a combination of *in situ* sampling of sediments and water quality, combined with numerical modeling, this study was developed to estimate the potential influences that re-suspension of reservoir deposits may have on DO levels in the Klamath River downstream of the dams. A numerical model was developed to help in understanding these dynamics, using approaches similar to those described in USEPA (1985, 1987) and detailed below.

1.1 Background

As a means of resolving long-standing disputes regarding water use in the Klamath River basin, governmental, non-governmental, and tribal participants in the Klamath settlement process approved the Klamath Hydroelectric Settlement Agreement (KHSA) and the Klamath Basin Restoration Agreement (KBRA) in 2010. As part of the KHSA, information gathering and analyses are being conducted in support of a determination by the U.S. Secretary of the Interior regarding whether removal of four dams owned by PacifiCorp (FERC Project No. 2082): 1) will advance restoration of the salmonid fisheries of the Klamath Basin; and 2) is in the public interest, which includes but is not limited to, consideration of potential impacts on affected local communities and tribes. Summary characteristics of the four dams considered for removal are shown in Table 1, including J.C. Boyle, Copco 1 and 2, and Iron Gate dams.

Table 1. Summary characteristics of the four dams being considered for removal. Source: Table 3-16, FERC [2007].

Reservoir	Downstream RM	Upstream RM	Maximum Total Storage (ac-ft)	Total Reservoir Sediment Deposit (yd^3)[a]	Average Theoretical HRT[b] (days)
J.C. Boyle	224.7	228.3	3,495	635,664	1.1
Copco 1	198.6	203.1	33,724	10,879,528	10.7
Copco 2	198.3	198.6	73	–	0.0
Iron Gate	190.1	196.9	50,941	8,880,981	14.8
Total	–	–	**88,233**	**20,396,173**	**26.6**

[a] Stillwater Sciences (2008). Copco 2 sediment storage is assumed to be negligible.
[b] HRT = hydraulic residence time, calculated by dividing mean annual flow by total storage capacity (FERC 2007).

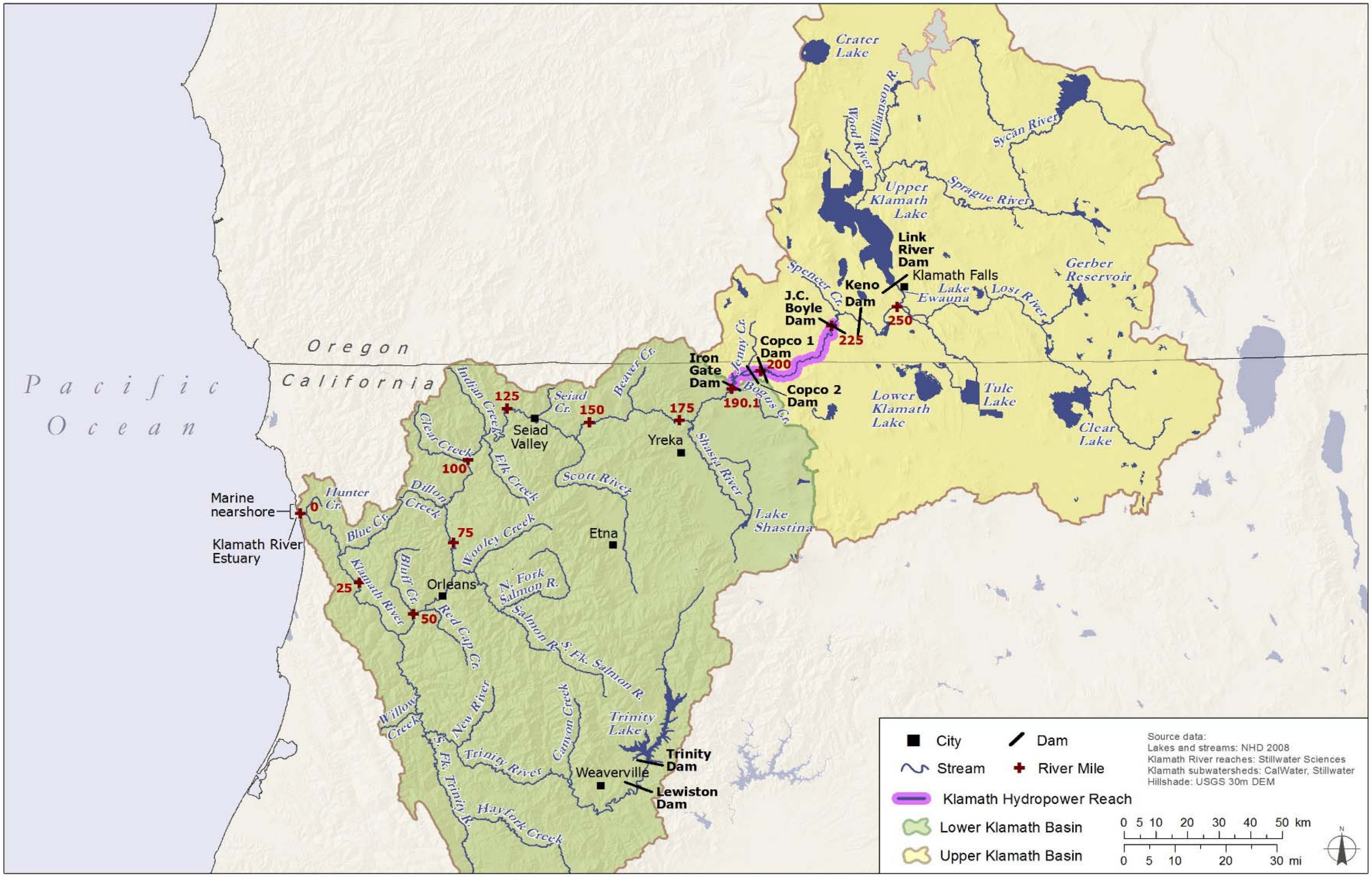

Figure 1. Overview Map of Klamath Hydroelectric Project Area. Upper and lower Klamath basins are shown as defined in the Klamath Facilities Removal Administrative Draft (CDM, February 28, 2011).

The KHSA includes provisions for the interim operation of these dams and describes the process to transfer, decommission, and remove the dams. The KBRA is primarily focused on fisheries restoration activities (i.e., prevention of fish entrainment, provision of fish passage, re-introduction of fish to the Upper Klamath River basin) and flow and water management (i.e., water allocations, diversions, storage). While its implementation is part of the Proposed Action, activities under the KBRA are not expected to affect short-term DO in the river; therefore, the KBRA is not considered further here.

1.2 Primary Short-term Water Quality Issues under the Proposed Action

The Proposed Action involves the concurrent removal of J.C. Boyle, Copco 1, Copco 2, and Iron Gate Dams in a 12-month period as described in KHSA. The Proposed Action would include the complete removal of power generation facilities, bypass canals, pipelines, and dam foundations, and it would rely on natural erosion to flush the sediment behind the dams downstream during facility removal. Although the time period of analysis for the Proposed Action is 50 years from the Secretarial Determination or 2012–2062, this study focuses on short-term impacts immediately following dam removal.

Under the Proposed Action, high suspended sediment concentrations ranging from 9,900 to 13,600 mg/L are expected to occur for 2–3 months following reservoir drawdown, with levels declining to near background (10–30 mg/L) within 6–10 months (Greimann et al. 2011). Mobilization of reservoir sediments following dam removal may result in extended periods of hypoxia due to the high organic content of the sediments (GEC 2006, Stillwater Sciences 2008) as well as oxygen demand associated with unoxidized sulfide minerals. Concerns regarding ambient DO concentrations following dam removal are based on whether resulting DO concentrations would not be suitable for aquatic life. Although the minimum acceptable water quality objective for DO in the Klamath River for warm freshwater, saline, and marine habitats was previously 5 mg/L (NCRWQCB 2006), recent Basin Plan amendments require 85-90% saturation (generally ranging from 6–11 mg/L) depending on location and month (NCRWQCB 2010).

In addition to the short-term release of suspended sediments and any associated DO depletion, sediment-associated nutrients (nitrogen and phosphorus) and contaminants may also be transported downstream and could result in short-term adverse effects on biota. An evaluation of the potential toxicity of reservoir sediments is being conducted separately as part of the Secretarial Determination process (Federal Klamath Staff Working Group 2010).

1.3 Project Alternatives

While the Secretarial Determination process stipulated in the KHSA focuses on the comparison between the Proposed Action and the No Action Alternative, additional project alternatives are currently under consideration as part of NEPA and CEQA compliance and the development of the Environmental Impact Statement/Environmental Impact Report (EIS/EIR). The Proposed Action and alternatives under consideration are the following:

- No Action/No Project
- Full Facilities Removal (Proposed Action)
- Partial Facilities Removal
- Fish Passage at Four Dams

- Fish Passage at Two Dams, Remove Copco 1 and Iron Gate

For future EIS/EIR application, estimates of oxygen demand under the various project alternatives may be informed by results for the Proposed Action. Because short periods of elevated suspended sediment concentrations are expected to occur for the Partial Facilities Removal alternative (Greimann et al. 2011). DO depletion at or below levels under the Proposed Action are also expected to occur. Although sequenced (i.e., extended) dam removal alternatives or those involving sediment removal prior to dam decommissioning have not been fully developed, it is expected that sediment concentrations in the Klamath River will be lower than those for the Proposed Action. Implementation of fish passage measures at the dams is not expected to result in elevated suspended levels or to adversely impact DO in the Klamath River.

As an example application of the oxygen demand model, results of multiple drawdown scenarios of the Proposed Action used in the Administrative Draft of the EIS/EIR are provided as Appendix A to this report. Below, we describe the model development and parameter sensitivity testing to evaluate the potential ranges of DO levels in the Klamath River downstream of the dams following implementation of these and other scenarios that may be developed in the future.

2 APPROACH

2.1 Summary of Oxygen Demand Modeling

Past research regarding the impacts of oxygen demanding discharges to natural waters has been primarily associated with the impacts of sewage disposal on downstream water quality. The phenomena of a DO “sag”, first studied by Streeter and Phelps (1925) along the Ohio River, results in a characteristic depletion of oxygen along the longitudinal profile of a flowing stream followed by a gradual return to near saturated conditions as the discharged organic matter is gradually oxidized by re-aeration at the air/water interface. Biological oxygen demand (BOD) refers to the amount of oxygen needed by aquatic microbes to metabolize organic matter, oxidize ammonia reduced nitrogen species, as well as to oxidize reduced mineral species such as ferrous iron. In addition to effects of DO depletion on biological communities, elevated BOD has the potential to affect sediment chemistry and the release of many compounds to the water column depending upon oxidizing or reducing conditions in the overlying water column. Lee and Jones-Lee (1999) provide a review of oxygen demand within sediments at open water dredge operations, and Eggleton et al. (2004) provide a recent review of contaminant release following the disturbance of anoxic sediments.

Focusing upon short-term impacts of sediment discharges on DO, the relatively low solubility of oxygen in water means that even low levels of microbial activity associated with the metabolism of organic matter will result in depletion of DO in the water column. Streeter and Phelps (1925), and many water quality models developed since (USEPA 1985), model the decay of BOD and interactions with stream reaeration across the air-water interface as a 1st order process. That is, the decay of the BOD is assumed to be proportional to its remaining concentration at any point in time, which results in a characteristic exponential decay. Fair (1939) later summarized parameter estimation methods for this “Streeter and Phelps” model and numerous models have since been developed to include the influence of stream temperature, dispersion, particle settling, sediment oxygen demand as well as the oxygen dynamics associated with suspended algae and zooplankton (e.g., Thomas 1948; Camp 1963; Thomann and Muller 1987).

2.2 Selected Approach and Model Formulation

The approach used for this study relies upon a combination of direct sampling for laboratory determination of oxygen-demand characteristics of the Klamath River sediments within the Project reservoirs, in conjunction with simplified modeling approaches that include channel geometry, tributary inflows, as well as estimates of the suspended sediment concentrations (SSC) expected following dam removal. Several publicly available water quality models (QUAL2E, QUAL2K, and WASP6) include modeling of BOD and could be applied to riverine systems such as the Klamath River. However, these models do not explicitly consider the high SSC and BOD conditions associated with short-term anoxia following dam removal. Additionally, given the possibility that additional dam removal alternatives may yet be developed and the understanding that additional studies would be undertaken if the Secretarial Determination is affirmative, a 1-dimensional reach-scale analysis of oxygen demand was deemed most appropriate by Water Quality Sub Team (WQST) and the Engineering/Geomorphology/Construction Sub Team (EGCST) for the Klamath Dam Removal Secretarial Determination process. For these reasons the WQST and the EGCST developed a simplified model in order to assess a range of potential downstream DO impacts on aquatic resources following dam removal. Stillwater Sciences later assisted the two sub teams in refinement of the model in a collaborative process. As it is a simplified model, predictions of particular DO levels at specific locations should be considered estimates, understanding that *in situ* conditions may differ from those used to estimate DO in the Klamath River following dam removal.

Although a number of factors are known to influence DO removal, we have taken an approach similar to the original Streeter and Phelps (1925) formulation, with the introduction of additional terms as follows:

$$\frac{dO}{dt} = k_a\left(O_{sat} - O\right) + \frac{dIOD}{dt} + \frac{dBOD}{dt} - k_b/d \tag{1}$$

where,

O = Dissolved oxygen concentration (mg/L);
O_{sat} = Saturated concentration of dissolved oxygen (mg/L)
IOD = Concentration of ultimate initial oxygen demand (mg/L);
BOD = Concentration of ultimate biological oxygen demand (mg/L);
k_a = Stream reaeration rate (d^{-1});
k_b = Bed sediment oxygen demand ($g\text{-}O_2/m^2\text{-}d$);
d = Average flow depth (m); and
t = Time (d)

Equation (1) includes terms for an "initial" oxygen demand (IOD) to represent the rapid depletion of water column DO followed by a microbially mediated BOD. IOD is typically expressed very rapidly with the release or resuspension of anoxic sediments due to the presence of iron and manganese sulfides, or other reduced chemicals in the sediments (Allen et al. 1993, Simpson et al. 1998). The governing equation for IOD is a 1st order relationship that allows for fitting to a separate rate constant (k_i) for IOD as shown in Equation (2). BOD is typically exerted more slowly, but is assumed to also follow a 1st order relationship with an associated decay constant (k_d). All rate constants are assumed to be affected by temperature (Section 2.3.4) with the exception of BOD removal due to settling (k_s) shown in Equation (3). As a conservative assumption, k_s was later set to zero (Appendix A).

$$\frac{dIOD}{dt} = -k_i IOD \tag{2}$$

$$\frac{dBOD}{dt} = -k_d BOD - k_s BOD \tag{3}$$

Equation (1) also includes a sediment oxygen demand (SOD) term (k_b) to represent bacterial and chemical reactions, as well as respiration by benthic macroinvertebrates, mollusks, and worms in the channel bed sediments downstream of the release point. Although diel DO variations in the Klamath River downstream of Iron Gate Dam can reach ±1 mg/L during summer (Ward and Armstrong 2010), this formulation excludes algal respiration because reservoir drawdown under the Proposed Action would occur in the winter (i.e., primarily January-March) when rates of algal respiration are typically low. Lastly, we have assumed that ammonia oxidation (i.e., nitrogenous BOD) is captured in the BOD parameterization based on laboratory jar test incubations (Section 3.1).

From the relationships in Equations (1) through (3) above, the equations above are represented in an Excel worksheet as first order differential equations that follow the form:

$$\frac{dX}{dt} = -aX + b \tag{4}$$

Where X is the variable of interest and a and b are constants. In order to include the influence of tributary dilution, we have introduced a node-network system with a characteristic exponential solution between each node at travel times t_1 and t_2:

$$X(\Delta t) = X(t_1)\exp(-a\Delta t) + \frac{b}{a}\left[1 - \exp(-a\Delta t)\right] \tag{5}$$

where $\Delta t = t_2 - t_1$. In order to estimate the reaction times above, a moving coordinate frame is introduced to translate time into distance between model nodes using the stream velocity. The value of t is then computed as the travel time between model nodes as a function of stream velocity (U) and stream location (x):

$$t = x/U \tag{6}$$

The above equations are included in a spreadsheet model and the equations solved exactly for segments of the river between major tributary inputs. Assuming a background concentration of DO at the upstream boundary of the modeled reach, steps in this procedure are to calculate the DO saturation and reaeration ignoring the initial oxygen and biological oxygen demand terms in Equation (1), but including the sediment oxygen demand term. The initial oxygen demand equation (2) is then computed. This is subtracted from the equation (1) result and if the stream DO is depleted below zero, then the initial oxygen demand is unmet and the remaining IOD is passed to the next downstream model node. If DO is present in the water column, this same process is also applied to the BOD and settling terms in Equation (3). Concentrations of DO, as well as IOD and BOD remaining unmet from upstream are adjusted at each tributary junction using a simple mixing equation to estimate this dilution, as described below.

Using hydrologic data developed in support of the Secretarial Determination process (King 2010), dilution factors were calculated as at each of seventeen Klamath River tributaries downstream of Iron Gate Dam. For each of three years representing a range of water year types (1976 [Median], 1984 [Typical Wet], 2001 [Typical Dry] [Greimann et al. 2011]) the average monthly tributary inflow was divided by the total flow in the mainstem Klamath River downstream of the tributary junction. Using this approach across the range of expected hydrology, Red Cap Creek and the Trinity River provide dilution of 20–32% and 22–23% of Klamath River flows in Typical Wet and Typical Dry water year types, respectively. Four tributaries (Shasta River, Clear Creek, Salmon River, and Bluff Creek) provide dilution of 10–17% of Klamath River flows, with the remaining tributaries contributing lower dilution.

2.3 Parameter Estimation

Parameter estimates for the resulting spreadsheet model are discussed below and rely upon a combination of laboratory sediment core incubation experiment results to determine IOD and BOD, literature values of general ranges of some parameters, as well as parameter estimates developed from other studies specific to the Klamath River.

2.3.1 Initial and biological oxygen demand

In order to estimate the magnitude of oxygen demanding substances within suspended sediments re-released following dam removal, a targeted field study was developed to sample sediment cores at a number of locations within Iron Gate and Copco 1 reservoirs (Figures 2 and 3) (Zedonis and Anderson 2010). Initially, sediment samples were collected at several locations within these reservoirs during November 4–17, 2009, with repeat samples collected on April 13–14, 2010. Vertical profiles of *in situ* water quality (Temperature, Dissolved Oxygen, pH, Conductivity) were simultaneously recorded while the sample cores and native water samples were collected. 2009 sediment samples were collected using auger cores while 2010 sediment samples were collected by SCUBA (Figure 4) using 18-inch by 3-inch PVC sample tubes. The top 4 to 6 inches and bottom 2 inches were discarded from the sample tubes to remove any disturbed or oxidized material, such that remaining composites represented material from approximately a sediment depth of 4 inches. Laboratory incubation and analysis for both 2009 and 2010 samples were conducted at Basic Laboratories, Redding, California.

Because of potential concerns regarding oxygen exposure of preliminary sediment core collections conducted in 2009, all core samples in April 2010 were collected in zero head-space capped corer tubes, and placed submerged in water and ice for transport to the laboratory (Zedonis and Anderson 2010). All 2010 sample processing and sediment/water BOD incubations were conducted in a nitrogen-sparged, oxygen-free, glove box. Sediment cores from each reservoir were sub-sampled, aliquots composited over a range of depths (1 to 7 feet) and set up in replicated BOD incubations at several combinations of sample mass (wet weight) and incubation temperature (Appendix B). The oxygen demand testing generally follows the methods as prescribed in Lee and Jones-Lee (1999). Laboratory incubations of several mass additions (i.e., 0.5 g, 2.0 g, and 8.0 g) in native water were conducted at two temperatures (4 °C and 20 °C) in standard 300-mL BOD bottles with a stirring apparatus and repeat measurements of DO over time (e.g., APHA 2005) to estimate the IOD and BOD values. The majority of the IOD incubations were conducted for a period of 3 hrs with DO readings initially recorded every 2 minutes. All

2009 BOD incubations were conducted for at least 5-days with several samples monitored for a period of 30-days. To include the exertion of BOD from ammonia and other nitrogenous compounds, the 2009 laboratory incubations were conducted without the use of a nitrification inhibitor.

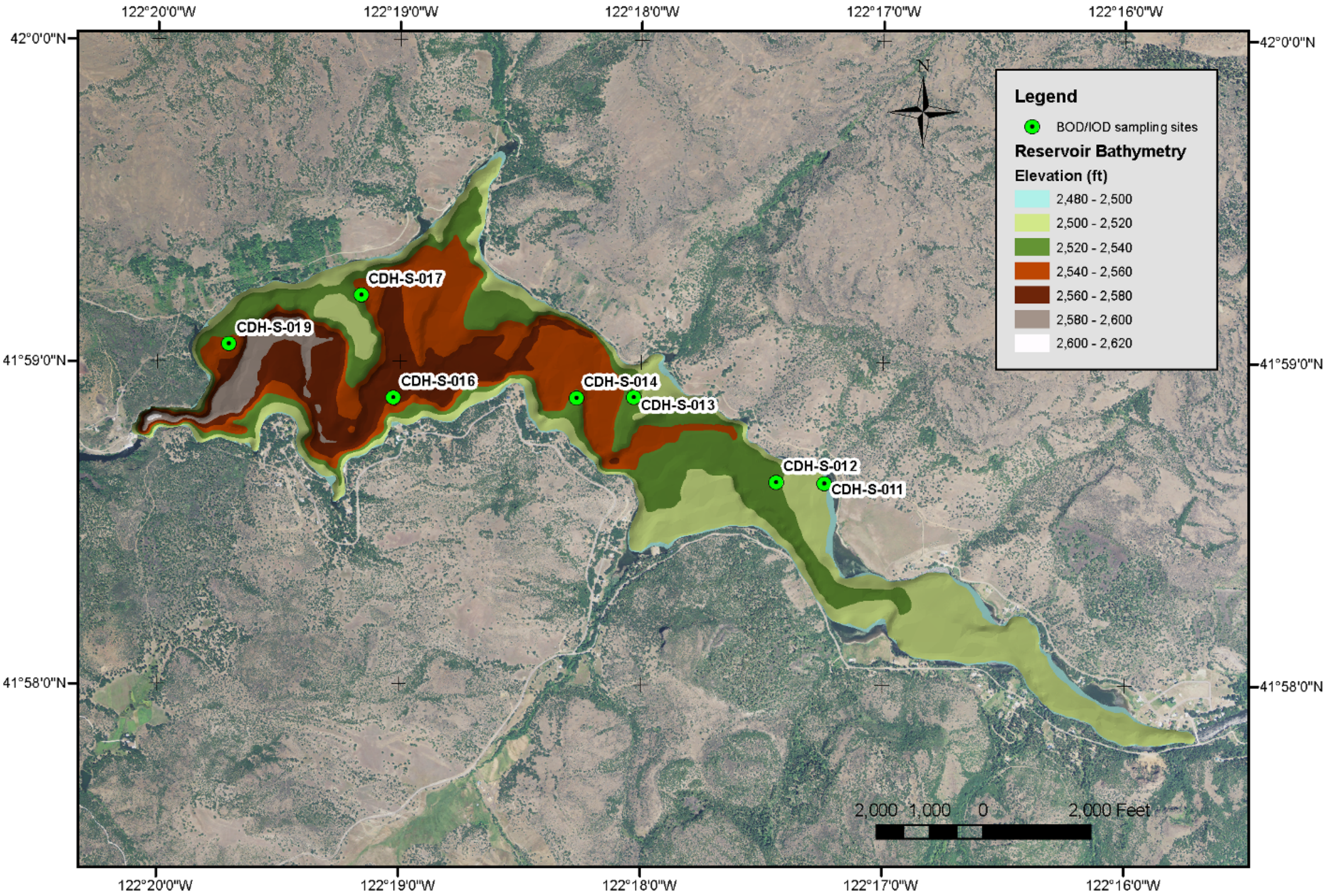

Figure 2. Copco 1 Reservoir bathymetry and 2009–2010 sediment sampling locations for laboratory BOD/IOD testing.

