Assessment of Technologies for Dissolved Oxygen Improvement in J.C. Boyle Reservoir

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Acronyms and Abbreviations

ac	acre
ac-ft	acre-feet
atm	atmospheres (related to air pressure)
BOD	biological oxygen demand
cfs	cubic feet per second
DO	dissolved oxygen
ft	feet
ft^3	cubic feet
g	grams
gpm	gallons per minute
ha	hectares
HRT	hydraulic residence time
L	liter
LOx	liquid oxygen
mg	milligrams
mg/L	milligram per liter (equivalent to parts per million, or ppm)
mgd	million gallons per day
mi	mile
msl	mean sea level (referring to elevation)
pH	potential of hydrogen (measurement of acidity of a water sample)
psi	pounds per square inch
SCFH	standard cubic feet per hour (regarding volumetric flow rate of a gas)
SCFM	standard cubic feet per minute (regarding volumetric flow rate of a gas)

SECTION 1

Introduction

1.1 Purpose

This report describes the results of an assessment of the availability and potential feasibility of technologies for improving dissolved oxygen (DO) conditions in J.C. Boyle reservoir (Figure 1). The reservoir is a narrow impoundment covering approximately 420 surface acres along a 3.5-mile stretch of the Klamath River from River Mile (RM) 224.7 to RM 228.2 in Oregon. J. C. Boyle reservoir is one of several facilities that comprise the Klamath Hydroelectric Project (Project), which is owned and operated by PacifiCorp Energy (PacifiCorp)[1].

The dominant influence on water quality, including DO, in the Klamath River is its source, Upper Klamath Lake (UKL). The lake has a history of nutrient enrichment problems and is currently hypereutrophic (Wee and Herrick 2005), and the lake's outlet at Link River dam (RM 254) contributes large amounts of nutrients and organic material to the Klamath River (Sullivan et al. 2011, Sullivan et al. 2009, ODEQ 2010, Deas and Vaughn 2006, PacifiCorp 2006, ODEQ 2002). These nutrients and organic materials from UKL (and other upstream sources) are the primary cause of low DO in J.C. Boyle reservoir and in the Klamath River downstream of J.C. Boyle dam at certain times of the year (NCRWQCB 2010, ODEQ 2010, PacifiCorp 2006, PacifiCorp 2004a, PacifiCorp 2004b). J.C. Boyle is generally well-mixed, but temporary vertical gradients (weak stratification) can occur during summer, particularly where the reservoir is deepest near the dam. During such temporary stratification, lower DO concentrations (to approximately 3 mg/L) can develop in the reservoir, particularly in the deeper area. A more detailed description of the J. C. Boyle reservoir morphology and water quality is provided in section 2 of this report.

The assessment described in this report is an action being conducted under Interim Measure 11 (IM 11) of the Klamath Hydroelectric Settlement Agreement (KHSA) executed on February 18, 2010. The KHSA includes provisions for the interim operation of the dams and implementation of interim measures prior to removal of the dams or the termination of KHSA. IM 11 – titled "Interim Water Quality Improvements" – includes actions to improve water quality in the Klamath River during the interim period leading up to potential removal of J.C. Boyle dam (and three other dams on the Klamath River in California owned by PacifiCorp – Copco 1, Copco 2, and Iron Gate dams) as described in the KHSA.

Specific objectives for DO improvement in J.C. Boyle reservoir are not assumed or analyzed in this report. This report simply assesses the relative effectiveness of technologies to improve DO in J.C. Boyle reservoir. To aid in assessing relative effectiveness, this report includes calculations and modeling of potential DO improvement technologies in the reservoir. However, these analyses are not intended to assess technologies to meet particular objectives, and no conclusions are expressed or implied in this report on these technologies from a regulatory perspective.

[1] As currently licensed by FERC, the Oregon portion of the Project on the mainstem Klamath River also includes the East Side and West Side powerhouses at RM 253 and Keno dam at RM 233. In its new license application to FERC, PacifiCorp has proposed to remove the East Side, West Side, and Keno facilities from the Project. The East Side and West Side facilities will be decommissioned, and no hydroelectric generating facilities are associated with Keno dam (and therefore it is not within FERC's regulatory jurisdiction).

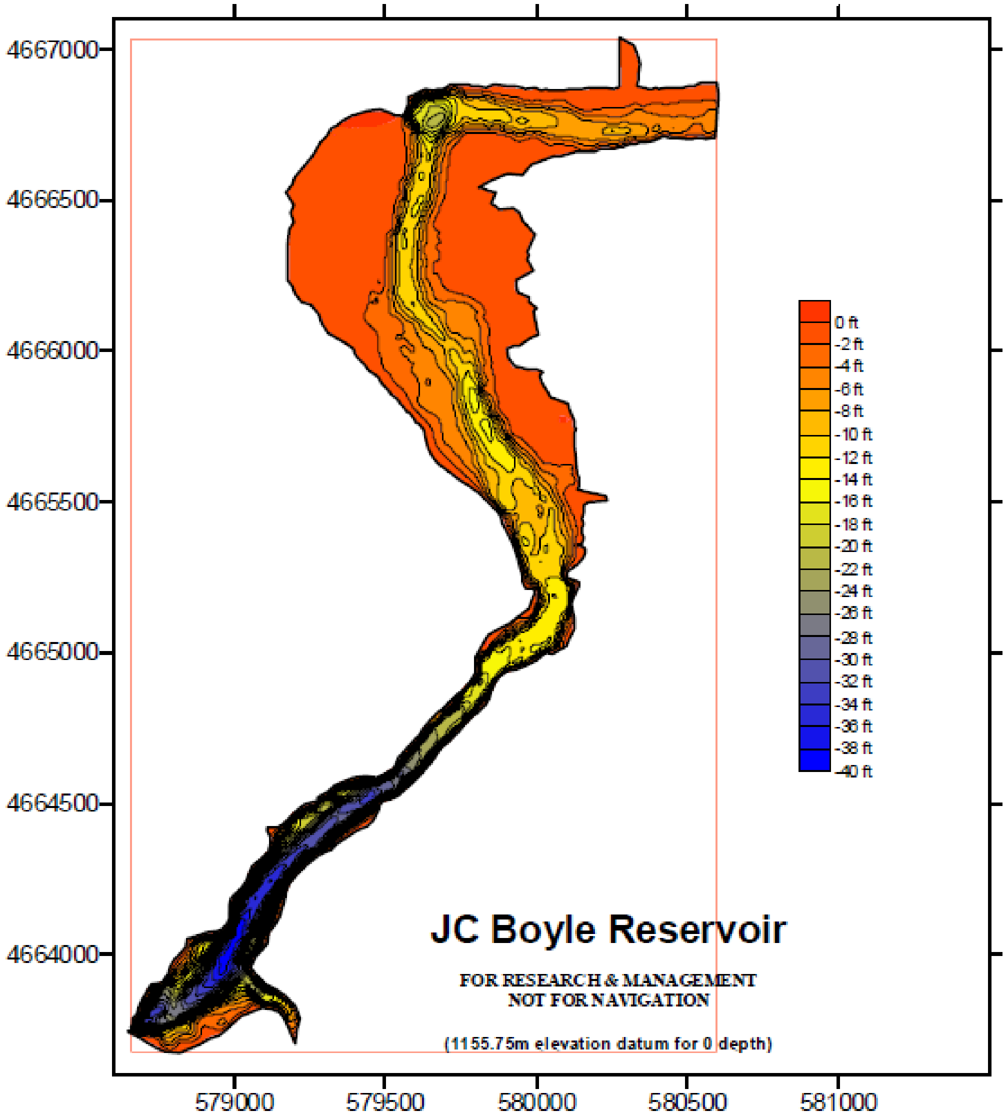

FIGURE 1
Bathymetric map of J.C. Boyle reservoir. The shallow areas (shown in red) in the north half (upper) of the lake were not navigable during the survey, and the depth in this region is estimated between zero and 2 feet.