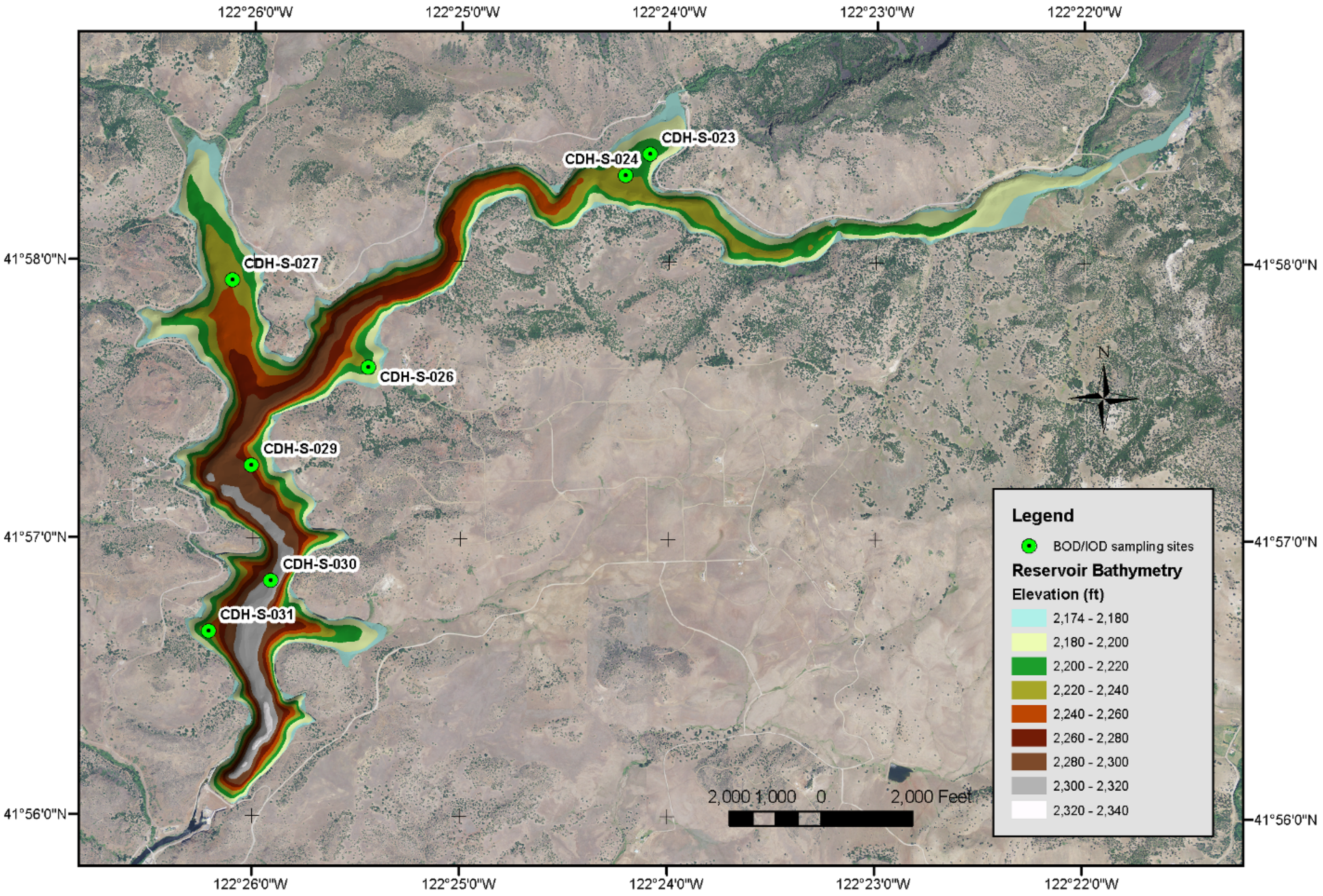

Figure 3. Iron Gate Reservoir bathymetry and 2009–2010 sediment sampling locations for laboratory BOD/IOD testing.

Figure 4. Sediments collected by SCUBA using 3-in by 8-in push tubes, with samples capped at depth to prevent oxidation, and stored upright on ice for transportation to laboratory, April 2010.

2.3.2 Stream reaeration

The first term in Equation (1), stream reaeration, is commonly associated with a stream reaeration constant (k_a) estimated from hydraulic parameters such as depth (H) and mean velocity (U). Although a large number of empirical regression formulas have been developed, the following nomograph (Figure 5) developed by Covar (1976) uses three common formulations (O'Connor and Dobbins 1958, Churchill et al. 1962, Owens et al. 1964), all expressed at a reference temperature of 20°C.

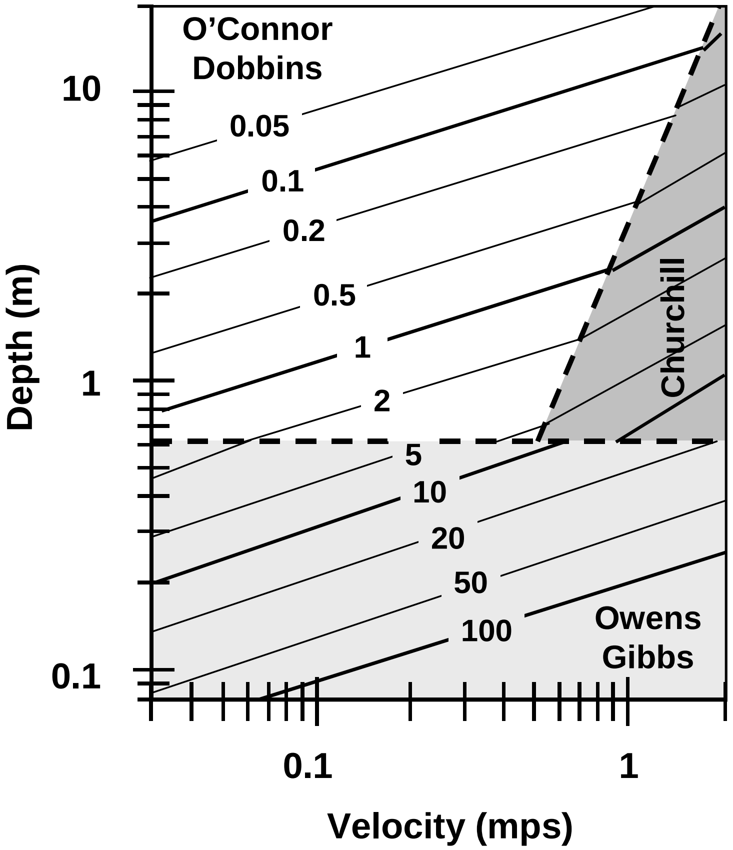

Figure 5. Reaeration rate (d^{-1}) as a function of and velocity (Covar 1976). Re-aeration rates are shown as solid diagonal lines with rate values ranging 0.05–100 d^{-1}.

Because air-water exchanges are affected by diffusive processes as well as advective ones due to turbulence, a number of mass transfer models have been proposed (e.g., two-film theory, surface renewal, penetration), with each formulation having particular limitations and applications. Using Figure 5, deeper and slower rivers are best modeled using the O'Connor-Dobbins (1958) formula, shallower and faster rivers modeled using the Owens-Gibbs (Owens et al. 1964) approach, and the Churchill et al. (1962) formulation intermediate between the two:

- if $H < 0.61$ m, use the Owens-Gibbs formula
- if $H > 0.61$ m and $H > 3.45U^{2.5}$, use the O'Connor-Dobbins formula
- Otherwise, use the Churchill formula

Based upon this classification, the Klamath River below Iron Gate dam is of intermediate depth and higher velocity and would best be modeled using the Churchill formula below:

$$k_a = 5.026 \frac{U}{H^{1.67}} \tag{7}$$

Farther downstream, the river channel broadens and deepens significantly, and at locations downstream of Orleans (RM 60) the O'Connor Dobbins formula would be used:

$$k_a = 3.93 \frac{U^{0.5}}{H^{1.5}} \tag{8}$$

USEPA (1985) and more recently Aristegi et al. (2009) provide review of these formulations as well as other methods to calculate stream reaeration rates. Aristegi et al. (2009) concluded that direct measurement of stream reaeration using day/night *in situ* comparisons of community respiration (Hornberger and Kelly 1975) was perhaps the most accurate method, but also that other formulations often resulted in large variations, particularly for shallower streams where productivity and mechanical aeration may play a larger role in reaeration. Of the reaeration coefficient formulations reviewed, the energy dissipation method (Tsivoglou and Neal 1976) appeared to represent *in situ* measurements most consistently, which can be represented as:

$$k_a = k' \frac{\Delta H}{\Delta X} U \tag{9}$$

Here, air-water exchanges are mediated through energy dissipation as calculated from water velocity (U) and local water surface slope ($\Delta H/\Delta X$), with an empirically derived coefficient k' that ranges from a low of 0.0162 m^{-1} in the flow ranges range of 0.75–90 m^3/sec to a high of 0.033 m^{-1} at flows of 0.03–0.3 m^3/sec.

In order to select a single reaeration model using the community respiration approach described above, we made a comparison of the Churchill et al. (1962), O'Connor-Dobbins (1958), and Tsivoglou and Neal (1976) formulations to *in situ* estimates developed by Ward and Armstrong (2010) from continuous DO data collected during 2001–2005 in the Klamath River. To estimate the reaeration coefficients in Equations 7–9, we used existing estimates of velocity and depths from the compiled HEC-RAS model for the Klamath River (Greimann et al. 2011), as well as the tributary dilution approach described in Section 2.2.

Overall, Figure 6 shows *in situ* estimates based upon July 2001 data that are higher than the empirical reaeration coefficient estimation methods, as noted by Aristegi et al. (2009); however, this is primarily because of particularly high *in situ* estimates at 100 km and 225 km downstream of Iron Gate Dam. Similar longitudinal variations in k_a were observed for the other water year types from 2002–2005 (Ward and Armstrong 2010). Comparison of the empirical and *in situ* k_a values indicates that all three methods typically underestimate *in situ* reaeration coefficients with the Churchill method best predicting *in situ* estimates for three out of four months in summer 2001 (Table 2).

Table 2. Model goodness of fit (observed vs. expected) for three reaeration models compared to summer 2001 *in situ* k_a estimates (Ward and Armstrong 2010) calculated using observed monthly flows.

Goodness of fit statistic[1]	Churchill	O'Connor-Dobbins	Tsivoglou-Neal
June			
Slope	0.46	0.30	0.57
R^2	0.78	0.68	0.68
p	0.006	0.016	0.016
July			
Slope	0.72	0.48	0.46
R^2	0.86	0.76	0.76
p	0.002	0.007	0.007
August			
Slope	0.73	0.48	0.51
R^2	0.84	0.71	0.83
p	0.003	0.012	0.003
September			
Slope	0.70	0.45	0.48
R^2	0.78	0.65	0.80
p	0.006	0.021	0.005

[1] Slope is a measure of the general correspondence between observations and model predictions; R^2 (coefficient of determination) ranges from 0 to 1 and measures variations of individual observations from model predictions; and p measures the probability that the overall model has a relationship to the observed values (i.e., the probability that the model slope is not actually zero).

For summer 2001, *in situ* reaeration rates in the Klamath River estuary were below Churchill and O'Connor-Dobbins model estimates but above Tsivoglou-Neal estimates, suggesting that assumptions related to channel geometry may not be met in low velocity estuarine settings (Figure 6). Based upon USEPA (1985) and Aristegi et al. (2009), reach-specific reaeration models for the Klamath River could be explored in the future. Nevertheless, although the spreadsheet model allows for comparisons in predicted DO using any of the Churchill, Tsivoglou-Neal and O'Connor-Dobbins formulations (see Section 3.3.4), the Churchill method was selected for evaluation of the dam removal drawdown scenarios (Appendix A). All reaeration models appear to under predict *in situ* reaeration when compared to Ward and Armstrong (2010) (Figure 6) and model results are considered to be conservative (i.e., lower reaeration potential) with respect to oxygen levels in the majority of the mainstem Klamath River.

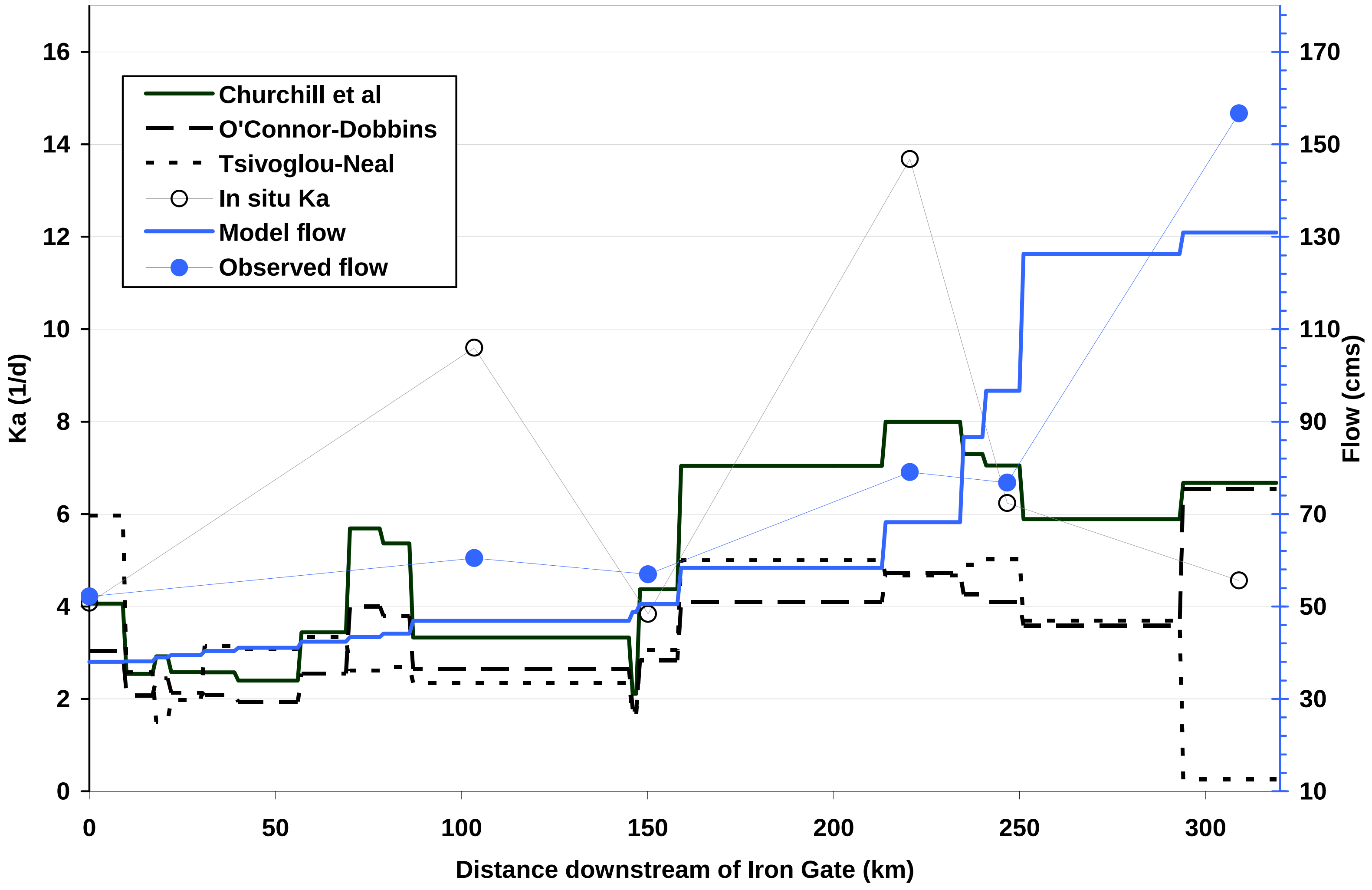

Figure 6. Comparisons of three reaeration models (Churchill et al. 1962, O'Connor and Dobbins 1958, and Tsivoglou and Neal 1976) estimated using July 2001 observed flows and compared with July 2001 *in situ* estimates by Ward and Armstrong (2010). See Table 2 for goodness of fit comparisons for June through September 2001.

2.3.3 Sediment oxygen demand

In addition to oxygen demand associated with Klamath River water and sediments released following dam removal, oxygen demand is continually exerted by both existing and newly deposited sediments on the channel bottom. Typical sediment oxygen demand rate (k_b) estimates based on laboratory experiments are on the order of 0.5–2.0 g-O_2/m^2-d (Thomann 1972, as cited in USEPA 1985). Ward and Armstrong (2010) reported a total (dark) dissolved oxygen consumption in chamber experiments in the Shasta River, 4-5 miles upstream from USGS gage no. 11517500 (station "SH") (Rounds and Doyle 1997) ranging from 0.14–0.26 mg/L/hr, with an average of 0.11 mg/L/hr absorbed by sediments and 0.08 mg/L/hr in the overlying water (all values being corrected to ambient temperature). At a chamber size of 0.225 m^2 and 52L used for these investigations, these estimates correspond to approximately 0.6 g/m^2/d, within the range of sediment oxygen demand coefficients cited by Thomann (1972) above.

2.3.4 Temperature adjustments to rate constants

Temperature effects upon chemical and biological reactions are well described by the Arrhenius relationship, which explains the common observations of approximately doubling reaction rates when ambient temperatures rise by 10ºC [18ºF]. Almost all models use the following relationship with a reference temperature of 20ºC [68ºF] assumed (USEPA 1985).

$$k(T) = k_{20C}\,\theta^{T-20} \tag{10}$$

Where T is the stream temperature (ºC) and θ is entered for each model parameter. Typical values cited in USEPA (1985) for θ are 1.02–1.04 for the decay rate terms and 1.08 for sediment oxygen demand rate (k_b).

2.3.5 Dissolved oxygen saturation

Dissolved oxygen saturation (O_{sat}) is expressed in mg/L and is typically a function of temperature, local atmospheric pressure, and salinity. Although differences exist among the results obtained by various formulations used to determine DO saturations, principally due to salinity, the variations in most formulations under fresh water conditions is typically less than 2 percent (USEPA 1985). For the purposes of this evaluation, we have used the Duke and Masch (1973) formula as a function of temperature (T) in ºC and stream elevation (E) in meters:

$$O_{sat} = \left(14.652 - 0.3898\ T + 0.006969\ T^2 - 5.897\cdot 10^{-5} T^3\right)\times\left(1 - 6.97\cdot 10^{-6} E\right)^{5.167} \tag{11}$$

2.3.6 Model verification

Model verification was performed to determine whether the model performs as intended by the supporting relationships. Since the BOD/IOD spreadsheet model has been developed with additional terms not included in the Streeter and Phelps (1925) formulation, model verification was undertaken by comparing estimated DO concentrations predicted by the BOD/IOD spreadsheet model with those of a separate Streeter and Phelps spreadsheet model (Figure 7). For the verification, values for the additional terms in the BOD/IOD spreadsheet model (i.e., IOD rate, sediment oxygen demand) were set to zero and average values for the channel cross-section geometry were used. In this way, the modified BOD/IOD spreadsheet model was reduced to its minimal possible behavior. Model verification indicated that the addition of a second oxygen demand term (IOD) as well as other model modifications (e.g., sediment oxygen demand, reach specific cross-section geometry, tributary dilution), did not alter performance of the BOD/IOD spreadsheet model relative to a Streeter and Phelps formulation (Figure 7). The results below using the verified spreadsheet model include additional sensitivity analyses to examine the influence of fitted, as well as selected model parameters.

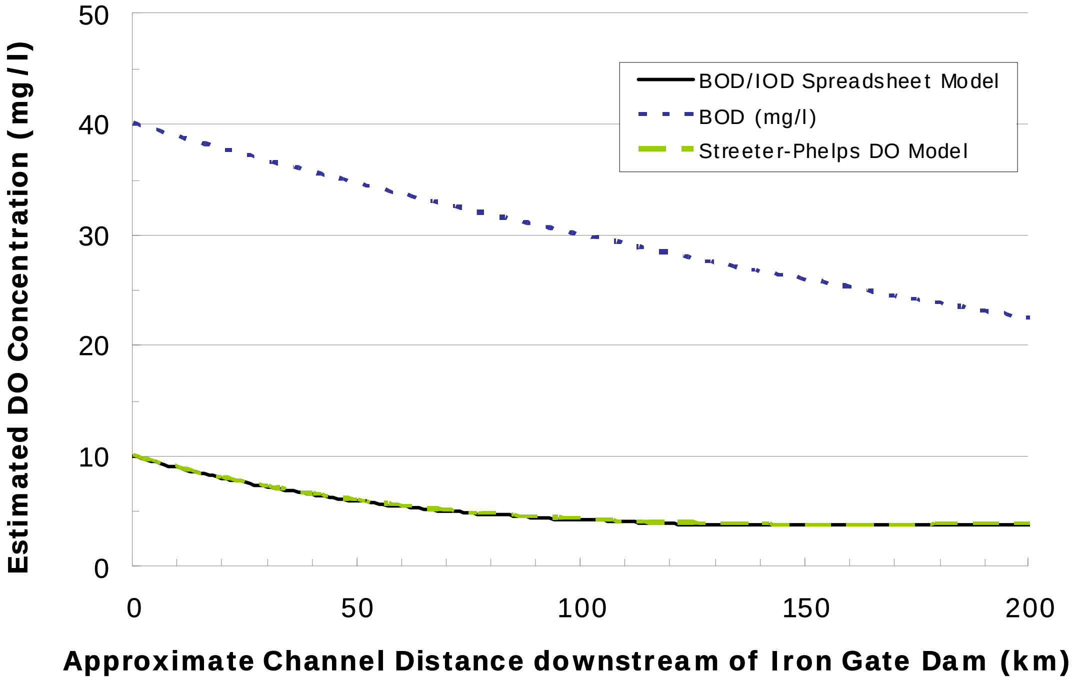

Figure 7. Model verification of estimated DO downstream of Iron Gate Dam comparing the BOD/IOD Spreadsheet Model to the Streeter and Phelps DO Model.

3 RESULTS

3.1 Sediment Core Analyses

Estimates of oxygen demand were developed from aliquots of sediment core samples collected in Iron Gate and Copco 1 reservoirs during 2009 for BOD, with additional samples collected in 2010 for determination of IOD. The form of the oxygen demand model is shown in Equation (12) as an exponential solution of the IOD and BOD terms of Equation (1) using the time series of observed DO values fitted to an “ultimate” IOD or BOD at time t = ∞.

$$OD = OD_{t=\infty}\left(1 - e^{-k(t-t_0)}\right) \tag{12}$$

Appendix B shows the rate estimates for the incubation experiments for each set of samples (i.e., the samples from the given reservoir and year) and each of two time intervals (0 to 30 minutes for IOD, 30 minutes to 30 days for BOD). Each incubation was carried out for differing combinations of sediment mass and incubation temperature (Section 2.3.1) with model parameters fitted as described below.

In the 2009 laboratory analyses, the DO at 30 minutes was not reported. For our analyses, we imputed a value at 30 minutes by log-linear interpolation between the reported DO values at 15 minutes and 60 minutes (Appendix B). In order to adjust to a common temperature, the DO curves for all the samples were fitted to a least-squares model with common rate constants (k_i or k_d), as modified by temperature (θ determined from Equation [10]). Based upon commonly observed temperature coefficients (USEPA 1985), the temperature-correction factor θ was constrained to lie between 1.01 and 1.07. Sample specific $OD_{t=\infty}$ values were fitted by log linear regression and averaged across each reservoir and oxygen demand component (IOD, BOD) (Table 3). Lastly, in order to adjust for the varying amounts of sample mass in each incubation, sample specific $OD_{t=\infty}$ values (mg/L) were normalized to SSC (mg/L dry weight), with intercept forced through zero. Here wet weights were corrected to dry weight by the percent moisture in each sample (2009) or the median of all samples within a composite (2010).

Table 3. 1st Order rate estimates and oxygen demand of sediments within Iron Gate and Copco 1 Reservoirs based upon laboratory tests of 2009 and 2010 sediment core samples.

Oxygen Demand Component	**Reservoir**	**Year**	**Fitted 1st Order Rate Constant [1] (k_i, k_d) at 20°C**		**Fitted Temperature Coefficient [2] θ**	**Average Oxygen Demand [3] ODu/SSC**	
			d^{-1} (95% CI)		**exp(1/°C)**	**mg-O/mg-dry-wt (95% CI)**	
IOD	Iron Gate	2010	353	(339–367)	1.01	6.27×10^{-4}	$(6.06\times10^{-4}$–$6.48\times10^{-4})$
	Copco 1	2010	384	(368–399)	1.01	6.35×10^{-4}	$(6.28\times10^{-4}$–$6.43\times10^{-4})$
	Combined	2010	368	(361–375)	1.01	6.31×10^{-4}	6.23×10^{-4}–$6.38\times10^{-4})$
BOD	Iron Gate	2009	0.097	(0.090–0.104)	1.01	3.62×10^{-3}	$(2.81\times10^{-4}$–$4.44\times10^{-4})$
	Copco 1	2009	0.080	(0.073–0.086)	1.01	3.47×10^{-3}	$(3.06\times10^{-4}$–$3.87\times10^{-4})$
	Combined	2009	0.088	(0.086–0.091)	1.01	3.52×10^{-3}	$(3.32\times10^{-3}$–$3.72\times10^{-3})$

[1] k_i = first order rate constant for IOD. See equation (2). k_d = first order rate constant for BOD. See equation (3).

[2] θ held constant. Typical values cited in USEPA (1985) for θ are 1.02–1.04 for the decay rate terms and 1.08 for sediment oxygen demand rate (k_d).

[3] ODu = "ultimate" oxygen demand at time t = ∞. See equation (12).

The majority of samples collected in 2009 were tested over 30-day incubations. The 2010 samples focused upon short-term (3-hr) testing to evaluate IOD, with only a few samples being incubated to 5-days (Appendix B). For this reason, $BOD_{t=\infty}$ estimates and the corresponding rate constants were only available using the 2009 data, whereas IOD parameters were determined from the 2010 sample testing results (Appendix B). Since the oxidation of reduced sulfides within IOD occurs rapidly, within the first few minutes after exposure to oxygenated waters (Allen et al. 1993, Simpson et al. 1998), the corresponding decay rate for IOD (k_i) would typically be on the order of 100 d^{-1}, slightly lower to those determined from the 2010 incubations. By comparison, BOD decay rate constants (k_d) typically range from 0.1–0.3 d^{-1} (USEPA 1985) for natural waters, near the values found in this study.