1.2 DO Improvement Technologies Addressed in this Report

PacifiCorp previously prepared Reservoir Management Plans (RMPs) to evaluate the effectiveness and feasibility of various technologies and measures to improve water quality conditions in J.C. Boyle reservoir (PacifiCorp 2008a). PacifiCorp also prepared RMPs for Copco and Iron Gate reservoirs (PacifiCorp 2008b), which are located along the Klamath River in California (from RM 190.1 to RM 203.1).

The J.C. Boyle reservoir RMP identified several potential techniques for DO enhancement in lakes and reservoirs as described by Cooke et al. (2005), Thornton et al. (1990), and Cooke and Kennedy (1989). Of these techniques, three targeted at improving DO were further evaluated in the RMP development process: (1) water column circulation, (2) epilimnion methods, and (3) hypolimnetic methods. Because J.C. Boyle reservoir is generally well-mixed with only temporary weak stratification (as noted above), specific epilimnion and hypolimnetic methods lack applicability to J.C. Boyle reservoir, leaving water column circulation as the most appropriate approach for potential application to J.C. Boyle reservoir.

For this report, IM 11 study activities have included gathering information on the potential use of three technologies for improving DO conditions in J.C. Boyle reservoir: (a) aeration or air injection; (b) oxygenation; and (c) mechanical mixing. Aeration or air injection is addressed in section 3 of this report. Aeration or air injection (diffuser) systems are a common water column circulation (destratification) method. Aeration-driven circulation is intended to mix the entire vertical water column to prevent or interrupt vertical stratification. This technique thereby introduces oxygen to the bottom waters of the reservoir by mixing the oxygen produced by algae out of the euphotic zone (i.e., the surface zone with sufficient light for algal growth).

Aeration or air injection (diffuser) systems consist of a compressor on shore that delivers air through lines connected to a perforated pipe(s) or other simple diffuser(s) placed near the bottom, typically in the deep area of the lake. The rising air bubbles cause water in the bottom water layer to also rise, entraining water and transporting it into the surface water layer. This aeration technique is sometimes referred to as the air-lift method of circulation, since bottom waters are “lifted” to the lake surface through the action of the injected air.

The second technology – oxygenation – is addressed in section 4 of this report. Oxygenation systems are similar to aeration systems (as described above) except that pure oxygen rather than air is used. The typical applications of oxygenation in lakes and reservoirs have been to treat stratified bottom waters of the lake or reservoir (e.g., hypolimnion), where low DO or anoxia can often occur, particularly during summer (Cooke et al. 2005). However, oxygenation focused on the hypolimnion is not considered a prudent choice for J.C. Boyle reservoir because the reservoir does not strongly stratify (Horne et al. 2009). Therefore, stratification is not the underlying cause of lower DO conditions in J.C. Boyle reservoir. Instead, the lower DO conditions are caused by oxygen demand imparted by the inflow loading of organic matter to the reservoir from upstream. As a result, the more appropriate candidate oxygenation techniques include those that would directly treat oxygen demand in the reservoir.

The two types of oxygenation systems considered most suitable for augmenting DO in J.C. Boyle reservoir are: (1) side-stream oxygenation; and (2) linear diffuser oxygenation. For both types of systems, oxygen is typically transported to the site as liquid oxygen (LOx) and stored onshore, or can be generated on-site by a pressure swing compressor and molecular sieve. Side-stream oxygenation pulls water from the reservoir, oxygenates it onshore, and then returns it to the reservoir. Linear diffuser oxygenation provides delivery of oxygen using a system of pipes with small holes laid within the reservoir. Gaseous oxygen is passed to the underwater pipes and fine oxygen bubbles rise, releasing oxygen to the water as they do so.

The third technology – mechanical mixing – is addressed in section 5 of this report. Mechanical mixing is a common technique for water column circulation targeted at mixing the water column to improve water quality by distributing the oxygen produced by algae from the surface zone (where algal growth mostly occurs) to the bottom waters of the reservoir. Mechanical mixing can also elevate low DO bottom water to the surface, where it can mix with the higher oxygen in the surface or gain oxygen from the atmosphere. Under special circumstances, the circulation may actually reduce photosynthesis by mixing algae into darker water.