3.2 Base Case Results

To evaluate *in situ* IOD and BOD and the corresponding depletion rates for a particular SSC concentration, the mass of suspended sediment in the laboratory incubations was scaled to the modeled estimate of SSC in the Klamath River following dam removal (Greimann et al. 2011) using the "combined" values for IOD and BOD per unit mass of SSC (Table 1; ODu/SSC [mg O/mg dry wt]. As a base case, Table 3 presents variations in modeled DO corresponding to the estimated IOD and BOD at 5,000 mg/L SSC, with average flows and water temperatures for December, March, June, and September in each of the three water year types represented (typical wet [1984], median [1976], typical dry [2001]). Channel geometry (width, depth) for the Klamath River were estimated from HEC-RAS model cross-sections (Greimann et al. 2011) along with estimates of flows, tributary dilution factors, and water surface slopes for the three representative water year types (1976, 1984, and 2001).

Table 4. Estimates of DO downstream of Iron Gate Dam for December, March, June, and September for a base case of 5,000 mg/L SSC (equivalent IOD[1] = 3.15 mg/L, BOD[1] = 17.61 mg/L).

Date	**Avg. flow[2]**	**Avg. temperature[3]**	**Initial dissolved oxygen (at 100% saturation)**	**Estimated minimum DO**	**Approximate location of minimum DO**	
	(cfs)	**(deg C)**	**(mg/L)**	**(mg/L)**	**(km)[4]**	**RM**
Typical Wet Hydrology (Water Year 1984 Conditions Assumed)						
December	13,490	3.1	12.4	9.2	4	187.6
March	9,923	5.0	11.8	8.6	4	187.6
June	5,438	17.2	8.8	5.8	2	188.9
September	2,864	16.3	9.0	5.9	2	188.9
Median Hydrology (Water Year 1976 Conditions Assumed)						
December	4,308	3.1	12.4	9.3	3	188.2
March	4,626	5.0	11.8	8.7	3	188.2
June	2,560	17.2	8.8	5.8	2	188.9
September	2,264	16.3	9.0	6.0	2	188.9
Typical Dry Hydrology (Water Year 2001 Conditions Assumed)						
December	2,490	3.1	12.4	9.3	2	188.9
March	3,298	5.0	11.8	8.7	2	188.9
June	2,303	17.2	8.8	5.8	2	188.9
September	1,847	16.3	9.0	6.0	2	188.9

[1] Values scaled using laboratory sediment core IOD and BOD results (Section 3.1).

[2] Model data provided by USBR. Flow and SSC modeling approach described in Greimann et al. (2011).

[3] Raw daily water temperature data for 2009 from http://www.pacificorp.com/es/hydro/hl/kr.html# (PacifiCorp 2009).

[4] Distance downstream of Iron Gate Dam.

The months selected in Table 3 were intended to represent a range of flows and temperatures that may be expected depending upon the start date of the Preferred Alternative. For the base case in Table 3, estimated DO by kilometer in the Klamath River downstream of Iron Gate Dam is shown in Figures 8–10 for each of the three representative water year types. Results are presented using the SSC, IOD, and BOD estimates from Table 3, with average monthly water temperatures at each model node (Section 2.2) estimated using continuous DO data recorded by PacifiCorp (PacifiCorp 2009).

For the base case, DO was assumed to be at 100% saturation immediately upstream of Iron Gate Dam. This condition would presumably represent a simplified best-case scenario, such that no oxygen demand would exist from SSC mobilization during removal of the three upstream dams (J.C. Boyle, Copco 1 and Copco 2). Although existing data indicates that background DO in the river downstream of Keno Reservoir and, in some cases, downstream of J.C. Boyle, Copco 1 and Iron Gate Reservoirs, is less than 100% saturation during the late summer/fall, the same initial DO saturation was used for all months in the base case as a simplifying assumption for the purposes of testing model sensitivity. Actual model runs should consider the month of drawdown and use existing data to set initial DO with respect to water temperature and typical background DO concentrations. It is anticipated that model runs conducted for late summer/fall months would possess the lowest initial DO saturation values[1].

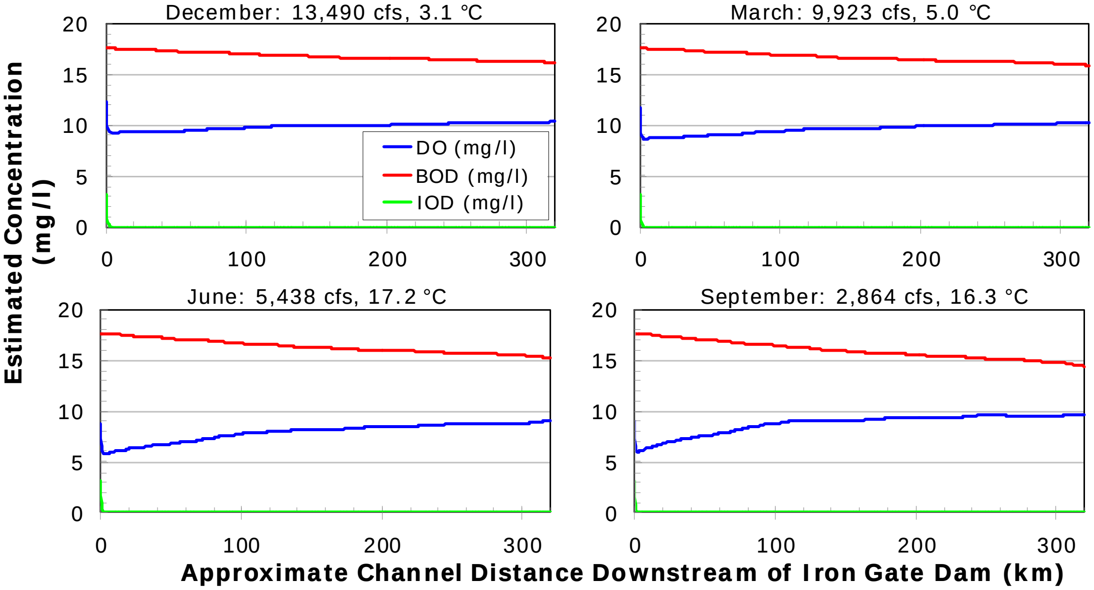

Figure 8. Estimated DO, BOD, and IOD (mg/L) downstream of Iron Gate Dam for Typical Wet Hydrology (WY 1984) and a base case of 5,000 mg/L SSC for December, March, June, and September reservoir drawdown start dates[2].

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[1] Current reservoir drawdown scenarios do not include a late summer/fall drawdown date. Appendix A presents example applications of the DO spreadsheet model for three reservoir drawdown scenarios considered in preliminary analyses of the Full Facilities Removal of Four Dams on the Klamath River (Proposed Action) in the Administrative Draft of the EIS/EIR

[2] The apparent segmentation of the graphs is an artifact of the image rendering. Model results are currently calculated for a 1,000-meter node spacing, but they could be calculated at any spacing without loss of

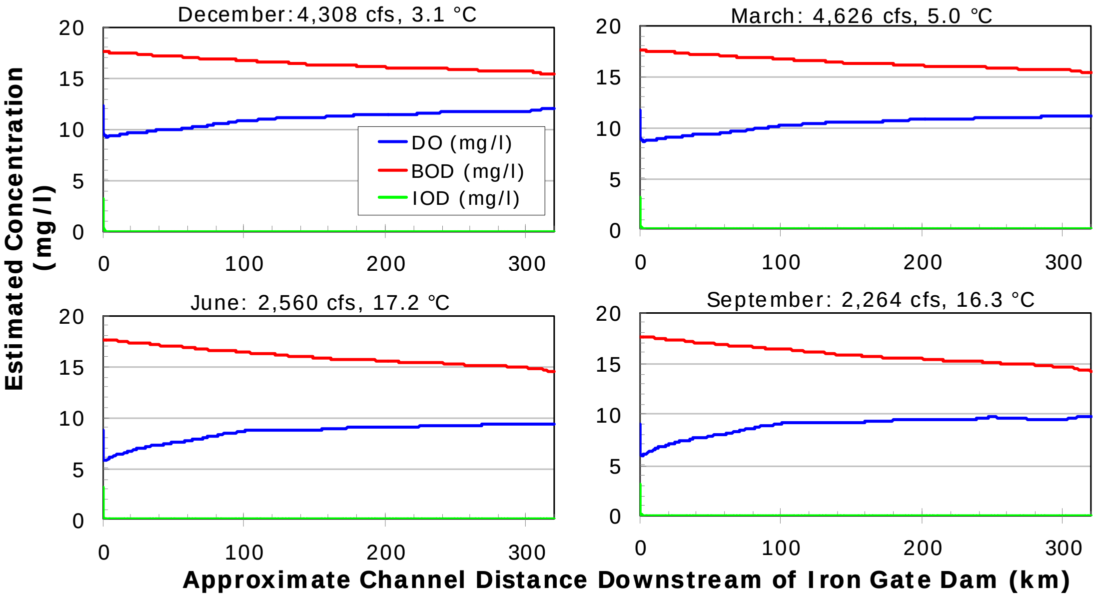

Figure 9. Estimated DO, BOD, and IOD (mg/L) downstream of Iron Gate Dam for Median Hydrology (WY 1976) and a base case of 5,000 mg/L SSC for December, March, June, and September reservoir drawdown start dates.

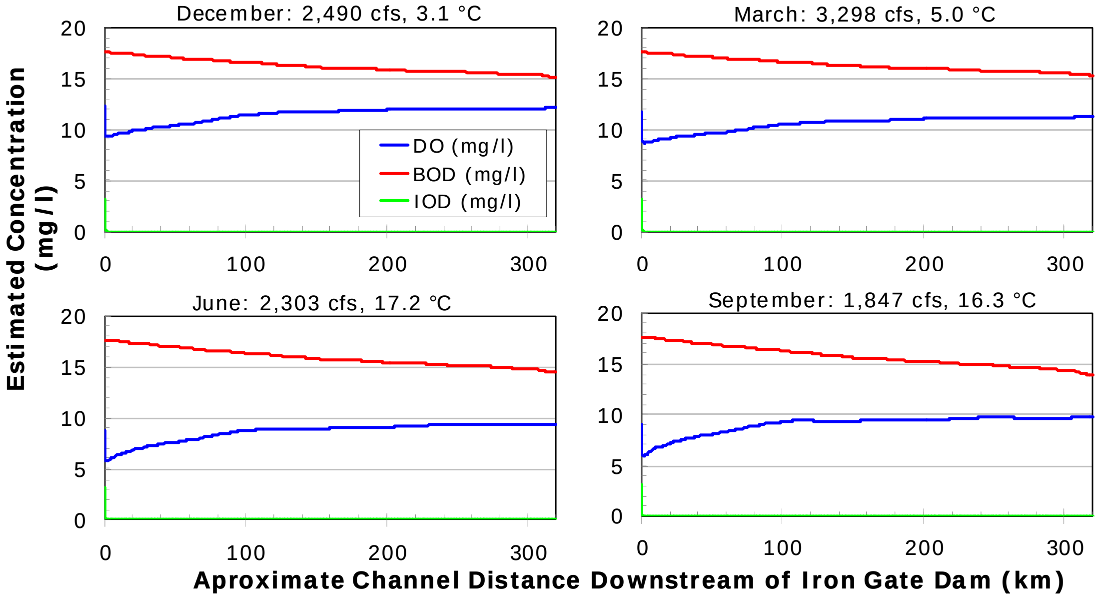

Figure 10. Estimated DO, BOD, and IOD (mg/L) downstream of Iron Gate Dam for Typical Dry Hydrology (WY 2001) and a base case of 5,000 mg/L SSC for December, March, June, and September reservoir drawdown start dates.

information. Although represented as constant values between each node, the roughly exponential decay model applies for the length of each segment. As described in previous, we have also qualified the interpretation of the results as within 10 km of model predictions.

Under the base case, model results indicate that minimum DO downstream of Iron Gate Dam would range approximately 5.8–9.3 mg/L for all water year types considered (i.e., typical wet, median, typical dry) and for the four months (seasons) modeled (Table 4). Therefore, DO concentrations downstream of Iron Gate Dam would remain greater than 5 mg/L, the minimum acceptable DO concentration for warm freshwater, saline, and marine habitats (NCRWQCB 2006). This concentration would occur within the first 10 km downstream of Iron Gate Dam regardless of season. Note that 5 mg/L is lower than the amended Basin Plan Klamath River specific water quality objectives, which generally range from 6–11 mg/L and are based on percent saturation (NCRWQCB 2010). However, 5 mg/L represents a DO value below which short-term fish effects are likely to be acute and may cause mortality.

3.3 Parameter Sensitivity Analysis

Parameter sensitivity analyses were conducted to examine the potential variations in predicted DO with variations in model parameters. The analyses were performed using the base case hydrology (i.e., median water year type [WY1976]) and assumed drawdown month (i.e., December) while varying one other parameter (i.e., SSC, IOD rate, BOD rate, reaeration, SOD, water temperature, and background DO) at a time. For ease of comparison, recovery to 10 mg/L DO is used to gage model sensitivity within a given parameter.

3.3.1 Sensitivity model run 1—suspended sediment concentration

Depending primarily upon the selected date for reservoir drawdown as well as modeled seasonal hydrology, Greimann et al. (2011) identified a range of suspended sediment levels of approximately 1,000–13,000 mg/L SSC immediately downstream of Iron Gate Dam in the first 2–3 months following dam removal, falling below 100 mg/L within 5–7 months, and at or below 10 mg/L within 1 year (more for the Typical Dry water year type). Because of the relatively large amounts of un-oxidized mineral and organic matter in the reservoir sediments (Section 3.1), variations in SSC may result in large changes in IOD, BOD, and DO in the Klamath River following dam removal. To illustrate the effect of changing the levels of suspended sediment on DO, Figure 11 shows longitudinal DO profiles from scaled IOD and BOD corresponding to a series of hypothetical suspended sediment levels (100, 1,000, 5,000, and 15,000 mg/L) for average December flows and water temperatures assuming median hydrology (WY1976). As with the base case, DO was assumed to be at 100% saturation immediately upstream of Iron Gate Dam.

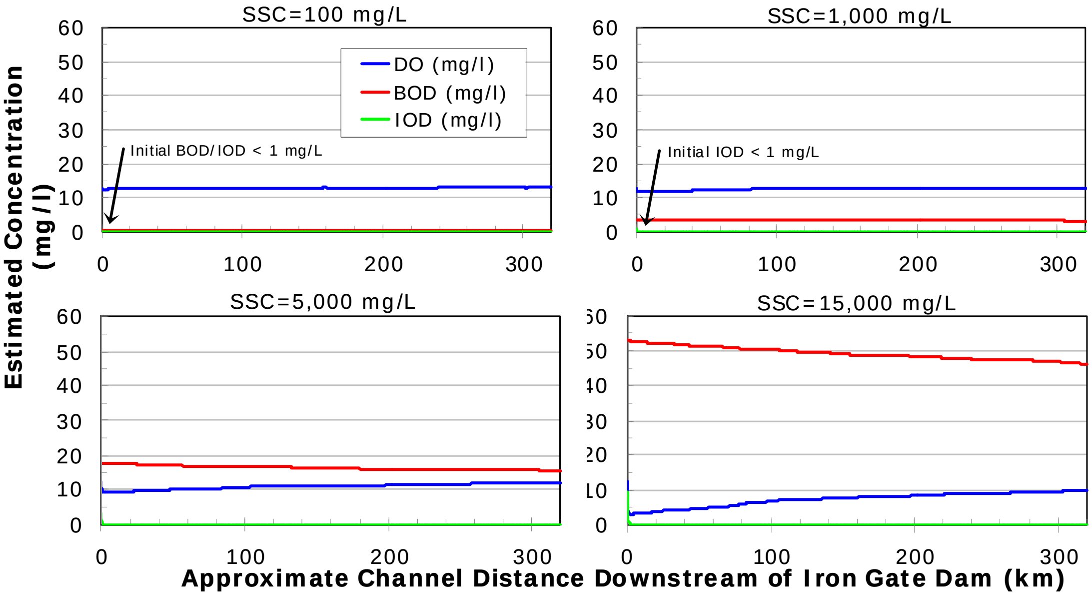

Figure 11. Estimated DO, BOD, and IOD downstream of Iron Gate Dam corresponding to Median Hydrology (WY 1976) for December and using a range of hypothetical suspended sediment concentrations (SSC).

Overall, minimum DO levels are at or above 10 mg/L for all but the highest SSC level of 15,000 mg/L, which results in a minimum DO of approximately 3 mg/L immediately downstream of Iron Gate Dam and recovery to 10 mg/L by approximately 240 km (RM 41) downstream of the dam due to channel reaeration. Since the final decision regarding the preferred dam removal method and timing may involve conditions other than the wintertime cold water and high flows modeled here, Section 3.3.6 examines model sensitivity with respect to water temperature in order to capture conditions that would occur at other times of year.

3.3.2 Sensitivity model run 2—initial oxygen demand rate

Due to variable amounts and rates of surficial oxidation of sulfide minerals, it is expected that the IOD associated with the existing reservoir sediment deposits will be heterogeneously distributed. Although Table 4 shows a fairly narrow range of fitted IOD decay rates (339–399 d^{-1}) from the laboratory sediment incubations conducted for this study, it is therefore possible, if not likely, that *in situ* IOD will be expressed as DO depletion above or below the empirically determined rates. Figures 12 and 13 show the effect of a ten-fold increase or decrease in the laboratory-determined IOD rate constant upon DO in the lower Klamath River using the base case conditions presented in Section 3.2. The 10-fold sensitivity test indicates that although IOD rates greater than those determined in this study would result in more rapid exertion of IOD in the river immediately downstream of Iron Gate Dam, differences in the approximate location of the DO minimum are minor (Figure 13). Further, since overall IOD is relatively low compared to BOD (Table 3), it is unlikely that deviations from the fitted IOD rate (k_i) would result in large changes in minimum DO than those shown for the Base Case.

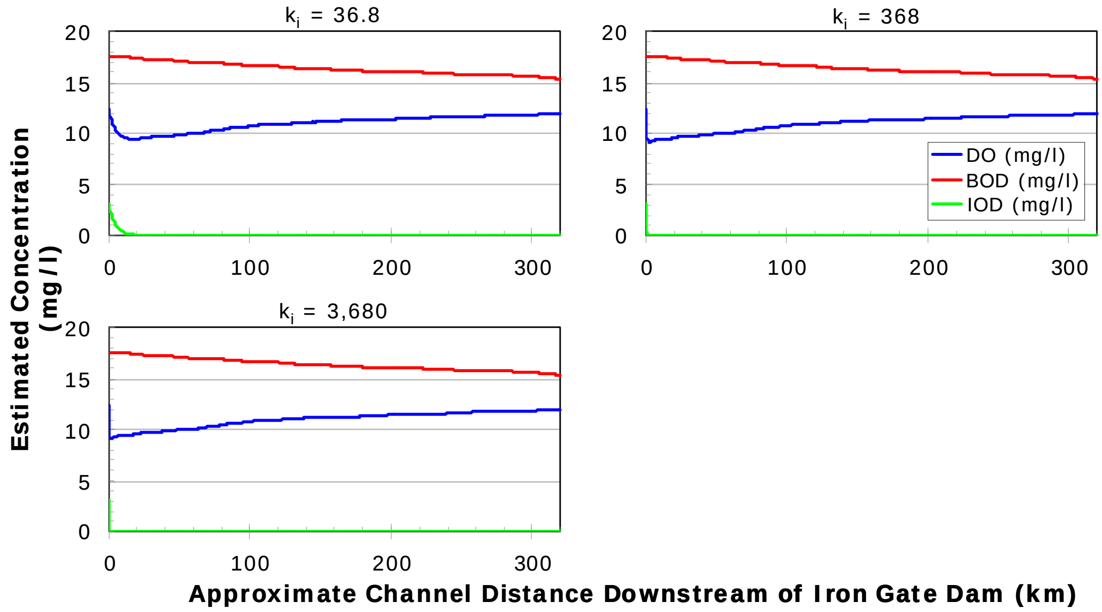

Figure 12. Estimated DO, BOD, and IOD downstream of Iron Gate Dam corresponding to Median Hydrology (WY 1976) for December and using a range of hypothetical IOD rate constants (k_i) for the base case of 5,000 mg/L suspended sediments. ODu/SCC remains constant at 6.31x10^{-4} mg O/mg dry wt (see Table 3).

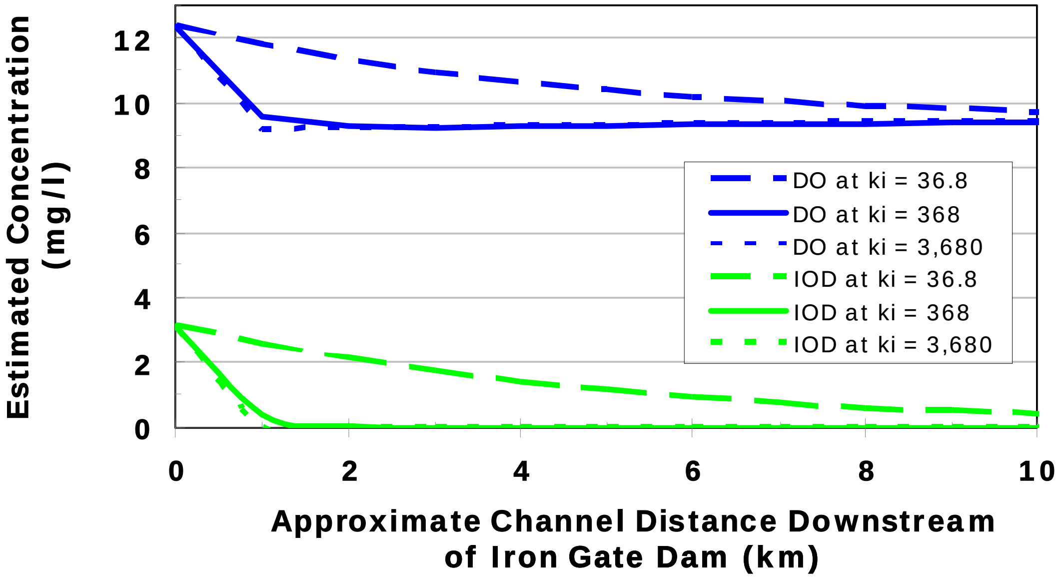

Figure 13. Estimated DO and IOD for the first ten kilometers (10 km) downstream of Iron Gate Dam corresponding to Median Hydrology (WY 1976) for December and using a range of hypothetical IOD rate constants (k_i) for the base case of 5,000 mg/L suspended sediments. ODu/SCC remains constant at 6.31x10^{-4} mg O/mg dry wt (see Table 3).

3.3.3 Sensitivity model run 3—biological oxygen demand rate

The potential for differences in carbon and nitrogen content of the existing reservoir sediment deposits may result in considerable heterogeneity of BOD rates following dam removal. Further, it may be that the density of highly oxygen demanding bacteria (i.e., obligate aerobes) within the sediment profile will be relatively low, resulting in actual rates at or below those observed in the laboratory incubations conducted for this study (Table 3). Figures 14 and 15 show the effect of a ten-fold increase or decrease in observed BOD decay rates upon DO in the lower Klamath River following dam removal. Although BOD rates greater than those empirically determined in this study would result in more rapid exertion of BOD in the river downstream of Iron Gate Dam, Figure 14 shows that for the Base Case minimum DO levels near 6-7 mg/L would be reached only at the highest BOD decay rate examined (0.884 d^{-1}).

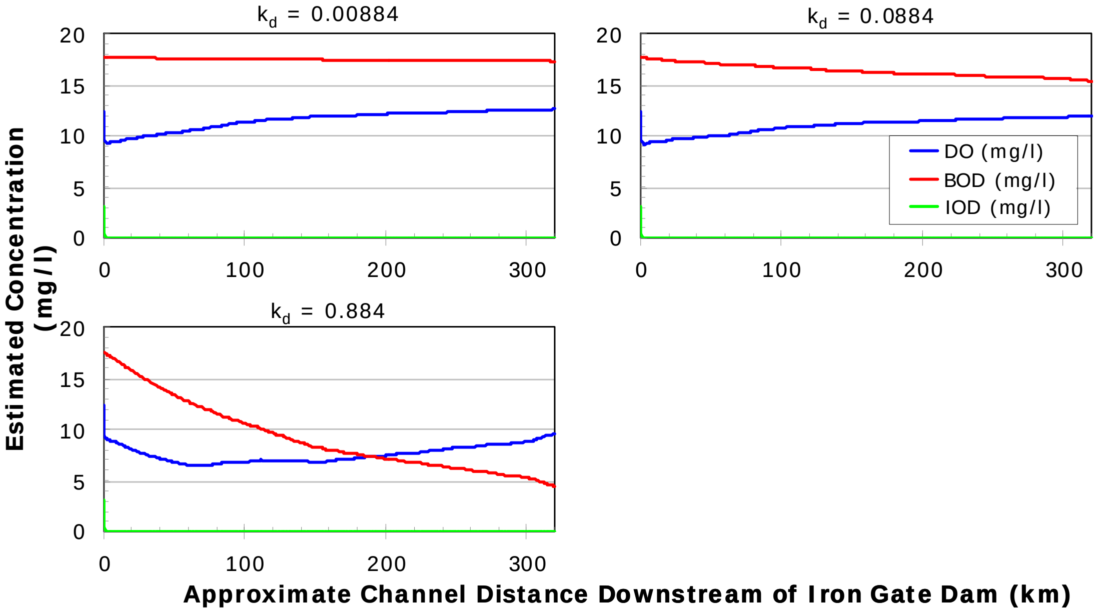

Figure 14. Estimated DO, BOD, and IOD downstream of Iron Gate Dam corresponding to Median Hydrology (WY 1976) for December and using a range of hypothetical BOD rate constants (k_d) for the base case of 5,000 mg/L suspended sediments. ODu/SCC remains constant at 6.31×10^{-4} mg O/mg dry wt (see Table 3).

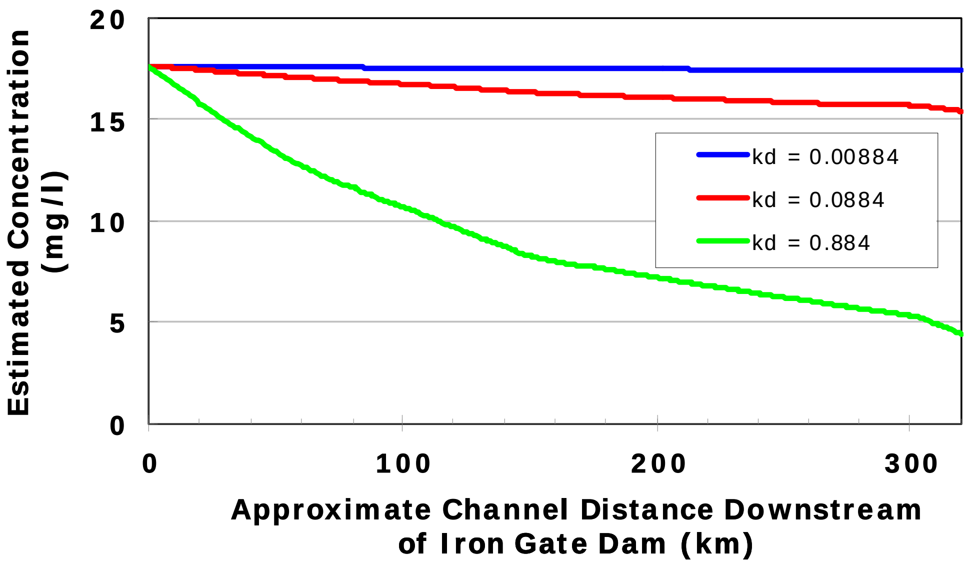

Figure 15. Estimated BOD downstream of Iron Gate Dam corresponding to Median Hydrology (WY 1976) for December and using a range of hypothetical BOD rate constants (k_d) for the base case of 5,000 mg/L suspended sediments. ODu/SCC remains constant at $6.31x10^{-4}$ mg O/mg dry wt (see Table 3).

3.3.4 Sensitivity model run 4—channel reaeration

In addition to background DO, the rate of channel reaeration will determine how quickly IOD and BOD are met in the river downstream of Iron Gate Dam. The empirical reaeration models used for model development vary in their approach (Section 2.2), and thus their predictive capacity. In order to evaluate the effect of alternative estimates of channel reaeration, Figure 16 shows modeled DO downstream of Iron Gate Dam using each of the three reaeration models considered for this study, with corresponding k_a values calculated using the base case of 5,000 mg/L SSC and assuming average December water temperature and median water-year hydrology (WY1976). For Sensitivity Model Run 4, we assumed 60% DO saturation, which corresponds to 7.4 mg/L at 3.1°C (37.6ºF) and an elevation of 707 m (2,320 ft) (i.e., just downstream of Iron Gate Dam), to ensure that a sufficient reaeration would be required and the efficacy of the channel reaeration models can be clearly demonstrated.

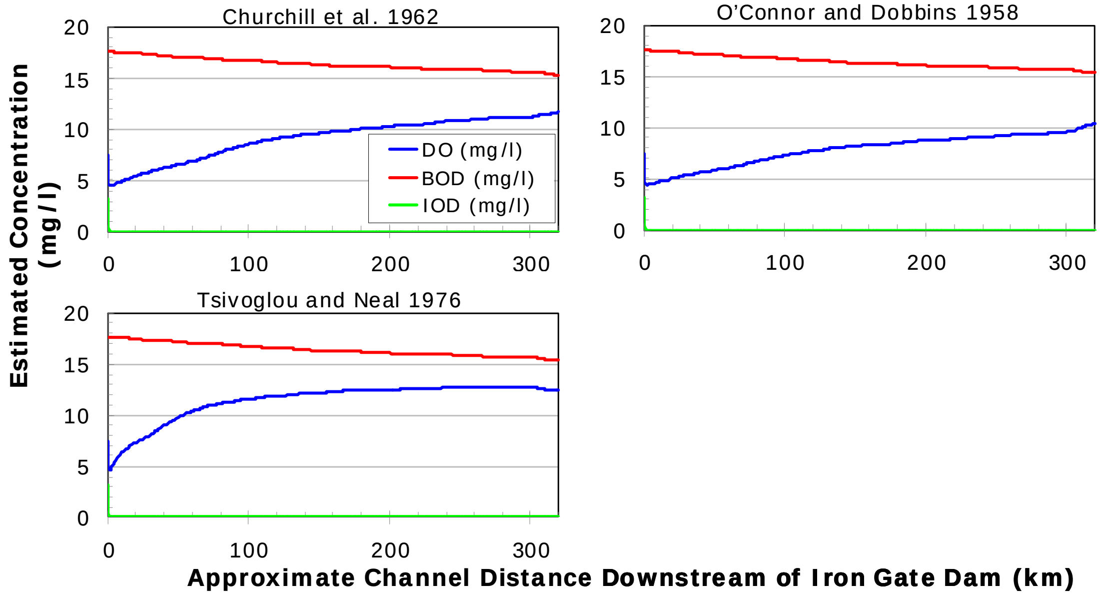

Figure 16. Estimated DO, BOD, and IOD downstream of Iron Gate Dam corresponding to Median Hydrology (WY 1976) for December and using a background DO at 60% saturation for three reaeration models and the base case of 5,000 mg/L SSC.

As shown in Figure 16, recovery to 10 mg/L occurs within approximately 160 km (RM 91) downstream of the dam for the Churchill et al. (1962) relationship, 300 km (RM 4) for O'Connor and Dobbins (1958), and 75 km (RM 144) for Tsivoglou and Neal (1976). Thus, it is apparent that the three empirical models result in quite different rates of DO increase with increasing distance downstream. Although the O'Connor and Dobbins relationship appears to be the most conservative relationship for the modeled DO conditions, Figure 6 indicates that this model did not capture longitudinal variations in the *in situ* reaeration rate estimates made in the Ward and Armstrong (2010) study.

3.3.5 Sensitivity model run 5—stream-bed sediment oxygen demand

Although *in situ* estimates of SOD rates (k_b) were on the order of 0.6 g-O_2/m^2/d, typical values based on laboratory experiments can range from 0.5–2.0 g-O_2/m^2-d (Thomann 1972). In the Klamath River Basin, SOD rates measured by Doyle and Lynch (2005) in Lake Ewauna and the Klamath River range up to 3.0 mg/L. In order to examine the effect of variations in the *in situ* sediment oxygen demand, Sensitivity Model Run 5 varies SOD using the base case of 5,000 mg/L SSC and assuming average December water temperature and median water-year hydrology (WY 1976). Figure 17 shows longitudinal DO profiles for a series of assumed sediment oxygen demand rates ranging an order of magnitude (0.3–3 g-O_2/m^2-d). Overall, model results were shown to be insensitive to the selected range of SOD rates, suggesting that this factor may be of less importance than others reviewed.

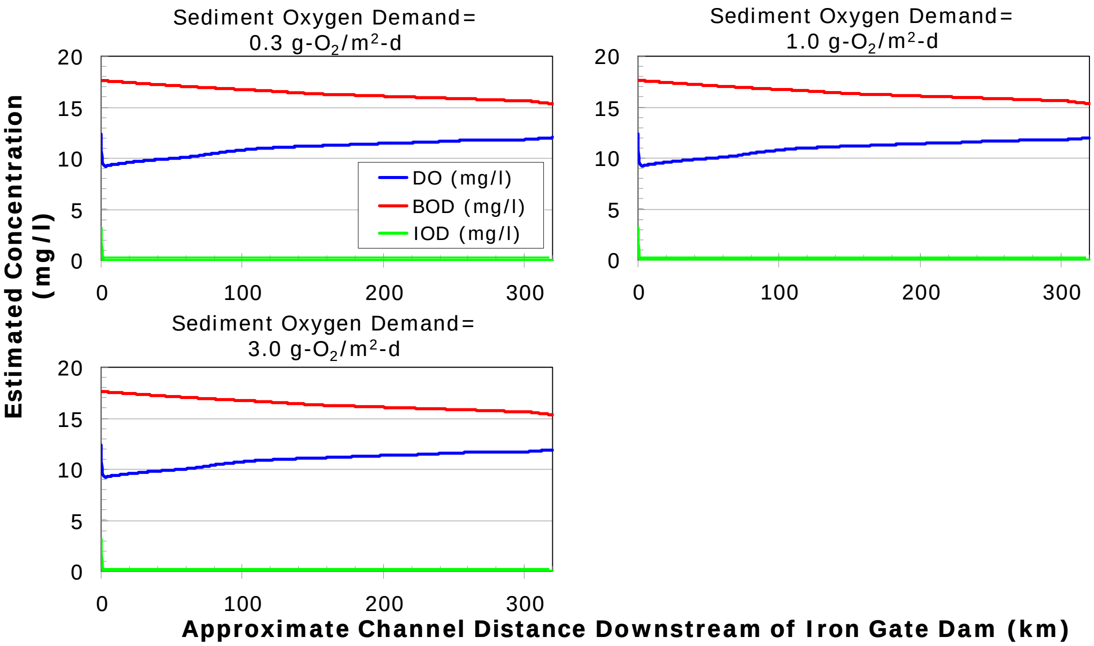

Figure 17. Estimated DO, BOD, and IOD downstream of Iron Gate Dam corresponding to Median Hydrology (WY 1976) for December and using a range of artificial sediment oxygen demand rates for the base case of 5,000 mg/L suspended sediments.

3.3.6 Sensitivity model run 6—water temperature

As stated in Section 2.3.4, the rates of biological and chemical reactions as well as DO solubility are a function of water temperature. To examine the potential effects of water temperature variations for dam removal alternatives occurring in colder or warmer times of year, the spreadsheet model was run for both low and high water temperatures using the base case of 5,000 mg/L SSC and assuming average December water temperature and median water-year hydrology (WY1976). Figure 18 shows longitudinal DO profiles for a series of assumed water temperatures (2, 10, 15, and 20°C [35.6, 50, 59, and 68ºF]) to examine a hypothetical circumstance of higher water temperatures, and recognizing that the particular flows and temperatures and flows at other times of year would be different than those used to demonstrate model sensitivity.

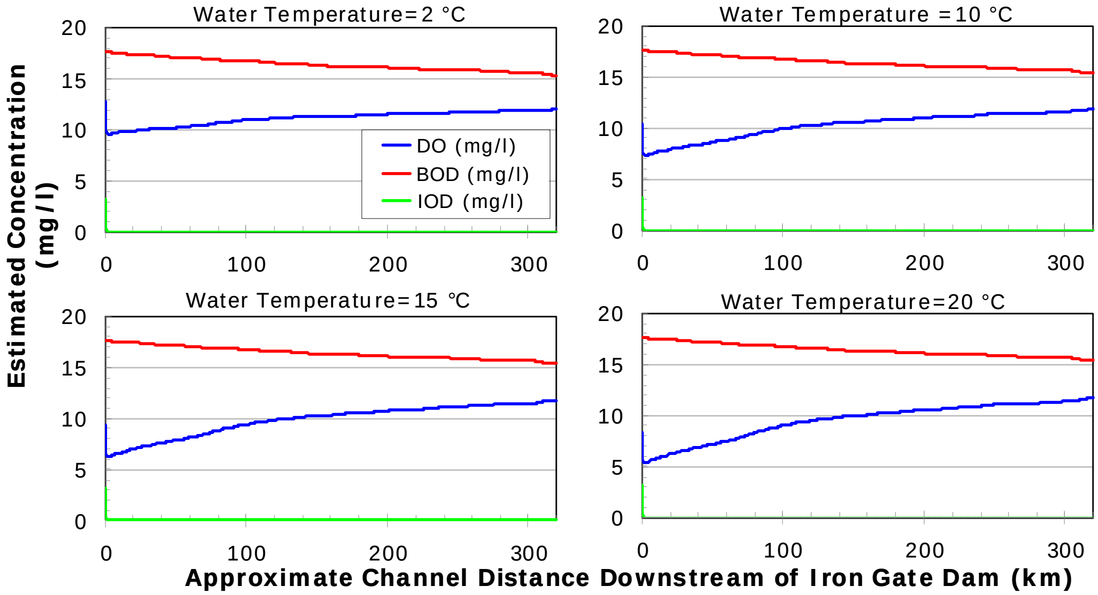

Figure 18. Estimated DO, BOD, and IOD (mg/L) downstream of Iron Gate Dam corresponding to Median Hydrology (WY 1976) for December and using a range of artificial water temperatures to demonstrate model sensitivity for the base case of 5,000 mg/L SSC.

Overall, Figure 18 shows moderate model sensitivity to ambient water temperatures, with minimum DO below downstream of Iron Gate Dam ranging from 5.3 mg/L to 9.6 mg/L between 20°C (68°F) and 2°C (35.6°F), respectively. Minimum DO levels for the 15°C (59°F) and 20°C (68°F) temperature simulations recovered to 10 mg/L approximately 100 km and 140 km downstream of Iron Gate Dam (RM 177 and RM 168, respectively).

3.3.7 Sensitivity model run 7—background DO

Dissolved oxygen depletion from the water column following reservoir drawdown will depend upon the amount of DO arriving from upstream locations. This means that background DO levels will be affected by both oxidation of naturally occurring organic matter in the water column as well as oxidation of organic matter in suspended sediments mobilized during reservoir drawdown. Native water collected with the sediment core samples used for this study generally possessed BOD less than 3 mg/L, similar to the IOD and BOD associated with the sediments themselves (Appendix B), suggesting that background DO levels may be below 100% saturation. To examine the sensitivity of the model to background DO, the spreadsheet model was run for a range of DO assumptions immediately upstream of Iron Gate Dam ("background DO") using the base case of 5,000 mg/L SSC and assuming average December water temperature and median water-year hydrology (WY1976). Figure 19 illustrates the effect of the range of assumed background DO values (0–100% saturation) on modeled DO downstream of Iron Gate Dam.

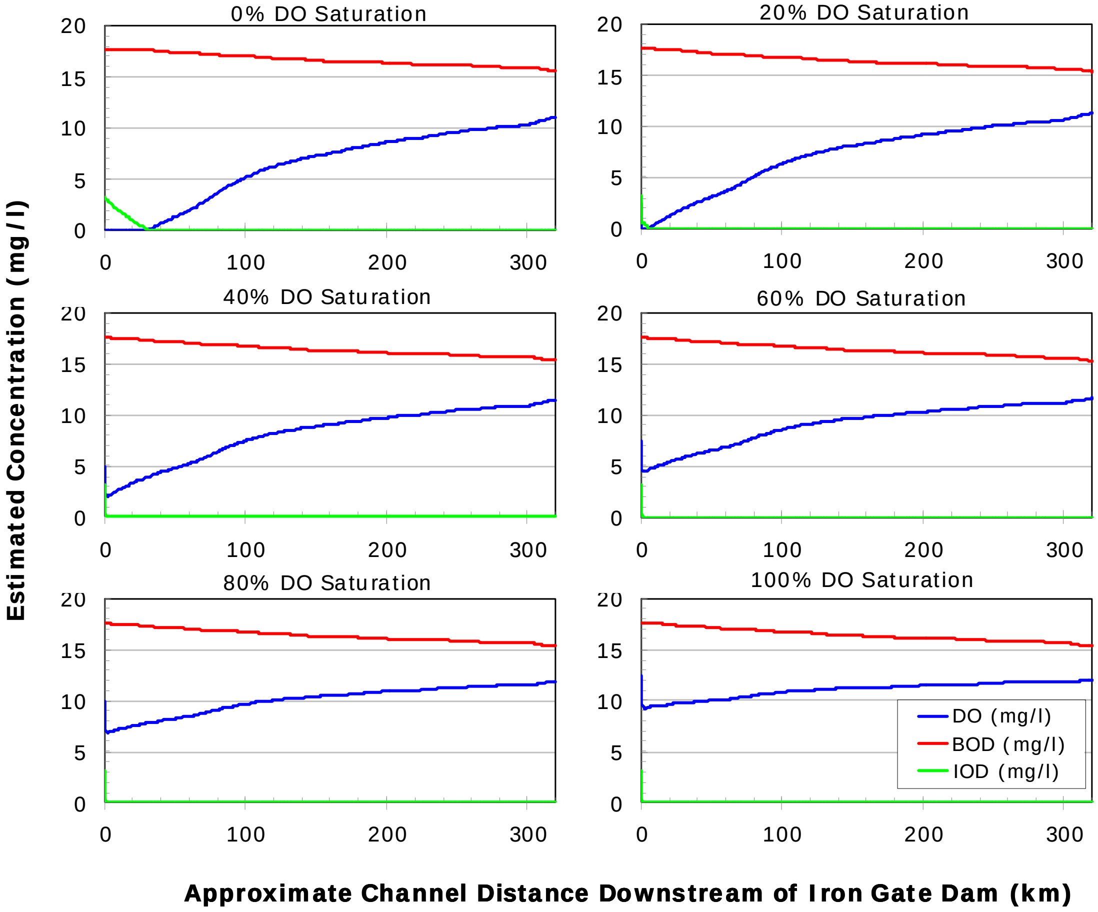

Figure 19. Estimated DO, BOD, and IOD (mg/L) downstream of Iron Gate Dam corresponding to Median Hydrology (WY 1976) and water temperature for December and using an artificial range of background DO (% saturation) to demonstrate model sensitivity for the base case of 5,000 mg/L.

Results indicate that the DO spreadsheet model is highly sensitive to background DO; for the lowest background DO (0%), DO in the downstream river does not rise above zero for 30 km downstream of Iron Gate Dam and does not rise above 10 mg/L for a distance of 250 km. DO remains near or above 10 mg/L throughout the river for background DO values of 80% and 100%, with intermediate lengths of hypoxic conditions for the remaining background DO conditions (Figure 19).

Table 5. Estimates of DO downstream of Iron Gate Dam corresponding to Median Hydrology (WY 1976) and water temperature for December and using an artificial range of background DO (% saturation) for the base case of 5,000 mg/L suspended sediments (IOD = 3.15 mg/L, BOD = 17.61 mg/L).

Initial Dissolved Oxygen Saturation	Initial DO	Minimum DO downstream of Iron Gate Dam	Approximate Location of Minimum DO		Approximate Location at which DO returns to 10 mg/L	
(%)	(mg/L)	(mg/L)	(km)	RM	(km)[2]	RM
0%	0.000	0.00	0	190.1	276	18.6
20%	2.471	0.00	1	189.5	247	36.6
40%	4.942	1.99	2	188.9	220	53.4
60%	7.414	4.42	2	188.9	176	80.7
80%	9.885	6.85	2	188.9	116	118
100% [1]	12.356	9.26	3	188.2	0	190.1

[1] Base case (see Section 3.2).
[2] Distance downstream of Iron Gate Dam.

4 DISCUSSION

Based on results of the DO spreadsheet model sensitivity analysis, it is apparent that short-term DO levels in the Klamath River following reservoir drawdown and mobilization of sediment deposits will be most strongly affected by background DO conditions, SSC, and water temperature. Assumptions regarding the rates of channel reaeration were also apparent, with the Churchill et al. (1962) and Tsivoglou and Neal (1976) relationships indicating higher reaeration rates closer to *in situ* measurements conducted by Ward and Armstrong (2010), particularly in the higher gradient reaches of the Klamath River where more mixing energy is available.

Although the base case and sensitivity model run results are reported by kilometer and tenth of a river mile (see Tables 4 and 5), the resolution of model output for actual model runs is not expected to possess this level of precision. Since uncertainty estimates were only available for oxygen demand (IOD, BOD) and associated decay rate constants (k_i, k_d), propagation of uncertainties to develop a prediction interval corresponding to a specific uncertainty for downstream DO and locations of minimum DO was not feasible. Although application of plausible ranges of several parameters found in the literature could be carried out, it is unlikely that this uncertainty range is relevant to the conditions modeled here. Thus, *approximate* locations of minimum DO or locations at which DO returns to a particular benchmark are reported for the base case and sensitivity model runs and, in general, the interpretation of results from actual model runs should be assumed to be within 10 km of model predictions.

Although a number of project alternatives are still in development as part of the EIS/EIR process, Appendix A presents results of the analyses of several preliminary alternatives using the spreadsheet model under assumptions regarding SSC, river flows, water temperatures, and background DO. Based on these preliminary analyses, the Klamath River could experience hypoxia for several river miles downstream of Iron Gate Dam in the initial days and weeks following dam removal. Tributary dilution along with channel reaeration are the primary mechanisms for IOD and BOD removal from the water column, as improvements in DO from reaeration may occur at a different rate than for SSC dilution. Potential short-term impacts to biota from low DO should be considered alongside analyses of the biological impacts of corresponding SSC levels for particular dam removal scenarios.

In the longer term (i.e., beyond the initial days and weeks following dam removal), oxidation of sediments remaining on exposed reservoir terraces is anticipated to occur once the water has been drawn down and the sediments are exposed to air. Thus, oxygen demand is expected to be greatest during the initial period of reservoir drawdown, and it will be reduced, if not eliminated, during subsequent months and years. Even if DO concentrations are relatively low in pore-water draining from the terraces, the long-term impact on the Klamath River would likely be minimal due to dilution by the river itself and, even further, by dilution from downstream tributaries. Any sediment that is mobilized from exposed reservoir terraces during future storm events should have already been mostly oxidized; restoration activities aimed at stabilizing the surface of the sediment on reservoir terraces and minimizing erosion (O'Meara et al. 2010) will further decrease the likelihood that organic-rich sediments will be transported downstream and decrease DO in the river in the long-term. While the DO modeling effort does not address nutrients transported along with the sediments, a decrease in erosion due to restoration activities would also be expected to decrease nutrient transport to downstream reaches of the Klamath River.

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Appendices

Appendix A

Preliminary Results of Reservoir Drawdown Scenarios 2, 7, and 8 for Full Facilities Removal of Four Dams on the Klamath River (Proposed Action)

A.1 INTRODUCTION

As example applications of the DO spreadsheet model, results of several reservoir drawdown scenarios considered in preliminary analyses of the Full Facilities Removal of Four Dams on the Klamath River (Proposed Action) in the Administrative Draft of the EIS/EIR are provided in the sections below. Modeled drawdown scenarios include Scenario 2, Scenario 7, and Scenario 8, as defined in Greimann et al. (2011). Model parameters used in DO spreadsheet model for the preliminary analyses varied slightly between model runs for the three scenarios due to ongoing model development and investigation of drawdown scenarios by the Lead Agencies; values that were used are presented in Table A-1. As described in Section 4 of the main report, the interpretation of results from actual model runs considers predictions to be within roughly 10 km of model output.

Table A-1. Model parameters used in reservoir drawdown scenario model runs.

Model parameter		Scenario 2	Scenario 7	Scenario 8
Stream reaeration model		Churchill	Churchill	Churchill
Stream reaeration rate (k_a)	Theta (θ)	1.02	1.02	1.02
Stream-bed sediment oxygen demand (k_b)	Value	0.6	0.6	0.6
	Theta (θ)	1.08	1.08	1.08
IOD rate constant (k_i)	Value	368.1	368.1	368.1
	Theta (θ)	1.01	1.01	1.01
BOD rate constant (k_d)[1]	Value	0.332	0.088	0.088
	Theta (θ)	1.01	1.01	1.01
BOD settling rate (k_s)	Value	0	0	0
	Theta (θ)	1	1	1
Background dissolved oxygen (% Saturation)[2]		100%	80%	70% November, 80% December–April
2010 IOD/SSC (combined) (mg O_2)/(mg dry wt)		6.31×10^{-4}	6.31×10^{-4}	6.31×10^{-4}
2009 BOD/SSC (combined) (mg O_2)/(mg dry wt)[3]		2.17×10^{-3}	3.52×10^{-3}	3.52×10^{-3}

[1] Scenario 2 k_d based on earlier estimate of 5-day oxygen demand tests (excluding NBOD). Updated k_d values using 30-day oxygen demand was used for drawdown scenarios 7 and 8.

[2] Scenario 2 background DO % saturation based upon professional judgment during preliminary analyses. Scenario 7 and 8 background DO % saturation values based on typical monthly values using raw data from http://www.pacificorp.com/es/hydro/hl/kr.html# (PacifiCorp 2009).

[3] Scenario 2 ODu for BOD based on earlier estimate from 5-day oxygen demand tests (excluding NBOD). Updated ODu values using 30-day oxygen demand was used for drawdown scenarios 7 and 8.

A.2 DRAWDOWN SCENARIO MODEL RUNS

A.2.1 Drawdown Scenario 2

In November 2010, the DO spreadsheet model was run for Drawdown Scenario 2, a preliminary reservoir drawdown scenario developed by the Lead Agencies that assumes drawdown begins on November 15, 2019 (Greimann et al. 2010). As an early model run, background DO was assumed to be at 100% saturation for Drawdown Scenario 2. Later model runs considered existing data and set the background DO% saturation based on existing data (see also footnote in Table A-1).

Modeled dates and flows correspond to the predicted peak SSC for each month based on USBR model output (Greimann et al. 2011). Model results indicate that IOD downstream of Iron Gate Dam under Drawdown Scenario 2 would range 0.01–5.7 mg/L and BOD would range 0.03–19.5 mg/L for all water year types considered (i.e., typical wet, median, typical dry) and for all five months following drawdown (Table A-2). The highest predicted IOD and BOD would occur during the first four weeks following drawdown regardless of water year type. Overall, under Drawdown Scenario 2, predicted DO minimum values would occur within 1–3 km (RM 188.2–189.5) downstream of Iron Gate Dam. Recovery to 5 mg/L, the generally applicable minimum acceptable DO concentration for warm water habitat (NCRWQCB 2006), would occur within a distance of 19–67 km (RM 148.5–178.3) downstream of the Klamath Hydropower Reach, for all water year types considered and for all six months following drawdown (Table A-3). Modeled dissolved oxygen concentrations immediately downstream of Iron Gate Dam would also meet the recently amended minimum acceptable site-specific DO concentrations identified for the Klamath River from Iron Gate Dam to the Klamath River estuary for all modeled months except November, when minimum modeled concentrations within the first 10 km downstream of the dam would be 6.3 mg/L, or less than the 9.6–10.1 mg/L required by the Basin Plan (NCRWQCB 2010).

Table A-2. Estimated IOD and BOD by month for modeled flow and suspended sediment concentrations downstream of Iron Gate Dam for drawdown Scenario 2 under the Proposed Action.

Date	Avg. monthly temperature (deg C)[1]	DO (100% Saturation)[2]	Flow (cfs)[3]	Flow (cms)	SSC (mg/L)[4]	IOD (mg/L)	BOD (mg/L)
Typical Wet Hydrology (WY1984 Conditions Assumed)							
11/26/2019	7.0	11.2	4,224	119.6	7,756	4.9	16.9
12/25/2019	3.1	12.4	6,588	186.5	839	0.5	1.8
2/15/2020	2.6	12.6	3,844	108.8	2,620	1.7	5.7
3/1/2020	5.0	11.8	4,544	128.7	75	0.05	0.2
4/1/2020	8.5	10.8	7,098	201.0	15	0.01	0.03
Median Hydrology (WY1976 Conditions Assumed)							
11/27/2019	7.0	11.2	2,012	57.0	8,974	5.7	19.5
12/29/2019	3.1	12.4	1,419	40.2	1,727	1.1	3.8
2/10/2020	2.6	12.6	3,102	87.8	2,886	1.8	6.3
3/1/2020	5.0	11.8	2,093	59.3	652	0.4	1.4
4/1/2020	8.5	10.8	554	15.7	34	0.02	0.07
Typical Dry Hydrology (WY2001 Conditions Assumed)							
11/30/2019	7.0	11.2	1,447	41.0	8,436	5.3	18.3
12/16/2019	3.1	12.4	1,576	44.6	1,900	1.2	4.1
2/9/2020	2.6	12.6	742	21.0	3,688	2.3	8.0
3/1/2020	5.0	11.8	653	18.5	434	0.3	0.9
4/1/2020	8.5	10.8	2,049	58.0	542	0.3	1.2

[1] Raw daily water temperature data from http://www.pacificorp.com/es/hydro/hl/kr.html# (PacifiCorp 2009)

[2] Background DO downstream of Iron Gate Dam calculated as 100% saturation using average monthly water temperature, salinity = 0 ppt, and elevation = 707 m (2,320 ft).

[3] Predicted daily flow values from USBR hydrologic model output (Greimann et al. 2011). Daily flow values correspond to the peak SSC for each month.

[4] Predicted peak SSC by month from USBR model output under Drawdown Scenario 2, Proposed Action (Greimann et al. 2011).

Table A-3. Location of minimum dissolved oxygen and locations at which dissolved oxygen returns to 5 mg/L downstream of Iron Gate Dam at selected dates for drawdown Scenario 2 under the Proposed Action.

Date	Boundary conditions at Iron Gate Dam			Spreadsheet model output				
	Background DO (100% saturation)[1]	IOD	BOD	Minimum dissolved oxygen	Approximate location of minimum dissolved oxygen		Approximate location at which dissolved oxygen returns to 5 mg/L[2]	
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(km)[3]	RM	(km)[3]	RM
Typical Wet Hydrology (WY1984 Conditions Assumed)								
11/26/2019	11.2	4.9	16.9	6.3	3	188	-	190
12/25/2019	12.4	0.5	1.8	11.9	3	188	-	190
2/15/2020	12.6	1.7	5.7	11.0	3	188	-	190
3/1/2020	11.8	0.05	0.2	11..8	1	190	-	190
4/1/2020	10.8	0.01	0.03	10.8	1	190	-	190
Median Hydrology (WY1976 Conditions Assumed)								
11/27/2019	11.2	5.7	19.5	5.6	2	189	-	190
12/29/2019	12.4	1.1	3.8	11.4	2	189	-	190
2/10/2020	12.6	1.8	6.3	10.8	2	189	-	190
3/1/2020	11.8	0.4	1.4	11.4	1	190	-	190
4/1/2020	10.8	0.02	0.07	10.8	-	190	-	190
Typical Dry Hydrology (WY2001 Conditions Assumed)								
11/30/2019	11.2	5.3	18.3	6.0	2	189	-	190
12/16/2019	12.4	1.2	4.1	11.2	2	189	-	190
2/9/2020	12.6	2.3	8.0	10.3	1	190	-	190
3/1/2020	11.8	0.3	0.9	11.6	1	190	-	190
4/1/2020	10.8	0.3	1.2	10.5	1	190	-	190

[1] Initial DO downstream of Iron Gate Dam calculated for 100% saturation using average monthly water temperature, salinity = 0 ppt, and elevation = 707 m (2,320 ft). Raw daily water temperature data from http://www.pacificorp.com/es/hydro/hl/kr.html# (PacifiCorp 2009).

[2] Minimum acceptable DO concentration for warm water habitat (NCRWQCB 2006).

[3] Distance downstream of Iron Gate Dam.

A.2.2 Drawdown Scenario 7

In December 2010, the DO spreadsheet model was run for Drawdown Scenario 7, a preliminary reservoir drawdown scenario developed by the Lead Agencies that assumes drawdown begins on January 1, 2020 (Greimann et al. 2011). Background DO was assumed to be at 80% saturation based on typical monthly values using raw data from http://www.pacificorp.com/es/hydro/hl/kr.html# (PacifiCorp 2009). Modeled dates and flows correspond to the predicted peak SSC for each month based on USBR model output (Greimann et al. 2011). Model results indicate that IOD downstream of Iron Gate Dam would range 0–4 mg/L and BOD would range 0.2–22.5 mg/L for all water year types considered (i.e., typical wet, median, typical dry) and for all six months following drawdown (

Table A-4). DO concentrations downstream of Iron Gate Dam would remain greater than 5 mg/L, the generally applicable minimum acceptable DO concentration for warm water habitat (NCRWQCB 2006) (Table A-5), but they would not meet the recently amended minimum acceptable site-specific DO concentrations identified for the Klamath River immediately downstream of Iron Gate Dam for all modeled months, which range from 6.5–10.8 mg/L (NCRWQCB 2010).

The highest predicted oxygen demand levels (i.e., IOD and BOD) would occur during the first four weeks following drawdown for typical wet (WY1984) and median (WY1976) hydrology, and within six weeks for typical dry hydrology (WY2001). However, because cold water temperatures in January, February, and March decrease the rate of microbial metabolism of organic matter contained within mobilized sediments (i.e., the rate is temperature dependent) and background DO concentration (i.e., DO entering the model reach) at saturation is relatively greater in cold water, the river capacity to assimilate the BOD and IOD is also greatest immediately following dam removal. This assimilative capacity decreases with time due to changes in DO saturation with seasonally increasing water temperatures; the predicted minimum DO concentration for the six months following dam removal occurs as late as May/June for typical wet hydrology, in February and March for median hydrology and in March for typical dry hydrology. Overall, under Drawdown Scenario 7 of the Proposed Action, predicted DO minimum values would occur within 1–3 km (RM 188–189) downstream of Iron Gate Dam.

Table A-4. Estimated IOD and BOD by month for modeled flow and suspended sediment concentrations downstream of Iron Gate Dam for drawdown Scenario 7 under the Proposed Action.

Date	Avg. monthly temperature (deg C)[1]	DO (80% saturation)[2]	Flow (cfs)[3]	Flow (cms)	SSC (mg/L)[4]	IOD (mg/L)	BOD (mg/L)
Typical Wet Hydrology (WY1984 Conditions Assumed)							
1/29/2020	3.7	9.7	8,918	253	1,303	0.8	4.6
2/8/2020	4.4	9.6	5,050	143	4,000	2.5	14.1
3/2/2020	6.7	9.0	6,186	175	2,007	1.3	7.1
4/15/2020	8.4	8.6	3,199	91	1,643	1.0	5.8
5/12/2020	17.4	7.0	3,042	86	947	0.6	3.3
6/3/2020	19.3	6.8	2,853	81	202	0.1	0.7
Median Hydrology (WY1976 Conditions Assumed)							
1/17/2020	3.7	9.7	4,833	137	3,437	2.2	12.1
2/6/2020	4.4	9.6	4,203	119	6,388	4.0	22.5
3/31/2020	6.7	9.0	477	14	3,558	2.2	12.5
4/4/2020	8.4	8.6	2,148	61	4,573	2.9	16.1
5/4/2020	17.4	7.0	2,127	60	238	0.2	0.8
6/12/2020	19.3	6.8	2,008	57	48	0.0	0.2
Typical Dry Hydrology (WY2001 Conditions Assumed)							
1/14/2020	3.7	9.7	3,991	113	5,058	3.2	17.8
2/1/2020	4.4	9.6	1,804	51	3,894	2.5	13.7
3/11/2020	6.7	9.0	647	18	5,240	3.3	18.5
4/1/2020	8.4	8.6	2,065	58	3,458	2.2	12.2
5/7/2020	17.4	7.0	1,937	55	720	0.5	2.5
6/4/2020	19.3	6.8	2,772	78	1,163	0.7	4.1

[1] Raw daily water temperature data from http://www.pacificorp.com/es/hydro/hl/kr.html# (PacifiCorp 2009)

[2] Initial DO downstream of Iron Gate Dam calculated for 80% saturation using average monthly water temperature, salinity = 0 ppt, and elevation = 707 m (2,320 ft).

[3] Predicted daily flow values from USBR hydrologic model output (Greimann et al. 2011). Daily flow values correspond to the peak suspended sediment concentration (SSC) for each month.

[4] Predicted peak suspended sediment concentration (SSC) by month from USBR model output under Drawdown Scenario 7, Proposed Action (Greimann et al. 2011).

Table A-5. Location of minimum dissolved oxygen and locations at which dissolved oxygen returns to 5 mg/L downstream of Iron Gate Dam at selected dates for drawdown Scenario 7 under the Proposed Action.

	Boundary conditions at Iron Gate Dam			Spreadsheet model output				
Date	**Background DO (80% saturation)[1]**	**IOD**	**BOD**	**Minimum dissolved oxygen**	**Approximate location of minimum dissolved oxygen**		**Approximate location at which dissolved oxygen returns to 5 mg/L[2]**	
	(mg/L)	**(mg/L)**	**(mg/L)**	**(mg/L)**	**(km)[3]**	**RM**	**(km)[3]**	**RM**
Typical Wet Hydrology (WY1984 Conditions Assumed)								
1/29/2020	9.7	0.8	4.6	9.0	3	188	-	190
2/8/2020	9.6	2.5	14.1	7.1	3	188	-	190
3/2/2020	9.0	1.3	7.1	7.8	2	189	-	190
4/15/2020	8.6	1.0	5.8	7.7	2	189	-	190
5/12/2020	7.0	0.6	3.3	6.6	1	189	-	190
6/3/2020	6.8	0.1	0.7	6.7	1	189	-	190
Median Hydrology (WY1976 Conditions Assumed)								
1/17/2020	9.7	2.2	12.1	8.8	2	189	-	190
2/6/2020	9.6	4.0	22.5	5.7	2	189	-	190
3/31/2020	9.0	2.2	12.5	7.0	1	189	-	190
4/4/2020	8.6	2.9	16.1	5.9	2	189	-	190
5/4/2020	7.0	0.2	0.8	7.0	1	189	-	190
6/12/2020	6.8	0.0	0.2	6.8	0	190	-	190
Typical Dry Hydrology (WY2001 Conditions Assumed)								
1/14/2020	9.7	3.2	17.8	6.7	2	189	-	190
2/1/2020	9.6	2.5	13.7	7.3	2	189	-	190
3/11/2020	9.0	3.3	18.5	5.9	1	189	-	190
4/1/2020	8.6	2.2	12.2	6.6	2	189	-	190
5/7/2020	7.0	0.5	2.5	6.7	1	189	-	190
6/4/2020	6.8	0.7	4.1	6.1	1	189	-	190

[1] Initial DO downstream of Iron Gate Dam calculated for 80% saturation using average monthly water temperature, salinity = 0 ppt, and elevation = 707 m (2,320 ft). Raw daily water temperature data from http://www.pacificorp.com/es/hydro/hl/kr.html# (PacifiCorp 2009).

[2] Minimum acceptable DO concentration for warm water habitat (NCRWQCB 2006).

[3] Distance downstream of Iron Gate Dam.

A.2.3 Drawdown Scenario 8

In February 2011, the DO spreadsheet model was run for Drawdown Scenario 8, the reservoir drawdown scenario developed by the Project team and incorporated into the EIS/EIR Administrative Draft (02/28/2011). Drawdown Scenario 8 is currently the preferred drawdown scenario. Drawdown Scenario 8 assumes a three-phase drawdown for Copco 1 Reservoir beginning November 1, 2019, and a single-phase drawdown for J.C. Boyle and Iron Gate reservoirs beginning January 1, 2020 (Greimann et al. 2011). Background DO was assumed to be at 80% saturation. Modeled dates and flows correspond to the predicted peak SSC for each month based on USBR model output (Greimann et al. 2011). Model results indicate that IOD downstream of Iron Gate Dam would range 0–8.6 mg/L and BOD would range 0.3–43.8 mg/L for all water year types considered (i.e., typical wet, median, typical dry) and for all six months following drawdown (Table A-6). The highest predicted oxygen demand levels (i.e., IOD and BOD) would occur during the first four to eight weeks following drawdown of Copco 1 and Iron Gate Reservoirs (i.e., in February 2020) corresponding to peak SSC in the river. Despite the relatively high predicted IOD and BOD values, DO concentrations downstream of Iron Gate Dam would generally remain greater than 5 mg/L (Table A-7), the minimum acceptable DO concentration for warm water habitat (NCRWQCB 2006). Exceptions include predicted concentrations in February 2020 for median (WY1976) and typical dry year (WY2001) hydrologic conditions, which exhibit minimum values of 3.5 mg/L and 1.3 mg/L, respectively.

The predicted dissolved oxygen minimum values would occur approximately 1–3 km (~RM 188–190) downstream of Iron Gate Dam and would return to 5 mg/L within 20–25 km (~ RM 175–177) of the dam, or near the confluence with the Shasta River (RM 176.7). Modeled dissolved oxygen concentrations immediately downstream of Iron Gate Dam would not meet the recently amended minimum acceptable site-specific DO concentrations identified for the Klamath River downstream of the dam for all modeled months, which range from 7.8–10.9 mg/L (NCRWQCB 2010). However, recovery to concentrations at or near 90 percent saturation (i.e., 10–11 mg/L) would occur within a distance of 100–150 km (62–93 mi) downstream of the Klamath Hydropower Reach, or generally in the reach from Seiad Valley to the mainstem confluence with Clear Creek, for all water year types considered.

Table A-6. Estimated IOD and BOD by month for modeled flow and suspended sediment concentrations downstream of Iron Gate Dam for drawdown Scenario 8 under the Proposed Action.

Date	Avg. monthly temperature (deg C)[1]	80% Dissolved oxygen[2]	Flow (cfs)[3]	Flow (cms)	SSC (mg/L)[4]	IOD (mg/L)	BOD (mg/L)
Typical Wet Hydrology (WY 1984 Conditions Assumed)							
11/30/2019	9.9	7.3	3,343	95	444	0.3	1.6
12/1/2019	5.0	9.4	7,139	202	430	0.3	1.5
1/21/2020	3.7	9.7	8,675	246	1,962	1.2	6.9
2/15/2020	4.4	9.6	3,949	112	7,116	4.5	25.1
3/1/2020	6.7	9.0	4,753	135	593	0.4	2.1
4/15/2020	8.4	8.6	4,374	124	939	0.6	3.3
Median Hydrology (WY 1976 Conditions Assumed)							
11/12/2019	9.9	7.3	2,074	59	96.2	0.1	0.3
12/12/2019	5.0	9.4	2,156	61	202.5	0.1	0.7
1/22/2020	3.7	9.7	6,533	185	2,593.5	1.6	9.1
2/14/2020	4.4	9.6	2,933	83	9,893.2	6.2	34.8
3/1/2020	6.7	9.0	3,016	85	1,461.2	0.9	5.1
4/7/2020	8.4	8.6	2,657	75	509.3	0.3	1.8
Typical Dry Hydrology (WY 2001 Conditions Assumed)							
11/19/2019	9.9	7.3	1,141	32	79.1	0.0	0.3
12/23/2019	5.0	9.4	1,284	36	122.2	0.1	0.4
1/17/2020	3.7	9.7	4,245	120	3,513.7	2.2	12.4
2/16/2020	4.4	9.6	1,040	29	13,573.5	8.6	47.8
3/2/2020	6.7	9.0	1,344	38	2,420.7	1.5	8.5
4/5/2020	8.4	8.6	1,150	33	551.1	0.3	1.9

[1] Raw daily water temperature data for 2009 from http://www.pacificorp.com/es/hydro/hl/kr.html# (PacifiCorp 2009).

[2] Initial dissolved oxygen downstream of Iron Gate Dam calculated for 80% saturation using average monthly water temperature, salinity = 0 ppt, and elevation = 707 m (2,320 ft). An initial DO at 70% saturation was used for the November model runs based on 2009 conditions.

[3] Predicted daily flow values from USBR hydrologic model output (Greimann et al. 2011). Daily flow values correspond to the peak suspended sediment concentration (SSC) for each month.

[4] Predicted peak suspended sediment concentration (SSC) by month from USBR model output under the Proposed Action (Greimann et al. 2011).

Table A-7. Location of minimum dissolved oxygen and locations at which dissolved oxygen returns to 5 mg/L downstream of Iron Gate Dam at selected dates for drawdown Scenario 8 under the Proposed Action.

Date	Boundary conditions at Iron Gate Dam			Spreadsheet model output				
	Background DO(80% saturation)[1]	IOD	BOD	Minimum dissolved oxygen	Approximate location of minimum dissolved oxygen		Approximate location at which dissolved oxygen returns to 5 mg/L[2]	
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(km)[3]	RM	(km)[3]	RM
Typical Wet Hydrology (WY 1984 Conditions Assumed)								
11/30/2019	7.3	0.3	1.6	7.1	1	190	-	190
12/1/2019	9.4	0.3	1.5	9.2	2	189	-	190
1/21/2020	9.7	1.2	6.9	8.6	3	188	-	190
2/15/2020	9.6	4.5	25.1	5.2	2	189	-	190
3/1/2020	9.0	0.4	2.1	8.7	2	189	-	190
4/15/2020	8.6	0.6	3.3	8.1	2	189	-	190
Median Hydrology (WY 1976 Conditions Assumed)								
11/12/2019	7.3	0.1	0.3	7.3	0	190	-	190
12/12/2019	9.4	0.1	0.7	9.3	1	189	-	190
1/22/2020	9.7	1.6	9.1	8.2	3	188	-	190
2/14/2020	9.6	6.2	34.8	3.5	2	189	24	175
3/1/2020	9.0	0.9	5.1	8.2	2	189	-	190
4/7/2020	8.6	0.3	1.8	8.4	1	189	-	190
Typical Dry Hydrology (WY 2001 Conditions Assumed)								
11/19/2019	7.3	0.0	0.3	7.3	0	190	-	190
12/23/2019	9.4	0.1	0.4	9.4	0	189	-	190
1/17/2020	9.7	2.2	12.4	7.6	2	188	-	190
2/16/2020	9.6	8.6	47.8	1.3	1	189	21	177
3/2/2020	9.0	1.5	8.5	7.6	1	189	-	190
4/5/2020	8.6	0.3	1.9	8.4	1	189	-	190

[1] Initial dissolved oxygen downstream of Iron Gate Dam calculated for 80% saturation using average monthly water temperature, salinity = 0 ppt, and elevation = 707 m (2,320 ft). An initial DO at 70% saturation was used for the November model runs. Raw daily water temperature data from http://www.pacificorp.com/es/hydro/hl/kr.html# (PacifiCorp 2009).

[2] Minimum acceptable dissolved oxygen concentration for warm water habitat (NCRWQCB 2006).

[3] Distance downstream of Iron Gate Dam.

Appendix B

Initial Oxygen Demand-Biochemical Oxygen Demand Rate Estimates

Table B-1. 2009 Sediment biological oxygen demand test data.

Laboratory ID		9110887-01				9110887-02				9110887-03				9110887-04[a]				9110887-05			
Client Sample ID		CDH-S-017 (0.0-1.2)				CDH-S-014 (0.0-5.3)				CDH-S-011 (0.0-1.3)				CDH-S-007 (0.0-5.1)				CDH-S-013 (0.0-5.7)			
Location		Copco, Non Thalweg, Main Body				Copco, Non-Thalweg, near north shore, mid-length				Copco Non Thalweg, near north shore, upstream				Copco Thalweg, Open Body				Copco Thalweg, mid-length			
Analysis	**Time (days)**	BOD_5 / BOD_{30}				BOD_5 / BOD_{30}				BOD_5				BOD_5 / BOD_{30}				BOD_5 / BOD_{30}			
Date Setup		11/25/2009				11/25/2009				12/1/2009				12/1/2009				12/1/2009			
Grams of Sample (ww)		0.5	2.0	2.0	8.0	0.5	2.0	2.0	8.0	0.5	2.0	2.0	8.0	0.5	2.0	2.0	8.0	0.5	2.0	2.0	8.0
Temperature (°C)		20	20	4	4	20	20	4	4	20	20	4	4	20	20	4	4	20	20	4	4
Initial DO	0	9.0	8.6	10.2	9.5	8.9	8.5	10.3	9.3	9.2	8.9	10.6	10.2	9.2	9.0	10.5	10.1	9.2	9.0	10.4	9.8
3 min	0.002083333	9.0	8.4	10.2	9.1	8.8	8.3	10.2	8.7	9.1	8.8	10.6	9.9	9.2	8.7	10.5	9.7	9.2	8.8	10.4	9.4
6 min	0.004166667	9.0	8.4	10.2	8.9	8.8	8.2	10.2	8.5	9.1	8.8	10.5	9.7	9.1	8.6	10.4	9.4	9.1	8.7	10.3	9.2
9 min	0.00625	9.0	8.3	10.2	8.7	8.8	8.1	10.1	8.3	9.1	8.7	10.5	9.6	9.1	8.6	10.3	9.1	9.1	8.7	10.3	9.0
12 min	0.008333333	8.9	8.3	10.2	8.6	8.8	8.1	10.1	8.1	9.1	8.7	10.4	9.6	9.1	8.5	10.3	8.8	9.1	8.7	10.3	9.0
15 min	0.010416667	8.9	8.3	10.1	8.5	8.8	8.1	10.1	8.0	9.1	8.7	10.4	9.5	9.1	8.5	10.2	8.6	9.1	8.6	10.2	8.9
1 hour	0.041666667	8.8	8.1	9.8	7.9	8.6	7.8	9.8	7.6	9.1	8.6	10.1	9.3	9.0	8.1	9.9	7.4	9.1	8.5	10.0	8.5
3 hours	0.125	8.6	7.9	9.5	7.1	8.6	7.6	9.6	7.1	9.1	8.4	9.9	8.8	9.0	7.6	9.7	6.0	9.1	8.4	10.1	7.9
24 hours	1	8.4	7.4	9.5	5.6	8.5	6.8	9.7	5.6	8.7	7.3	9.5	7.0	8.3	4.7	8.9	2.6	8.6	7.2	9.6	5.5
48 hours	2	8.4	6.8	9.4	4.5	8.3	6.3	9.4	4.5	8.3	6.5	9.4	5.6	7.8	2.6	8.6	0.0	8.3	6.6	9.3	4.0
72 hours	3	8.1	6.3	9.5	3.9	8.1	6.0	9.4	3.4	8.2	6.0	9.2	4.6	7.8	1.8	7.9		8.3	6.3	9.2	3.0
96 hours	4	8.0	5.8	9.2	3.3	8.0	5.7	9.3	2.4	8.1	5.4	9.2	3.6	7.7	1.3	7.5		8.2	6.1	9.1	2.0
120 hours	5	7.8	5.1	9.0	2.9	7.9	5.3	9.1	1.1	7.9	4.6	9.1	3.1	7.6	0.6	6.9		8.1	5.8	9.2	1.4
6 days	6	7.7	4.4	9.0	2.5	7.9	4.8	9.2	0.5					7.3	0.0	5.9		7.9	5.3	9.1	0.4
10 days	10	7.3	2.3	8.7	0.9	7.5	3.2	8.7	0.0					4.3		3.5		5.5	1.8	7.8	0.1
15 days	15	4.8	0.1	6.9	0.3	5.1	0.6	6.9						2.7		2.7		4.8	0.3	6.8	0.0
20 days	20	4.1	0.0	5.3	0.0	4.5	0.0	6.1						0.4		2.4		4.0	0.0	7.4	
25 days	25	3.4		6.0		3.9		6.6						0.0		2.3		3.4		6.9	
30 days	30	3.0		5.2		3.2		5.8								1.7		2.7		6.3	
Final mg/kg $BOD_{15\ min}$		60.0	45.0	15.0	37.5	60.0	60.0	30.0	48.8	60.0	30.0	30.0	26.3	60.0	75.0	45.0	56.3	60.0	60.0	30.0	33.8
Final mg/kg $BOD_{3\ hr}$		240.0	105.0	105.0	90.0	180.0	135.0	105.0	82.5	60.0	75.0	105.0	52.5	120.0	210.0	120.0	153.8	60.0	90.0	45.0	71.3
Final mg/kg $BOD_{1\ day}$		360.0	180.0	105.0	146.3	240.0	255.0	90.0	138.8	300.0	240.0	165.0	120.0	540.0	645.0	240.0	281.3	360.0	270.0	120.0	161.3
Final mg/kg $BOD_{3\ day}$		540.0	345.0	105.0	210.0	480.0	375.0	135.0	221.3	600.0	435.0	210.0	210.0	840.0	1080.0	390.0	**>379**	540.0	405.0	180.0	255.0
Final mg/kg BOD_5:*		**720**	**525**	**180**	**248**	**600**	**480**	**180**	**308**	**780**	**645**	**225**	**266**	**960**	**1260**	**540**	**>379**	**660**	**480**	**180**	**315**
Final mg/kg BOD_{30}:*		**3600**	**>1290**	**750**	**>356**	**3420**	**>1275**	**675**	**>349**					**>5520**	**>1350**	**1320**	**>379**	**3900**	**>1350**	**615**	**>368**

Notes: Samples collected during November 4–17 2009 with locations shown by ID in Figures 2 and 3 of the main report. Sediment composites from depth (feet) range shown in parentheses were incubated using 300 mL BOD bottles. BOD values with a greater than sign indicate depletion before the end of the experiment. Sample IDs denoted by "a" were run as quality controls (i.e., duplicates and alternate hold times).

Table B-1, continued. 2009 Sediment biological oxygen demand test data.

Laboratory ID		9110887-06				9110887-07[a]				9110887-08[a]					9110887-09				9110887-10			
Client Sample ID		CDH-S-012 (0.0-5.4)				CDH-S-016 (0.0-7.5)				CDH-S-023 (0.0-5.4)					CDH-S-026 (0.0-2.0)				CDH-S-031 (0.0-4.8)			
Location		Copco Thalweg, upstream				Copco Thalweg, Open Body				Iron Gate, Non-Thalweg, Jenny Cr. Arm					Iron Gate, Non-Thalweg, S. Shore				Iron Gate, Non-Thalweg, N. Shore near Dam			
Analysis	**Time (days)**	BOD$_5$				BOD$_5$ / BOD$_{30}$				BOD$_5$ / BOD$_{30}$					BOD$_5$				BOD$_5$ / BOD$_{30}$			
Date Setup		12/2/2009				12/2/2009				12/3/2009					12/3/2009				12/3/2009			
Grams of Sample (ww)		0.5	2.0	2.0	8.0	0.5	2.0	2.0	8.0	0.5	2.0	2.0	5.0	8.0	0.5	2.0	2.0	8.0	0.5	2.0	2.0	8.0
Temperature (°C)		20	20	4	4	20	20	4	4	20	20	4	4	4	20	20	4	4	20	20	4	4
Initial DO	0	9.1	9.0	10.4	10.0	9.0	9.0	10.2	9.8	9.0	8.4	10.1	9.3	9.5	9.0	8.8	10.3	9.5	9.0	8.8	10.1	9.3
3 min	0.002083333	9.1	8.8	10.3	9.7	9.0	8.7	10.0	9.3	8.9	8.1	9.9	8.8	8.5	9.0	8.7	10.2	9.1	9.0	8.6	10.0	8.9
6 min	0.004166667	9.1	8.8	10.3	9.6	9.0	8.5	10.0	9.0	8.9	8.0	9.8	8.3	7.8	9.0	8.6	10.2	9.0	9.0	8.6	10.0	8.7
9 min	0.00625	9.1	8.7	10.3	9.5	9.0	8.5	10.0	8.8	8.9	7.9	9.7	8.0	7.2	9.0	8.6	10.1	8.8	9.0	8.5	9.9	8.6
12 min	0.008333333	9.1	8.7	10.2	9.4	9.0	8.4	9.9	8.7	8.8	7.8	9.6	7.7	6.5	9.0	8.6	10.1	8.7	9.0	8.5	9.9	8.5
15 min	0.010416667	9.1	8.7	10.2	9.3	9.0	8.4	9.9	8.6	8.8	7.7	9.6	7.5	6.0	9.0	8.6	10.0	8.7	9.0	8.5	9.8	8.4
1 hour	0.041666667	9.0	8.5	9.9	9.1	8.9	8.1	9.5	7.3	8.7	7.6	9.2	6.9	4.7	9.0	8.5	9.8	8.4	9.0	8.3	9.6	7.6
3 hours	0.125	8.9	8.3	9.8	8.8	8.7	7.6	9.4	4.7	8.7	7.3	9.1	6.2	3.5	8.8	8.2	9.8	8.1	8.7	8.0	9.7	6.8
24 hours	1	8.5	7.1	9.4	7.2	8.2	4.6	8.8	0.7	8.4	4.9	8.4	3.9	0.4	8.8	7.7	9.5	6.5	8.6	7.0	9.3	4.6
48 hours	2	8.4	6.7	9.3	5.6	7.9	2.4	8.2	0.0	8.2	3.8	8.0	2.8	0.0	8.6	7.4	9.6	5.5	8.5	6.6	9.3	3.0
72 hours	3	8.2	6.5	8.8	3.6	7.7	1.5	7.7		8.0	2.8	7.9	2.1		8.6	7.2	9.7	4.9	8.4	6.2	9.4	1.9
96 hours	4	8.0	6.0	8.9	2.9	7.6	0.6	7.3		7.8	1.8	7.5	1.0		8.4	6.8	9.5	4.0	8.1	5.6	9.1	0.3
120 hours	5	7.8	5.3	8.7	2.1	7.2	0.0	6.2		6.2	0.8	5.0	0.7		7.4	4.8	8.9	2.3	6.8	3.3	8.2	0.0
6 days	6					5.2		3.6		5.8	0.4	5.0	0.6						6.3	2.7	7.6	
10 days	10					4.1		2.9		5.2	0.0	4.7	0.0						5.8	1.2	7.3	
15 days	15					2.7		2.2		4.7		3.8							4.9	0.0	7.1	
20 days	20					1.6		1.6		4.0		3.0							4.0		6.4	
25 days	25					0.4		0.7		3.4		3.0							3.2		5.8	
30 days	30					-0.1		0.2		2.9		2.2							2.5		5.1	
Final mg/kg BOD$_{\text{15 min}}$		0.0	45.0	30.0	26.3	0.0	90.0	45.0	45.0	120.0	105.0	75.0	108.0	131.3	0.0	30.0	45.0	30.0	0.0	45.0	45.0	33.8
Final mg/kg BOD$_{\text{3 hr}}$		120.0	105.0	90.0	45.0	180.0	210.0	120.0	191.3	180.0	165.0	150.0	186.0	225.0	120.0	90.0	75.0	52.5	180.0	120.0	60.0	93.8
Final mg/kg BOD$_{\text{1 day}}$		360.0	285.0	150.0	105.0	480.0	660.0	210.0	341.3	360.0	525.0	255.0	324.0	341.3	120.0	165.0	120.0	112.5	240.0	270.0	120.0	176.3
Final mg/kg BOD$_{\text{3 day}}$		540.0	375.0	240.0	240.0	780.0	1125.0	375.0	**>368**	600.0	840.0	330.0	432.0	**>356**	240.0	240.0	90.0	172.5	360.0	390.0	105.0	277.5
Final mg/kg BOD$_5$:*		**780**	**555**	**255**	**296**	**1080**	**>1350**	**600**	**>368**	**1680**	**1140**	**765**	**517**	**>356**	**960**	**600**	**210**	**270**	**1320**	**825**	**285**	**>349**
Final mg/kg BOD$_{30}$:*						**>5400**	**>1350**	**1500**	**>368**	**3660**	**>1260**	**1185**	**>558**	**>356**					**3900**	**>1320**	**750**	**>349**

Notes: Sample locations shown by ID in Figures 2 and 3 of the main report. Sediment composites from depth (feet) range shown in parentheses were incubated using 300 mL BOD bottles. BOD values with a greater than sign indicate depletion before the end of the experiment. Sample IDs denoted by "a" were run as quality controls (i.e., duplicates and alternate hold times).

Table B-1, continued. 2009 Sediment biological oxygen demand test data.

Laboratory ID		9110887-11[a]				9110887-12				9110887-13				9110887-14					9110887-17[a]			
Client Sample ID		CDH-S-008 (0.0-3.2)				CDH-S-027 (0.0-1.9)				CDH-S-030 (0.0-2.9)				CDH-S-029 (0.0-4.8)					CDH-S-029 (0.0-4.8) **Duplicate**			
Location		Iron Gate, Non-Thalweg, Jenny Cr. Arm				Iron Gate, Thalweg of Camp Creek Arm				Iron Gate, Thalweg, ~1 mi US of Dam				Iron Gate Thalweg, ~2 mi US of Dam					Iron Gate Thalweg, ~2 mi US of Dam			
Analysis	**Time (days)**	BOD$_5$ / BOD$_{30}$				BOD$_5$ / BOD$_{30}$				BOD$_5$				BOD$_5$ / BOD$_{30}$					BOD$_5$ / BOD$_{30}$			
Date Setup		12/4/2009				12/5/2009				12/5/2009				11/24/2009					11/24/2009			
Grams of Sample (ww)		0.5	2.0	2.0	5.0	0.5	2.0	2.0	8.0	0.5	2.0	2.0	8.0	0.5	2.0	2.0	5.0	8.0	0.5	2.0	2.0	8.0
Temperature (°C)		20	20	4	4	20	20	4	4	20	20	4	4	20	20	4	4	4	20	20	4	4
Initial DO	0	9.1	8.6	10.4	9.9	9.1	9.0	10.7	10.3	9.0	8.9	10.6	10.2	9.0	8.2	10.6	9.8	8.8	9.0	8.1	10.7	9.0
3 min	0.002083333	9.0	8.3	10.3	9.6	9.1	8.6	10.7	9.6	9.0	8.9	10.5	9.5	8.9	7.9	10.6	9.6	8.0	8.9	7.8	10.7	8.1
6 min	0.004166667	8.9	8.1	10.2	9.3	9.0	8.6	10.6	9.3	9.0	8.7	10.4	9.2	8.9	7.7	10.5	9.3	7.2	8.8	7.6	10.6	7.3
9 min	0.00625	8.9	8.0	10.1	9.0	9.0	8.5	10.6	9.1	9.0	8.6	10.4	8.9	8.8	7.6	10.4	9.0	6.6	8.8	7.5	10.5	6.7
12 min	0.008333333	8.9	8.0	10.1	8.8	9.0	8.4	10.5	8.9	9.0	8.6	10.3	8.7	8.8	7.5	10.3	8.8	6.2	8.8	7.4	10.5	6.2
15 min	0.010416667	8.9	7.9	10.0	8.7	9.0	8.4	10.5	8.8	9.0	8.5	10.3	8.5	8.8	7.4	10.3	8.4	5.8	8.8	7.3	10.4	5.9
1 hour	0.041666667	8.9	7.7	9.6	8.1	9.0	8.2	10.2	8.0	8.8	8.2	10.2	6.7	8.8	6.9	9.6	6.8	3.5	8.6	6.7	9.7	3.2
3 hours	0.125	8.7	7.1	9.6	7.7	9.0	7.9	9.9	6.9	8.7	7.7	9.4	4.0	8.5	6.2	9.3	NA	1.2	8.6	6.2	9.3	1.3
24 hours	1	8.4	5.3	8.7	6.3	8.5	5.8	9.4	4.4	8.3	4.4	8.6	-0.1	7.7	4.0	8.3	3.3	-0.2	7.6	3.8	8.3	-0.2
48 hours	2	8.2	3.9	8.4	5.4	8.1	4.3	8.5	0.0	7.7	0.4	7.8		7.6	1.9	8.3	2.6		7.5	1.2	8.3	
72 hours	3	7.9	3.0	8.0	3.5	6.5	2.2	5.9		5.9	0.0	4.9		7.6	0.7	8.3	1.5		7.5	0.1	8.3	
96 hours	4	6.3	1.4	6.0	1.7	5.9	1.7	5.2		5.4		3.1		7.3	0.2	8.1	-0.2		7.1	-0.1	8.3	
120 hours	5	5.8	0.9	5.6	1.3	5.8	1.4	5.2		5.4		2.3		7.2	0.0	7.6			6.9		8.0	
6 days	6	5.8	0.6	5.6	1.2	5.3	0.8	4.9						6.8		6.5			6.6		7.1	
10 days	10	5.2	0.0	4.6	0.1	4.6	0.0	4.0						5.7		4.7			5.5		4.5	
15 days	15	4.5		4.2	0.0	3.9		3.7						2.1		2.9			2.4		2.8	
20 days	20	3.9		3.3		3.1		3.1						1.3		2.5			0.9		2.4	
25 days	25	3.3		2.6		2.5		1.9						0.6		2.5			0.6		2.2	
30 days	30	2.8		2.6		1.8		1.2						0.0		2.4			0.0		1.6	
Final mg/kg BOD$_{15\ \text{min}}$		120.0	105.0	60.0	72.0	60.0	90.0	30.0	56.3	0.0	60.0	45.0	63.8	120.0	120.0	45.0	84.0	112.5	120.0	120.0	45.0	116.3
Final mg/kg BOD$_{3\ \text{hr}}$		240.0	225.0	120.0	132.0	60.0	165.0	120.0	127.5	180.0	180.0	180.0	232.5	300.0	300.0	195.0		285.0	240.0	285.0	210.0	288.8
Final mg/kg BOD$_{1\ \text{day}}$		420.0	495.0	255.0	216.0	360.0	480.0	195.0	221.3	408.0	675.0	300.0	**>383**	780.0	630.0	345.0	390.0	**>338**	840.0	645.0	360.0	**>345**
Final mg/kg BOD$_{3\ \text{day}}$		720.0	840.0	360.0	384.0	1560.0	1020.0	720.0	**>386**	1860.0	1335.0	855.0	**>383**	840.0	1125.0	345.0	498.0	**>338**	900.0	1200.0	360.0	**>345**
Final mg/kg BOD$_5$:*		**1980**	**1155**	**720**	**516**	**1980**	**1140**	**825**	**>386**	**2160**	**>1335**	**1245**	**>383**	**1080**	**>1230**	**450**	**>588**	**>338**	**1260**	**>1215**	**405**	**>345**
Final mg/kg BOD$_{30}$:*		**3780**	**>1290**	**1170**	**>594**	**4380**	**>1350**	**1425**	**>386**					**>5400**	**>1230**	**1230**	**>588**	**>338**	**>5400**	**>1215**	**1365**	**>345**

Notes: Sample locations shown by ID in Figures 2 and 3 of the main report. Sediment composites from depth (feet) range shown in parentheses were incubated using 300 mL BOD bottles. BOD values with a greater than sign indicate depletion before the end of the experiment. Sample IDs denoted by "a" were run as quality controls (i.e., duplicates and alternate hold times).

Table B-1, continued. 2009 Sediment biological oxygen demand test data.

Laboratory ID		9110887-15[a]				9110887-16[a]				9110887-18		9110887-19	
Client Sample ID		CDH-S-029 (0.0-4.8) **10 Day Hold**				CDH-S-029 (0.0-4.8) **20 Day Hold**				Iron Gate Native Water		Copco Native Water	
Location		Iron Gate Thalweg, ~2 mi US of Dam				Iron Gate Thalweg, ~2 mi US of Dam							
Analysis	**Time (days)**	BOD_5 / BOD_{30}				BOD_5 / BOD_{30}				BOD_5 / BOD_{30}		BOD_5 / BOD_{30}	
Date Setup		12/4/2009				12/14/2009				11/24/2009		11/24/2009	
Grams of Sample (ww)		0.5	2.0	2.0	5.0	0.5	2.0	2.0	5.0	300mL	300mL	300mL	300mL
Temperature (°C)		20	20	4	4	20	20	4	4	20	4	20	4
Initial DO	0	9.0	8.9	10.3	10.2	8.9	8.3	10.0	8.8	9.2	11.4	9.2	11.5
3 min	0.002083333	9.0	8.6	10.2	9.8	8.9	8.1	9.9	8.7				
6 min	0.004166667	9.0	8.5	10.1	9.7	8.8	7.9	9.8	8.5				
9 min	0.00625	9.0	8.4	10.1	9.5	8.8	7.8	9.7	8.3				
12 min	0.008333333	9.0	8.4	10.1	9.4	8.7	7.7	9.7	8.1				
15 min	0.010416667	9.0	8.3	10.0	9.4	8.7	7.6	9.6	8.0				
1 hour	0.041666667	8.9	8.1	9.7	9.0	8.5	7.1	8.7	6.6	9.1	11.4	9.1	11.4
3 hours	0.125	8.7	7.5	9.6	8.4	8.5	6.0	8.2	5.3	9.1	11.4	9.0	11.4
24 hours	1	8.6	4.3	8.6	4.3	7.1	2.3	5.5	0.4	8.6	10.6	8.6	10.7
48 hours	2	8.1	2.5	7.9	0.8	6.5	1.4	4.4	0.0	8.8	10.6	8.8	10.6
72 hours	3	7.9	1.5	6.5	0.0	6.1	0.9	3.9		8.7	10.6	8.8	10.6
96 hours	4	6.2	0.7	4.3		6.0	0.5	3.9		8.6	10.8	8.5	10.7
120 hours	5	5.8	0.3	4.1		5.7	0.1	4.2		8.4	10.7	8.5	10.6
6 days	6	5.8	0.0	4.4		5.6	0.0	4.2		8.2	10.8	8.3	10.6
10 days	10	4.8		3.6		4.5		3.7		8.0	10.5	8.1	10.6
15 days	15	3.9		3.6		3.6		3.1		5.9	10.5	6.4	10.7
20 days	20	3.3		2.9		2.8		2.8		5.7	10.9	6.1	10.8
25 days	25	2.5		2.2		2.2		1.8		4.8	11.6	4.7	11.5
30 days	30	2.0		2.0		1.6		1.4		4.2	11.4	4.0	11.4
Final mg/kg $BOD_{15\ min}$		0.0	90.0	45.0	48.0	120.0	105.0	60.0	48.0	0.1	0.0	0.1	0.1
Final mg/kg $BOD_{3\ hr}$		180.0	210.0	105.0	108.0	240.0	345.0	270.0	210.0	0.1	0.0	0.2	0.1
Final mg/kg $BOD_{1\ day}$		240.0	690.0	255.0	354.0	1080.0	900.0	675.0	504.0	0.6	0.8	0.6	0.8
Final mg/kg $BOD_{3\ day}$		660.0	1110.0	570.0	612.0	1680.0	1110.0	915.0	**>528**	0.5	0.8	0.4	0.9
Final mg/kg BOD_5:*		**1920**	**1290**	**930**	**>612**	**1920**	**1230**	**870**	**>528**	**<3**	**<3**	**<3**	**<3**
Final mg/kg BOD_{30}:*		**4200**	**>1335**	**1245**	**>612**	**4380**	**>1245**	**1290**	**>528**	**5**	**<3**	**5**	**<3**

Notes: Sample locations shown by ID in Figures 2 and 3 of the main report. Sediment composites from depth (feet) range shown in parentheses were incubated using 300 mL BOD bottles. BOD values with a greater than sign indicate depletion before the end of the experiment. Sample IDs denoted by "a" were run as quality controls (i.e., duplicates and alternate hold times).

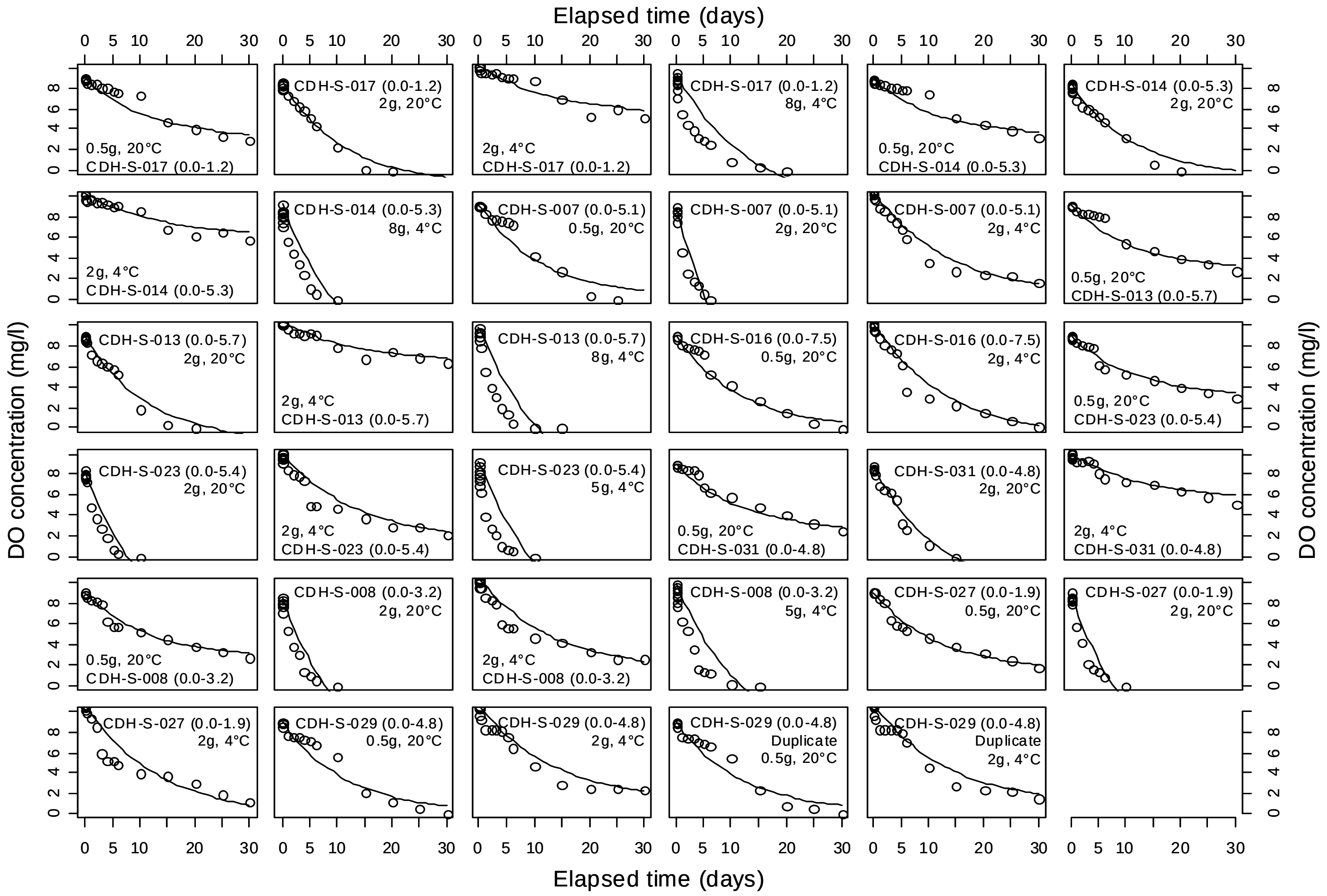

Figure B-1. Modeled DO depletion by mass (g) and incubation temperature (°C) for composited sediment samples (sample depth [feet] range shown in parentheses) collected during 2009 at all sample sites. Estimated 1st order BOD rate constants, temperature coefficient (theta), and average sediment oxygen demand (ODu/SSC) values are shown in Table 3 of the main report, with sample-specific ODu/SSC shown as the asymptotic ($t=\infty$) DO concentrations in the above tiles.

Table B-2. 2010 Sediment initial oxygen demand test data.

Sample ID	**Iron Gate Composite - Lab ID# 0040681-01**							**Copco Composite - Lab ID# 0040681-02**						
Analysis	Nitrogen Environment IOD / BOD5							Nitrogen Environment IOD / BOD5						
Date Sampled	Sampled 4/13/10 - Composited 4/15/10							Sampled 4/14/10 - Composited 4/16/10						
Date Setup	4/20/2010	4/20/2010	4/20/2010		4/20/2010	4/20/2010	4/21/2010	4/22/2010	4/22/2010	4/22/2010	-	4/22/2010	4/22/2010	4/22/2010
Grams of Sample (ww)	0.5	0.5	0.5		2.0	2.0	2.0	0.5	0.5	0.5		2.0	2.0	2.0
Temperature (^{o}C)	20	20	20		20	20	20	20	20	20		20	20	20
Start Time	7:25am	9:35am	11:45am		2:10pm	4:15pm	8:40am	6:35am	8:45am	10:50am		1:00pm	3:10pm	5:20pm
	DO Measurements							**DO Measurements**						
Initial DO	8.5	8.3	8.0		7.5	7.2	8.3	9.1	8.3	8.5		8.3	7.9	7.6
2 min	8.5	8.3	7.9		7.3	6.9	7.9	9.1	8.2	8.5		8.0	7.6	7.3
4 min	8.4	8.2	7.9		7.1	6.7	7.7	9.1	8.2	8.4		7.9	7.4	7.1
6 min	8.4	8.1	7.9		7.0	6.7	7.6	9.0	8.2	8.4		7.8	7.3	7.1
8 min	8.4	8.0	7.8		6.9	6.6	7.5	9.0	8.2	8.4		7.7	7.3	7.0
10 min	8.4	8.0	7.8		6.9	6.6	7.5	9.0	8.1	8.3		7.6	7.2	6.9
15 min	8.3	8.0	7.8		6.7	6.4	7.4	8.9	8.1	8.3		7.5	7.2	6.9
20 min	8.3	7.9	7.7		6.7	6.3	7.3	8.9	8.1	8.3		7.4	7.1	6.8
25 min	8.2	7.9	7.7		6.6	6.3	7.2	8.8	8.0	8.3		7.4	7.0	6.8
30 min	8.2	7.9	7.7		6.5	6.2	7.1	8.8	8.0	8.2		7.3	7.0	6.7
35 min	8.2	7.8	7.7		6.5	6.2	7.1	8.7	8.0	8.2		7.2	6.9	6.7
40 min	8.2	7.8	7.7		6.4	6.2	7.0	8.7	7.9	8.2		7.2	6.9	6.7
45 min	8.1	7.8	7.7		6.4	6.1	7.0	8.7	7.9	8.1		7.1	6.9	6.6
50 min	8.1	7.8	7.6		6.4	6.1	7.0	8.6	7.9	8.1		7.1	6.8	6.6
55 min	8.1	7.8	7.6		6.3	6.1	6.9	8.6	7.9	8.1		7.1	6.8	6.5
60 min	8.1	7.8	7.6		6.3	6.0	6.9	8.5	7.8	8.0		7.1	6.8	6.5
80 min	8.0	7.7	7.5		6.2	6.0	6.8	8.4	7.7	7.9		7.0	6.7	6.4
100 min	8.0	7.6	7.5		6.2	5.9	6.7	8.3	7.6	7.8		6.9	6.6	6.3
120 min	7.9	7.6	7.4		6.1	5.8	6.7	8.1	7.6	7.8		6.8	6.5	6.3
180 min	7.8	7.5	7.3		5.9	5.7	6.6	8.0	7.5	7.7		6.5	6.2	6.0
3 hour depletion (mg/L):	**0.7**	**0.8**	**0.7**		**1.6**	**1.5**	**1.7**	**1.1**	**0.8**	**0.8**		**1.8**	**1.7**	**1.6**

Notes: Composite samples collected at depths of approximately 4 inches on April 13-14, 2010, from Copco 1 Reservoir (CDH-S-012, CDH-S-014, CDH-S-016, CDH-S-019 [see Figure 2 in main report]) and Iron Gate Reservoir (CDH-S-024, CDH-S-027, CDH-S-029, CDH-S-031 [see Figure 3 in main report]). All samples were incubated using 300 mL BOD bottles.

Table B-2, continued. 2010 Sediment initial oxygen demand test data.

Sample ID	**Iron Gate Composite - Lab ID# 0040681-01**								
Analysis	Nitrogen Environment IOD / BOD5								
Date Sampled	Sampled 4/13/10 - Composited 4/15/10								
Date Setup	4/29/2010	4/29/2010	4/26/2010	4/26/2010	4/26/2010		4/27/2010	4/27/2010	4/27/2010
Grams of Sample (ww)	2.0	2.0	2.0	2.0	2.0		8.0	8.0	8.0
Temperature (^{o}C)	4	4	4	4	4		4	4	4
Start Time	12:45pm	2:50pm	6:40am	8:55am	11:05am		6:25am	8:35am	10:45am
			DO Measurements						
Initial DO	13.2	13.0	13.0	12.9	12.2		10.5	10.7	10.6
2 min	12.0	12.2	12.2	11.9	11.2		8.6	8.5	8.5
4 min	11.7	11.9	12.1	11.8	11.1		8.3	8.1	7.9
6 min	11.6	11.8	12.0	11.8	11.1		8.1	7.6	7.4
8 min	11.6	11.7	12.0	11.7	11.0		8.1	7.4	7.3
10 min	11.6	11.6	11.9	11.7	10.9		8.0	7.3	7.2
15 min	11.6	11.6	11.8	11.5	10.7		7.5	7.0	6.9
20 min	11.5	11.5	11.7	11.4	10.6		7.2	6.8	6.7
25 min	11.4	11.4	11.7	11.3	10.6		7.0	6.7	6.5
30 min	11.4	11.3	11.6	11.2	10.5		6.9	6.5	6.4
35 min	11.3	11.2	11.5	11.2	10.5		6.8	6.4	6.3
40 min	11.3	11.2	11.5	11.1	10.5		6.6	6.3	6.2
45 min	11.2	11.1	11.5	11.1	10.5		6.5	6.3	6.1
50 min	11.2	11.1	11.4	11.1	10.5		6.4	6.2	6.0
55 min	11.2	11.0	11.3	11.0	10.4		6.3	6.2	6.0
60 min	11.1	11.0	11.3	1.0	10.4		6.2	6.1	5.9
80 min	11.1	11.0	11.1	10.8	10.3		5.9	6.0	5.8
100 min	10.9	10.9	11.0	10.8	10.3		5.7	6.0	5.8
120 min	10.9	10.8	11.0	10.7	10.2		5.6	5.8	5.7
180 min	10.6	10.6	10.7	10.4	10.1		5.1	5.5	5.5
3 hour depletion (mg/L):	**2.6**	**2.4**	**2.3**	**2.5**	**2.1**		**5.4**	**5.2**	**5.1**

Notes: Composite samples collected at depths of approximately 4 inches on April 13–14, 2010, from Iron Gate Reservoir (CDH-S-024, CDH-S-027, CDH-S-029, CDH-S-031 [see Figure 3 in main report]). All samples were incubated using 300 mL BOD bottles.

Table B-2, continued. 2010 Sediment initial oxygen demand test data.

Sample ID	**Copco Composite - Lab ID# 0040681-02**						Copco Native Water		Iron Gate Native Water		Method Blank
Analysis	Nitrogen Environment IOD / BOD5						IOD / BOD5				
Date Sampled	Sampled 4/14/10 - Composited 4/16/10						4/14/2010		4/13/2010		
Date Setup	4/29/2010	4/29/2010	4/29/2010	4/27/2010	4/27/2010	4/27/2010	4/29/2010	4/28/2010	4/28/2010	4/19/2010	4/19/2010
Grams of Sample (ww)	2.0	2.0	2.0	8.0	8.0	8.0	300	300	300	300	300
Temperature (^{o}C)	4	4	4	4	4	20	4	20	4	20	20
Start Time	6:25am	8:30am	10:35am	1:05pm	3:10pm	5:16pm	5:00pm	9:40am	10:45am	12:55pm	10:50am
	DO Measurements						**DO Measurements**				
Initial DO	13.4	13.1	13.0	11.4	11.4	11.3	13.2	9.2	14.0	9.2	9.2
2 min	12.6	12.6	12.4	9.2	9.4	9.3	13.2	9.2	14.0	9.2	9.2
4 min	12.6	12.5	12.2	8.3	8.4	8.4	13.2	9.2	14.0	9.2	9.2
6 min	12.5	12.4	12.1	8.1	8.1	8.2	13.2	9.1	14.0	9.2	9.2
8 min	12.5	12.3	12.0	7.8	7.9	8.0	13.2	9.1	14.0	9.2	9.2
10 min	12.5	12.2	12.0	7.6	7.7	7.8	13.2	9.1	14.0	9.2	9.2
15 min	12.4	12.1	11.9	7.4	7.5	7.5	13.2	9.1	14.0	9.2	9.2
20 min	12.3	12.1	11.9	7.2	7.3	7.4	13.2	9.1	14.0	9.1	9.2
25 min	12.3	12.0	11.8	7.0	7.2	7.2	13.2	9.0	14.0	9.1	9.2
30 min	12.2	12.0	11.8	6.9	7.1	7.1	13.2	9.0	14.0	9.1	9.2
35 min	12.2	11.9	11.8	6.8	7.0	7.0	13.2	9.0	14.0	9.1	9.2
40 min	12.2	11.8	11.7	6.7	6.9	7.0	13.2	9.0	14.0	9.1	9.2
45 min	12.1	11.8	11.7	6.6	6.8	6.9	13.2	9.0	14.0	9.0	9.2
50 min	12.1	11.8	11.7	6.6	6.7	6.8	13.2	8.9	14.0	9.0	9.2
55 min	12.0	11.8	11.7	6.5	6.7	6.8	13.2	8.9	14.0	9.0	9.2
60 min	11.9	11.7	11.6	6.5	6.6	6.7	13.2	8.9	14.0	9.0	9.2
80 min	11.8	11.6	11.5	6.5	6.6	6.7	13.2	8.9	14.0	8.9	9.2
100 min	11.8	11.5	11.4	6.4	6.4	6.7	13.2	8.9	14.0	8.9	9.2
120 min	11.6	11.5	11.4	6.3	6.4	6.6	13.2	8.9	14.0	8.9	9.2
180 min	11.4	11.3	11.2	6.0	6.1	6.5	13.0	8.9	13.8	8.9	9.0
3 hour depletion (mg/L):	**2.0**	**1.8**	**1.8**	**5.4**	**5.3**	**4.8**	**0.2**	**0.3**	**0.2**	**0.3**	**0.2**

Notes: Composite samples collected at depths of approximately 4 inches on April 13-14, 2010, from Copco 1 Reservoir (CDH-S-012, CDH-S-014, CDH-S-016, CDH-S-019 [see Figure 2 in main report]) and Iron Gate Reservoir (CDH-S-024, CDH-S-027, CDH-S-029, CDH-S-031 [see Figure 3 in main report]). All samples were incubated using 300 mL BOD bottles.

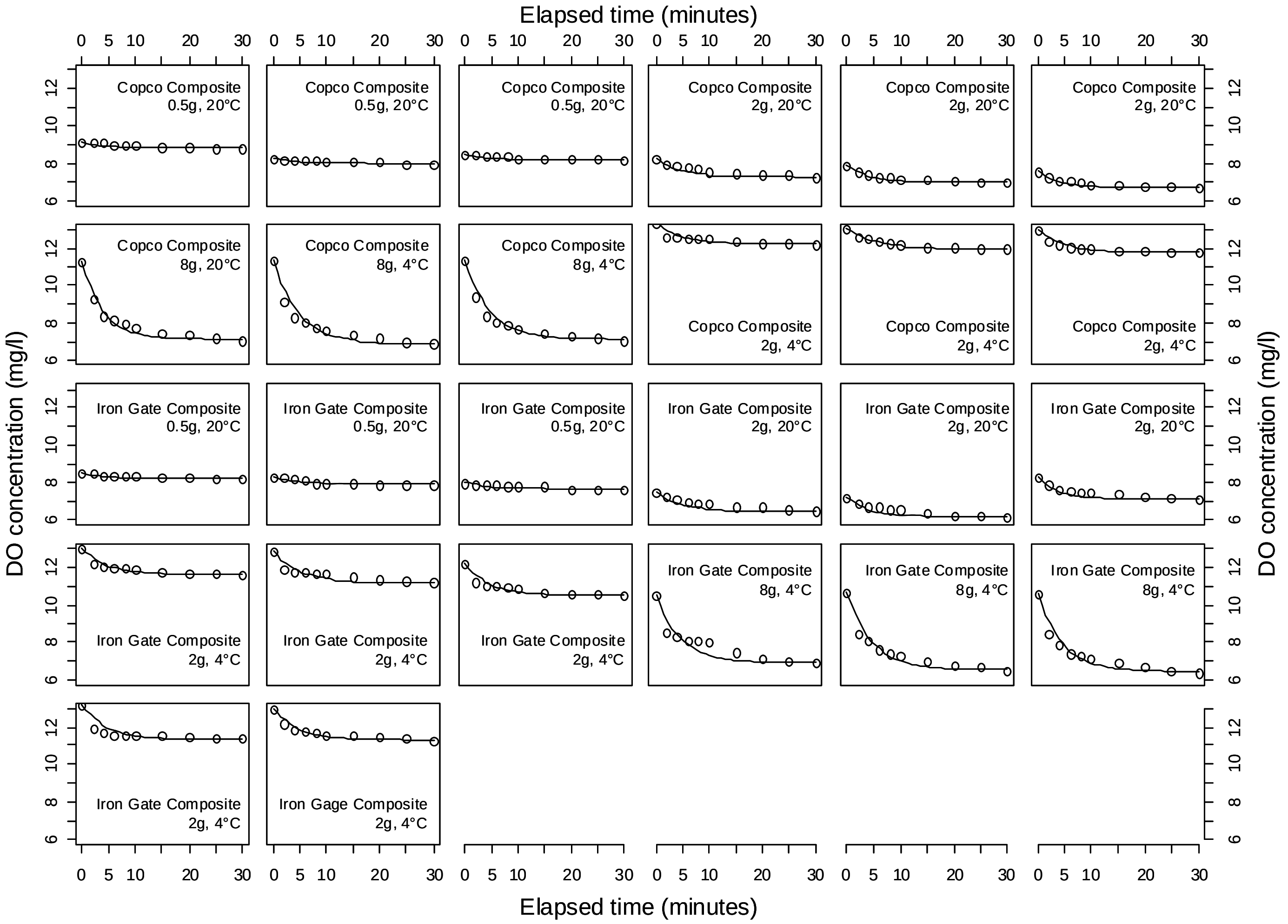

Figure B-2. Modeled DO depletion by mass (g) and incubation temperature (^{o}C) for composited sediment samples collected during 2010 at all sample sites. Estimated 1st order IOD rate constants, temperature coefficient (theta), and average sediment oxygen demand (ODu/SSC) values are shown in Table 3 of the main report, with sample-specific ODu/SSC shown as the asymptotic (t=∞) DO concentrations in the above tiles.

Addendum

Consistent with the peer review process for the Klamath Settlement Secretarial Determination, this report was reviewed by two independent peer reviewers. We thank Paul Conrads and Jim Eychaner at the U.S. Geological Survey (USGS) for their reviews; their expertise and insights helped to make the final report a better document. Atkins North America Inc. served as an independent third party referee for the peer review of this report. In addition to peer review, courtesy reviews were extended to scientists at PacifiCorp (Linda Prendergast), Watercourse Engineering, Inc. (Mike Deas), the Yurok Tribe (Eli Asarian, Riverbend Sciences), and the Center for Research in Water Resources Engineering at the University of Texas at Austin (Neal Armstrong) based upon the previous experience of these individuals with water quality and dissolved oxygen issues in the Klamath Basin. We appreciate the thoughtful feedback provided by these courtesy reviews.

Due to the limited scope of this investigation, only the USGS peer review comments could be fully incorporated into the final report. However, all of the reviewer comments were screened for indication of critical flaws in the modeling and/or analysis approach and brief responses to all comments received have been provided in this addendum. Should there be an affirmative Secretarial Determination, further investigation of potential BOD/IOD issues associated with dam removal could include the following key suggestions made by courtesy reviewers:

- Estimate the error associated with the numerical solution by comparing it to the explicit analytical solution(s) using a range of time steps/distance steps (model nodes). A comparison of numerical model results to traditional Streeter-Phelps solutions indicates that the numerical and exact solutions agree when accounting only for BOD and at smaller time/distance steps (see Section 2.3.6 model verification). As an alternative to the numerical solution, an exact solution incorporating CBOD, NBOD, IOD and sediment (bed) oxygen demand may be also developed that incorporates tributary dilution and variable channel geometry, as included in the current numerical solution.
- Consider direct measurement of *in situ* reaeration rates in the Klamath River downstream of Iron Gate Dam during the cold, winter months, when dam removal is anticipated to occur. This would allow more accurate estimates of the relationship between reaeration rate constants and water temperature at low temperatures (i.e., approximately 4^{o}C or less).
- Consider monitoring of *in situ* IOD/BOD and dissolved oxygen downstream of the dams, before and after reservoir drawdown.

Peer reviews were conducted by Paul Conrads and Jim Eychaner (U.S. Geolgical Survey)
Courtesy reviews were conducted by Linda Prendergast (PacifiCorp), Mike Deas (Watercourse Engineering, Inc.), Eli Asarian (Riverbend Sciences, consultant to the Yurok Tribe), and Neal Armstrong (Center for Research in Water Resources Engineering at the University of Texas at Austin

Review Type	Comment Number (if provided)	Section Number	Comment	Brief Response to Comment	Who Addressed Comment
Peer		Appendix B	The unnumbered tables at pages 43 and 61 present the original measurement data from which the IOD and BOD parameter values for the model were derived. Most of the latter is legible at 5-fold magnification, but none of the former is legible at any magnification. Both should be reformatted in multiple panels so readers can see the data.	Concur. Table has been reformatted	Stillwater
Peer		Appendix B	In all model cases in the report, the critical minimum DO concentration is estimated to occur within the first 5 km downstream from Iron Gate, which means the calculations are dominated by the IOD parameter. All of the graphs in appendix B compress the first 30 minutes of incubation data into less than 0.01 inch of the horizontal axis, making it impossible to see how well the estimated IOD rate coefficients fit the data. The early-time data should be graphed so they can be seen, either as separate panels for perhaps the first 60 minutes or by using a logarithmic horizontal axis.	Concur: All Appendix B figures have been revised and now show the model fit to 30 minutes for IOD and 30 days for BOD.	Stillwater
Peer		Section 3 and Appendix B	The estimated IOD and BOD rate coefficients for individual incubations shown in appendix B both vary by more than 3 orders of magnitude. In section 3.1, the report properly states the raw rates were adjusted for temperature and sediment concentration, although the statistical details are unclear. For predictive purposes, however, the model collapses all the estimates to single values. The authors should report the uncertainty of the values in Table 2, either as some relevant range or as standard error of prediction. The authors should consider presenting any statistical regressions as graphs in the report.	Concur. Appendix B has been revised to show a single rate estimate. Individual rate estimates are no longer presented. ODu is separately regressed against sediment concentration. Because the three model parameters (*ki* or *kd*, theta, and ODu/SSC) were fitted within a single statistical model, it is not possible to separate parameters in a series of (step-wise) regression figures. The resulting 95% confidence intervals (CIs) are shown in the revised table (now Table 3).	Stillwater
Peer		Section 3	The report properly explores the sensitivity of the results to variations in suspended sediment concentration, temperature, and other factors. Because the IOD rate coefficient is so important to the calculations, the authors also should estimate and report the sensitivity of the results to increasing or decreasing that rate by one standard error of prediction.	Concur. Additional sensitivity analyses of IOD rates have been added (see Section 3.3.2), exploring variations in rate by three orders of magnitude.	Stillwater
Peer		Section 2	p.4, eqn.1, 2, and 3: Caution is needed in the math of pluses and minuses. Dissolved oxygen will tend to decrease ($dO/dt < 0$) in proportion as IOD and BOD are consumed. Thus if ki, kd, ks, and kb are positively-valued rate terms, dIOD/dt and dBOD/dt will have negative values and should appear in eqn.1 as additions, not subtractions. The authors should confirm that the model computation sequence is consistent with the presentation in text.	Concur. Equation 1 has been changed to reflect this comment and the model results checked for consistency.	Stillwater
Peer		Section 2	p.4, eqn.3: Reasonably tracks the BOD inventory through time, but can't be substituted in eqn.1 because removal by settling does not directly remove dissolved oxygen from the water column	While the model formulation could be approached in a different manner, it is not readily apparent that removal of BOD through both settling and oxygenation is inappropriate. That is, BOD removed by non oxidative mechanisms will result in a lower remaining BOD inventory, which also affects the time rate of change of oxygen in solution (dO/dt in equation 1). Nevertheless, the substitution of eqn. 3 into eqn. 1 does not affect the model results presented since the BOD settling rate was later set to zero (see new Table A-1).	Stillwater
Peer		Section 2	p.11, eqn.7,8, and 9: Previous text defined the stream reaeration coefficient as ka. The addition of (20) here is undefined. How is the addition significant to the story? It appears to be a reference temperature, as discussed on p. 18 at 2.3.4. Rearrange or cross reference.	Concur. Text updated to explain all rate constants with the exception of settling are modified by temperature. ka (20) notation has been removed from Equations 7-9.	Stillwater
Peer		Section 2	p.11 and p.30: Citation is Hornberger at first and Homberger later.	Corrected	Stillwater
Peer		Section 2	Figures 1 and 2: Clarify here or in nearby text which sites were sampled to produce the data in appendix B.	Figures 1 and 2 updated to include only sites that were sampled for BOD and IOD incubations. These figures are now Figures 2 and 3 in the revised report.	Stillwater
Peer		Section 2	p.16-17, fig.5: The graph does not support the text conclusion very well, that the Churchill method most closely follows the pattern observed in the field. Consider an additional figure, plotting in situ ka on X axis versus each model ka for the same sites on Y axis. The model values should be calculated for the discharge actually present during the field measurements, even if H, U, or slope must be interpolated from hydraulic model runs. Comparing field-measured ka with models for different discharges introduces unnecessary errors.	Comment noted. Figure 5 (now Figure 6) developed using monthly average flows for the July 2001 period corresponding to empirical ka measurements estimated in the same month and year. New Table 2, which presents (observed vs. expected) model statistics for the three reaeration models in June, July, August, and September 2001, shows the Churchill model fit is better than the other models in 3 out of 4 months for all goodness of fit statistics used (slope, R2, p). The figure caption has been clarified to indicate the data used for flow and ka estimates come from July 2001 and that Table 2 provides model fit for other months.	Stillwater
Peer		Section 2	p.16: Explain more clearly how the choice of Churchill is conservative with respect to the field observed and O'Connor model estimates. I understand the term to imply smaller values of ka, thus less simulated reaeration and greater effect of oxygen demanding processes, but fig.5 reverses that order for most of the reach (km 75 to 300).	Comment noted. Text revised in this section to clarify that Churchill method under predicts in situ Ka and is conservative in that actual in situ reaeration will likely be higher than predicted by the model. The new Table 2 shows Churchill (and the other reaeration models) under predicted (slope less than 1) empirical in situ estimates developed by Ward and Armstrong (2010). Figure 6 (previously Figure 5) suggests close correspondence between in situ estimates and Churchill model predictions for 3 out of the 6 locations sampled/modeled, over prediction in 2 out of 6 locations, and under prediction in 1 out of 6 locations.	Stillwater
Peer		Section 2	p.34, table A-1: Scenario 2 uses BOD rate constant about 4 times larger than in the other scenarios, but the IOD rate is identical for all. The difference, if truly present in the model calculations, should be explained.	Footnote added: k_d based on earlier estimate of 5-day oxygen demand tests (excluding NBO	Stillwater

Review Type	Comment Number (if provided)	Section Number	Comment	Brief Response to Comment	Who Addressed Comment
Peer		Appendix B	Appendix B presents an abundance of data and parameter estimates in tables and figures without any explanation of what they represent. The only apparent text explanation is a single sentence at page 18. Please provide a brief explanation to address at least: 1. Sample identification convention, linked to sample dates, depths, and locations (figures 1 and 2); 2. Water volume used in the incubations; 3. Units of measure for all terms; 4. Summary of calculations applied to the data or references to applicable sections of the main body text; and 5. Whether the dashed lines in the figures correspond to oxygen demand at time t = ∞ (eqn.12).	Concur: All Appendix B figures have been revised and now show the model fit to 30 minutes for IOD, and 30 days for BOD. 1. Figures in main report (now Figures 2 and 3) have been updated to indicate sample ID associated with laboratory results shown in Appendix B. Appendix B tables footnotes revised to reference sample dates, depths, and locations. 2) Appendix B tables footnotes revised to indicate that all incubations were performed using 300 mL BOD bottles. 3) Units of measure for each incubation condition included in Appendix B tables and figures (including figure captions). 4) Sections 2.3.1 and 3.1 updated to describe calculation methods. 5) Although dashed lines did correspond to ODu (t=infinity), revised Appendix B figures no longer include this reference line.	Stillwater
Peer		Appendix B	The annotation of K1 and K2 in the appendix B figures is inconsistent with that used in report body (ka and kb?). Explain or make them consistent.	Concur. Appendix B has been revised to show a single rate estimate due to the use of a single (2 parameter) model. Thus, individual rate estimates are no longer presented.	Stillwater
Peer		Appendix B	For the BOD data visible in the figures, both apparent linear and curvilinear fits are displayed. Explain how these are consistent with model equations in text or which were excluded from the interpretations. If all the fits are curves, say something about the widely variable results from individual incubations.	Concur. Appendix B has been revised to show a single rate estimate due to the use of a single (2 parameter) model. Thus, individual rate estimates are no longer presented.	Stillwater
Peer		Appendix B	Several panels of the various figures show red data points far from the fitted lines for late time. Explain.	Comment noted. Although these points were excluded from these preliminary model fits, Appendix B has been updated to included all data reported as a single (2 parameter) model.	Stillwater
Peer		Appendix B	Most of these comments on appendix B might be dealt with efficiently using a couple examples and text something like this: For example, in the top left panel of figure B-1, the sediment sample was composited from the interval 0.0 to 5.1 ft below the bed of Copco 1 reservoir at site CDH-S-007 (figure 1), which was collected April 99, 2009. This incubation was carried out at 20 degrees C using 0.5 g of sediment composite and 250 mL of well-oxygenated DI water. The resulting IOD rate constant was 506.3/d, ultimate IOD of 9 mg/L (dashed black line), BOD rate constant 0.8027/d, and ultimate BOD 7.5 mg/L (dashed red line).	Comment noted. The Appendix B figures have all been updated such that the reviewer's comment is not completely germane anymore. Sample incubation conditions are shown for each tile in the new figures and the caption has been revised to be more clear.	Stillwater
Courtesy		General	Overall the approach taken and results appear reasonable. The tools used are appropriate for providing useful information for the Secretarial Determination regarding assessing the likely short-term effects of dam removal on dissolved oxygen levels in the Klamath River.	Comment noted	Stillwater
Courtesy		Section 2	Page 14, footnote 2 to Table 2: the footnote that reads "ODu = "ultimate" oxygen demand at time t = ∞. See equation (11)." should instead refer to equation 12? (equation 11 is DO saturation based on elevation and temperature, equation 12 is the one that refers to OD).	Corrected	Stillwater
Courtesy		Appendix A	Page A-1, Table A-1: the estimated background dissolved oxygen concentrations under drawdown scenarios 7 (80%) and 8 (70% for November, 80% for December-April) seem reasonable, but there is no documentation as to where that number comes from. If possible, some documentation/justification should be provided.	Comment noted. Scenario 2 background DO % saturation based upon professional judgment during preliminary analyses. Scenario 7 and 8 background DO % saturation values based on typical monthly values using raw data from http://www.pacificorp.com/es/hydro/hl/kr.html# (PacifiCorp 2009).	Stillwater
Courtesy		Appendix A	Pages A-2 through A-8: how were the calendar dates listed in Tables A-2 through chosen? And why do they vary by hydrologic type (i.e. Wet Hydrology uses 2/15/2020, Median Hydrology uses 2/10/2020, and Dry Hydrology uses 2/9/2020)? Do these dates correspond to key points in the hydrograph or SSC time series (i.e. peak monthly SSC concentration)? It would be helpful to explain this in the text.	Comment noted. Modeled dates and flows correspond to the predicted peak SSC for each month based on USBR model output (Greimann et al. 2010).	Stillwater
Courtesy		Appendix A	Page A-6, first paragraph: the description of the time period for scenario 8: "Drawdown Scenario 8 assumes a three-phase drawdown for Copco 1 Reservoir beginning in November 2019, and a single-phase drawdown for J.C. Boyle and Iron Gate reservoirs beginning in January 2020 (Greimann et al. 2010)". It would be better to mention specific dates (i.e. November 1, 2019 and January 1, 2020?).This comment also applies to the descriptions of scenarios 2 (page A-1, last paragraph) and 7 (page A-3, last paragraph).	Concur. Dates have been added for all of the drawdown scenarios modeled.	Stillwater
Peer	jhe1	Section 1	Metric range?	Comment noted. Metric range added.	Stillwater
Peer	jhe2	Section 3.3.1	Invalid reference	Comment noted. Reference updated.	Stillwater
Peer	p2	Section 1	A simple base map near the beginning of the report would help the uninitiated.	Comment noted. Project overview map is included as Figure 1.	Stillwater
Peer	p3	Section 2.2	Provide more discussion on the "order of magnitude estimate" as it pertains to the dam removal. Is it an order of magnitude analysis to determine the salient terms in the DO balance equation? Or is a constraint on the results to be in the "order of magnitude" ballpark?	Comment noted. The phrase "order of magnitude" has been replaced with "1-dimensional, reach-scale".	Stillwater

Review Type	Comment Number (if provided)	Section Number	Comment	Brief Response to Comment	Who Addressed Comment
Peer	p4	Section 2.2	Need to be careful classifying water years and then picking months within the years. The annual classification may not pick up the interannual variability so there may be dry months within wet years and visa versa. An alternative approach would be to rank monthly values.	The BOD/IOD report notes that "Using hydrologic data developed in support of the Secretarial Determination process (King 2010)..." Although we were unable to estimate inter-annual variability for each water year type, the selected representative years in King (2010) consider inter-annual variability. Further, hydrologic data from these particular years were used to be consistent with other reports in the SD. No changes made to the text.	Stillwater
Peer	p5	Section 2.3.1	Or "Initial" – used initial previously.	Heading updated to "Initial".	Stillwater
Peer	p6	Section 3.2	Can only see general trends in these plots and hard to see any subtleties. Consider using two axes. Consider presenting three plots (DO, BOD, and IOD) for the four conditions shown. It would be much easier to compare the response of DO, BOD, and IOD to the four conditions.	Unfortunately, because large IOD and DO changes occur only within the first 10 km downstream of the dams (and generally within the first 3 km), the use of two y-axes or presentation using three plots (DO, BOD, and IOD) does not qualitatively improve discernibility of the trends. Instead, as part of adding sensitivity analyses for ki and kd, early time (distance) has been expanded in a new IOD and BOD plot (Figure 13) to better show the behavior of these parameters immediately downstream of Iron Gate Dam. This approach was not taken for the other model parameters subjected to sensitivity testing because there isn't enough of a change just downstream of the dam to warrant figures with expanded x-axes.	Stillwater
Peer	p4	Section 2.2	Discuss these results as it applies to the "order of magnitude estimate" approach. Should these number be compared to a minimum target level?	To address the estimation approach, additional text has been added to Section 2.2 to indicate that "...model predictions of particular DO levels at specific locations should be considered estimates, understanding that in situ conditions may differ from those used to estimate DO in the Klamath River following dam removal." We have also added text to Section 1.2 to introduce the use of Basin Plan DO thresholds.	Stillwater
Peer	p8	Section 3.2	Need to define the target DO level for the analysis. Five mg/L is mentioned here, 6 mg/L later in the paragraphs, and the rest of the report uses 7 mg/L.	As of 2010, amended Basin Plan water quality objectives are expressed as percent saturation, with a range of DO values established from Iron Gate Dam to the Klamath River estuary depending on water temperature and location (NCRWQCB 2010). 5 mg/L is used throughout the report as a simplifying, conservative and generally applicable minimum value for warm water fish, with the more complex minimum values from the amended Basin Plan referenced as ranges for broader perspective. References to previously applicable Basin Plan (i.e., pre-2010) values of 7 mg/L and 9 mg/L have been removed from the report.	Stillwater
Peer	p9	Section 3.3	Need to include all the rate kinetics in the model in a sensitivity analysis. A normalized sensitivity index can be computed to be able to rank the sensitivity of the inputs to the models and the rate kinetics.	Concur. Additional parameter sensitivity analyses included for IOD rate (ki) and BOD rate (kD), bring the total number of parameters included in the sensitivity analysis to seven.	Stillwater
Peer	p10	Section 3.3	Include IOD and BOD rates.	Comment noted. Text changed.	Stillwater
Peer	p11	Section 3.3.1	Tabular output of the sensitivity analysis with a sensitivity index would make the cross-comparison on model input and rate kinetics easier.	Comment Noted. Although sensitivity index could be developed, graphical presentation of parameter sensitivity illustrates the effects on ODu and DO.	Stillwater
Peer	p12	Section 3.3.1	Should the sensitivity range (100 – 10,000 mg/L) go beyond the identified range (1,000 – 13,000 mg/L)?	Concur. Base case upper end of SSC has been run at 15,000 mg/L and the figure has been revised.	Stillwater
Peer	p13	Section 3.3.1	Could really use two axes.	Comment noted. Figure presentation revised, although the use of two axes did not sufficiently enhance presentation of the data. Instead, additional Figure 13 has been added (see also comment response line 30).	Stillwater
Peer	p14	Section 3.3.1	3.3.2?	Comment noted. Text updated.	Stillwater
Peer	p15	Section 3.3.3	What is going on with IOD and 0% DO saturation (upper left hand plot)? Is the travel time (~15 km) still in the time response for the initial oxygen demand?	Comment noted. Upper left tile shows that the IOD inventory is not consumed for the 1st 10-15 km downstream of Iron Gate Dam. Since initial DO saturation is zero, this reflects the characteristic time of the rate limiting process, which in this case, is re-aeration. For a Ka of 3.0 (1/d), t(1/2) is approximately -Ln(0.5)/3.0 = 0.23 days or 6 hrs.	Stillwater
Peer	p16	Section 3.3.3	See previous comment on consistency of target DO level for discussion.	Amended Basin Plan water quality objectives are now expressed as percent saturation, with a range of DO values established from Iron Gate Dam to the Klamath River estuary depending on water temperature (NCRWQCB 2010). 5 mg/L is used throughout the report as a conservative and generally applicable minimum value for warm water fish and the more complex minimum values from the Basin Plan are referenced as ranges. References to previously applicable values of 7 mg/L and 9 mg/L have been removed.	Stillwater
Peer	p17	Section 3.3.3	Should these be 0 and 0 instead of N/A	Concur. Zero and RM 190.1 at Iron Gate Dam. Also added footnotes to Table 4 and 5 to clarify distance downstream of Iron Gate Dam in kilometers.	Stillwater
Peer	p18	Section 3.3.5	Should the sensitivity range go beyond the range given in Thomann?	Concur. Re-ran model to include range of 0.3–3 g-O2/m2-d. Also added sentence: "In the Klamath River Basin, SOD rates measured by Doyle and Lynch (2005) in Lake Ewauna and the Klamath River range up to 3.0 mg/L."	Stillwater

Review Type	Comment Number (if provided)	Section Number	Comment	Brief Response to Comment	Who Addressed Comment
Peer	p19	Section 5	Did not review.	Comment noted	N/A
Peer	p20	Appendices	Read over, no comments	Comment noted	N/A
Courtesy		Title	This report is focused on the model development and the title should indicated that. Since the dam removal scenarios are still being developed, a modeling scenario to use to estimate the effects of dam removal on water quality is not available. A more appropriate title would be "Model Development to Estimate Short Term Impacts…".	Comment noted. Title revised.	Stillwater
Courtesy		General	Is there going to be any attempt to estimate long term impacts? It may be some time (years?) before the reservoir sites are stable, vegetated and properly functioning. How will this and the fact that the reservoirs had processed nutrients affect water quality?	Oxidation of the remnant sediments will occur once the water has been drawn down and they are exposed to air. Thus, we expect oxygen demand will be greatest during the initial drawdown, and will be reduced if not eliminated for subsequent years. Even if there is low-DO pore-water draining from the sites during rain events after the first year, its impact on the larger flow in the Klamath would likely be minimal just due to dilution effects. And sediment that is mobilized during such events should have already been mostly oxidized. A paragraph along these lines has been added to the discussion.	U.S. Geological Survey (C Anderson)
Courtesy		General	I know I keep bringing this up but what about the resident fish biomass – there are thousands of pounds of fish that will likely die and decompose in the river following dam removal.	This comment is beyond the scope of the report.	U.S. Geological Survey (C Anderson)
Courtesy		General	The model appears to be sensitive to background DO conditions. DO conditions (percent saturation and mg/l) recorded at PacifiCorp's Iron Gate water quality station appear to be low in the late fall (see http://www.pacificorp.com/es/hydro/hl/kr.html#). Not sure if that is a result of reservoir turnover or a function of still processing OM from UKL or both.	Added the following text to Section 3.2: "Although existing data indicates that background DO in the river downstream of Keno Reservoir and, in some cases, downstream of J.C. Boyle, Copco 1 and Iron Gate Reservoirs, is less than 100% saturation during the late summer/fall, the same initial DO saturation was used for all months in the base case as a simplifying assumption for the purposes of testing model sensitivity. Actual model runs should consider the month of drawdown and use existing data to set initial DO with respect to water temperature and typical background DO concentrations. It is anticipated that model runs conducted for late summer/fall months would possess the lowest initial DO saturation values.1" Also added the following text to Appendix A, Section A.2.1. "As an early model run, Background DO was assumed to be at 100% saturation for Drawdown Scenario 2. Later model runs considered existing data and set the background DO% saturation based on existing data (see also footnote in Table A-1)."	Stillwater
Courtesy		Section 3	I measured DO levels in J.C Boyle reservoir for a DO feasibility study (enclosed). I was surprised that the DO levels coming into the J.C. Boyle reservoir were low (e.g. 6.5 mg/l) at the surface even though there is an approximately 4-mile, high gradient reach between Keno Dam and J.C. Boyle Reservoir. Even though a sensitivity analysis was done for the reaeration, I have observed that mechanical mixing in the Klamath River does not occur as quickly as one would assume.	Comment noted. It appears that low % saturation as a background conditions is appropriate, and this was assumed for drawdown Scenarios 7 and 8 (see Appendix A).	Stillwater
Courtesy		Section 2	Certain elements of the document were consistent with the use of the Streeter-Phelps equation as a simple screening tool to assess potential impacts of sediment oxygen demand on downstream river reaches, such as - modifying the equation to include the sediment oxygen demand (SOD) as well as the biological oxygen demand (BOD) and the initial oxygen demand (IOD) that are already represented within the standard Streeter-Phelps equation; - setting the settling rate of BOD to zero to allow for the most conservative estimates; - using dilution factors for the tributaries to the Klamath River based on the average monthly tributary flows of three representative year-type water years; - selection of one reaeration equation for the upper portion and one reaeration equation for the lower portion of the river based on known river depths and velocities; - performing calculations for three representative water years (wet-1984, median-1976, dry-2001) and for 4 representative months for each of those years (December, March, June, and September) as a method for encompassing different types of hydrology and meteorology whic	Comments noted.	Stillwater

Review Type	Comment Number (if provided)	Section Number	Comment	Brief Response to Comment	Who Addressed Comment
Courtesy		Section 2	Use of velocity and depth data from a model of the Klamath River for the calculation of reaeration constants that do not compare with measured data is "inconsistent" with use of the Streeter-Phelps equation.	Comment noted. Given the extent of available information, velocities and channel geometry used for re-aeration rates are based upon hydraulic model data for the flows of interest (citation provided in the text). In the case of comparisons to available*in situ* reaeration data (from Ward and Armstrong), summer 2001 flow data were used together with summer *in situ* reaeration rates to allow an appropriate comparison and to guide the selection of the most appropriate empirical model.	Stillwater
Courtesy		Section 3	lack of sensitivity analysis of reaeration constants and lack of sensitivity analysis of BOD and IOD reaction rates. Reaeration rates were adopted from Ward and Armstrong that the authors identify that "[This result requires more detailed study." To rely on this elevated reaeration rate, while neglecting long-standing, widely applied approaches is overly optimistic in estimating recovery of dissolved oxygen in downstream reaches;	Comment noted. Reaeration rates from Ward and Armstrong were not used to calculate reaeration in the model; they were used only as a basis of comparison to guide the selection of the most appropriate empirical model. Additional senstivity analysis of reaeration rates was undertaken and included in the revised report (Section 3.3.5) Also, acknowledgement that direct measurement of in situ reaeration would be a good element of additional study, should there be an affirmative Secretarial Determination, has been added as one of the elements of a report addendum.	Stillwater
Courtesy		Section 3	correction to rate constants via the can't Hoff-Arrhenius approach at low temperatures (e.g., in the neighborhood of 4oC) has considerable limitations, and can result in overestimated decay rates that can have direct implications on DO conditions in downstream reaches;	Comment noted. Neal Armstrong indicated that it would be helpful for the reviewer to expand on this point about alternative approaches to correcting rates at low temperatures. Although the Arrhenius relationship is commonly used for temperature corrections and was used here, the fitted "theta" was very low (1.01) making the risk of overestimation of rates at lower (or higher) temperatures unlikely. Further, all dam removal scenarios evaluated were for winter or spring water temperatures, so this consideration may not apply in practice. However, a bullet suggesting further investigation of the rate constants at lower water temperatures has been added to the addendum to acknowledge that it would be best to measure in situ rate constants, which would inherently include temperature effects.	Stillwater
Courtesy		Section 3	the assumption that the microbial population is both sufficient in population and distributions within the sediment and water column to provide decomposition at the rates identified should be explored by examining a wider range of decay rates; and	Concur. Additional sensitivity analyses regarding order of magnitude variations in BOD decay rates was developed and included in the revised report (Section 3.3.3).	Stillwater
Courtesy		General	Overall, the modeling approach was too simplified to provide kilometer-by-kilometer estimates of impacts. Uncertainty around IOD, reaeration rates, assumed baseline condition, temperature correction method, decay rate dynamics, implications of upstream activities (e.g., coincident removal of Copco Reservoir), uncertainty in hydrology during sediment mobilization, fate of sediment transport to downstream reaches, and uncertainty around other factors (let alone modeling this system with a Streeter-Phelps approach) suggests that resolution of results would probably be on the order of 10 kilometer versus 1 kilometer. Uncertainty is not quantified and ranges of potential outcomes are not clearly identified.	Comment noted. Unfortunately, since uncertainty estimates were only available for oxygen demand (IOD, BOD) and associated decay rate constants, propagation of uncertainties to develop a prediction interval corresponding to a specific uncertainty was not feasible. Although application of plausible ranges of several parameters found in the literature could be carried out, it is unlikely that this uncertainty range is relevant to the conditions modeled. Nevertheless, we have qualified the interpretation of the results as within 10 km of model predictions and we have added the following background info to Section 2.2 "...given the possibility that additional dam removal alternatives may yet be developed and the understanding that additional studies would be undertaken if the Secretarial Determination is affirmative, a 1-dimensional reach-scale analysis of an order of magnitude estimate of oxygen demand was deemed most appropriate by Water Quality Sub Team (WQST) and the Engineering/Geomorphology/Construction Sub Team (EGCST) for the Klamath Dam Removal Secretarial Determination process. For these reasons the WQST and the EGCST w	Stillwater
Courtesy		Section 3	The ability of this model to provide specific distances downstream where critical water quality conditions occur is a valid question and one that should be addressed in the uncertainty analysis.	Comment noted. Unfortunately, since uncertainty estimates were only available for oxygen demand (IOD, BOD) and associated decay rate constants, propagation of uncertainties to develop a prediction interval corresponding to a specific uncertainty was not feasible. Although application of plausible ranges of several parameters found in the literature could be carried out, it is unlikely that this uncertainty range is relevant to the conditions observed here. Nevertheless, we have qualified the interpretation of the results as within 10 km of model predictions in the Discussion section and Appendix A. We also added the following sentences to Section 2.2: "For these reasons the Water Quality Sub Team and the Engineering/Geomorphology/Construction Sub Team for the Klamath Dam Removal Secretarial Determination process we have developed a simplified model in order to assess a range of potential downstream DO impacts on aquatic resources following dam removal. Stillwater Sciences later assisted the two sub teams in refinement of the model in a collaborative process. As it is a simplified model, predictions of particular DO levels at specifi	Stillwater
Courtesy		General	It has never been clear to me why the particular numerical solution method used was chosen. I have asked but not received an explanation. There are exact solution methods available in the references cited by the authors for the DO equations that comprise the DO model and that include CBOD, NBOD, IOD, and DO, they are easy to program in a spreadsheet, and they permit one to quite easily see the concentration changes in each of these constituents downstream and to take into account inflows of tributaries and the loading of these constituents from those tributaries. Indeed, some modifications of the plug models George Ward and I used for N and P could be made so that a range of river flows and tributary inputs could be well beyond the three representative water years and months for each year. Besides the exact solutions, there are other numerical solution methods available that are simple to program in a spreadsheet as well.	Comment noted. Although it is our understanding that the numerical form of the relationship within the model is an exact solution with an exponential decay with time (converted from water velocity and distance), the model was constructed to allow circumstances when DO would be predicted to drop to zero, a condition that most numerical solutions would not accommodate. Here, the model is comprised of numerically linked segments which receive boundary conditions of remaining DO, IOD, and BOD from the next upstream segment. We agree that alternative modeling approaches could be applied. We included an acknowledgement of the usefulness of comparing an exact solution to the model results developed for this report to an addendum. We also added the following sentences to Section 2.2: "For these reasons the Water Quality Sub Team and the Engineering/Geomorphology/Construction Sub Team for the Klamath Dam Removal Secretarial Determination process we have developed a simplified model in order to assess a range of potential downstream DO impacts on aquatic resources following dam removal. Stillwater Sciences later assisted the two sub teams in refinement of the model in a collaborat	Stillwater

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Courtesy		Section 2.3.6	Whatever computational method is chosen, it is critical that the model can be trusted to produce computationally correct results, and that has not been demonstrated for this model. The accuracy of numerical solutions for differential equations representing temporal and spatial changes in water quality such as those represented in this model are dependent on the time step, and that accuracy improves with decrease in the size of the time step. In this model the time step is based on the length of the segment and the water velocity, and one had to hope that this time step is small enough that an accurate solution is obtained. This can be easily tested by comparing the results of a numerical solution to that of an exact solution, and in my view this needs to be done to add to the confidence one can place in the model results.	Comment noted. Blair Greimann (USBR) provided an approach to verifying the model in an Excel spreadsheet. Model verification figure and supporting text added to Section 2.3.6. While it is beyond the scope of the report to develop and test a numerical solution, as suggested by the reviewer, an addendum has been added to the final report, with the following bullet: "Estimate the error associated with the numerical solution by comparing it to the explicit analytical solution(s) using a range of time steps/distance steps (model nodes). A comparison of numerical model results to traditional Streeter-Phelps solutions indicates that the numerical and exact solutions agree when accounting only for BOD and at smaller time/distance steps (see Section 2.3.6 model verification). As an alternative to the numerical solution, an exact solution incorporating CBOD, NBOD, IOD and sediment (bed) oxygen demand may be also developed that incorporates tributary dilution and variable channel geometry, as included in the current numerical solution."	Stillwater/U.S. Bureau of Reclamation
Courtesy		General	Also, water quality models need to be calibrated to demonstrate that they are calculating constituent concentrations accurately so that calculated values match observed values under given river flow, temperature, and tributary loading conditions. Even a screening model should be calibrated to this level. To my knowledge, this model has not been checked in this way, i.e., by applying the model to a set of field results under known flow, velocity, depth, and temperature. Comparison of predicted results of BOD and DO to actual field results would provide additional confidence in the model.E52	Comment noted. However, no field based data are available with which to calibrate the model. That is, without an experimental sediment release, few of the modeling assumptions or predictive accuracy can be tested. However, an addendum has been added to the final report, with the following bullet: "Estimate the error associated with the numerical solution by comparing it to the explicit analytical solution(s) using a range of time steps/distance steps (model nodes). A comparison of numerical model results to traditional Streeter-Phelps solutions indicates that the numerical and exact solutions agree when accounting only for BOD and at smaller time/distance steps (see Section 2.3.6 model verification). As an alternative to the numerical solution, an exact solution incorporating CBOD, NBOD, IOD and sediment (bed) oxygen demand may be also developed that incorporates tributary dilution and variable channel geometry, as included in the current numerical solution."	Stillwater
Courtesy		Section 3	On another matter, namely the graphs presented in the report beginning on page 16, it is not clear to me why the graphs appear to be linked line segments where the line segments represent constant concentrations of BOD and DO. Why do the graphs have that appearance? Are the concentrations represented in fact constant within those segments? What do the segment lengths represent – not intervals between tributaries or the segments in the DO and BOD lines would show distinctive concentration changes at the same distance downstream? Such representations of BOD and DO raise concerns about the ability of the model to provide specific distances downstream as Mike Deas noted in his Bullet #5.	Comment noted. The apparent segmentation of the graphs are artifacts of the image rendering. Further, the model results are currently calculated on a 1,000 m node spacing, but could be calculated at any spacing without loss of information. That is, although represented as constant values between each node, it should be recognized that the roughly exponential decay model applies across the length of each segment. We have also explained the apparent segmentation of the graphs in As described in previous comments, we have also qualified the interpretation of the results as within 10 km of model predictions.	Stillwater