Mechanical mixing is accomplished using axial flow pumps in a “top-down” approach to set up a vertical circulation pattern through the water column of the reservoir. A floatation platform and frame support an electric motor, gearbox, drive shaft, and large propeller (6 to 15 foot diameter). The propeller is suspended just a few feet below the water surface. Its rotation “pushes” water from the reservoir surface downward, setting up the vertical circulation pattern.

SECTION 2

J.C. Boyle Reservoir Features and Existing DO Conditions

2.1 Reservoir Features and Influences on Water Quality

J.C. Boyle reservoir has a maximum depth of 40 feet, and contains approximately 3,495 acre-feet of total storage capacity and 1,724 acre-feet of active storage capacity. The normal maximum and minimum operating levels of the reservoir are between El. 3,793 feet and El. 3,788 feet msl, a range of 5 feet. J.C. Boyle reservoir has two distinct sections: (1) a wide and shallow section (of about 3 to 5 feet depth) in the upper part of the reservoir; and (2) a narrow and deeper section (of about 25 to 40 feet depth) in the lower part of the reservoir (Figure 1). The bathymetry in the lower section includes a relatively deeply-incised remnant river channel that has been inundated by the reservoir up to the dam (Figure 1).

A key feature of J.C. Boyle reservoir that affects water quality conditions is its short hydraulic residence time (HRT). HRT is the ratio of reservoir volume (V) to outflow rate (Q). J.C. Boyle reservoir has an HRT of 1 to 2 days at average annual flow of 1,500 cfs, 2 to 3 days at a typical summer flow of 750 cfs, and less than a day at a relatively high flow of 3,000 cfs. A short HRT (a few days) is indicative of a high flushing rate in the reservoir, which results in conditions in J.C. Boyle reservoir that are dictated by conditions in the upstream Klamath River flowing into the reservoir.

A key feature of these advected conditions to J.C. Boyle reservoir is the high biochemical oxygen demand (BOD) of the water in the Klamath River that enters the reservoir. The advected BOD of Klamath River water discharged to J.C. Boyle reservoir represents a large amount of oxygen demand in the reservoir. Typically, lakes and streams have a 5-day biochemical oxygen demand (BOD_5)[2] of 1 to 2 mg/L. Unlike most lakes and reservoirs, the BOD_5 of UKL as it flows out of the lake and into the upper Klamath River can be as much as 30 mg/L (Tetra Tech 2004, Doyle and Lynch 2005, Deas and Vaughn 2006). The BOD in UKL is mostly due to living and decaying algal biomass that is abundant in UKL (Wood et al. 2006).

The short HRT and relatively shallow depth of J.C. Boyle reservoir also results in little thermal stratification in the reservoir driven by solar heating. However, a slight temperature gradient occurs in the reservoir during summer as a result of the diurnal variation in the temperature of the influent river (Figure 2). In summer, cooler water entering the reservoir at night has relatively low dissolved oxygen and tends to flow under the warmer water at the surface of the reservoir, while warmer water flowing in during the day has relatively higher dissolved oxygen and tends to remain close to the surface. Model results and field data indicate that the typical mid-July diurnal range of temperature in the upstream Klamath River flowing into J.C. Boyle reservoir is approximately 20 to 27°C (PacifiCorp 2008). This corresponds to the vertical temperature gradient of about 18 to 22°C in J.C. Boyle reservoir (Figure 2).

2.2 Existing Dissolved Oxygen Conditions in the Reservoir

Daily average DO concentration in the Klamath River flowing into J.C. Boyle reservoir is less than 8 mg/L for most of the period from April through October, and is 6 mg/L or less in July and August (Figure 3). As described above, the BOD associated with loading of organic matter from the upstream Klamath River flowing into J.C. Boyle reservoir causes reduced DO concentrations in J.C. Boyle reservoir. There is a strong relationship between high organic content of the upstream Klamath River water (as measured at Keno dam as BOD_5) and low DO

[2] The amount of DO consumed in five days by biochemical processes breaking down organic matter.

concentrations (Figure 4). DO conditions in J.C. Boyle reservoir are explained in further detail in PacifiCorp (2008), Raymond (2009), and Horne et al. (2009), and are summarized further below.

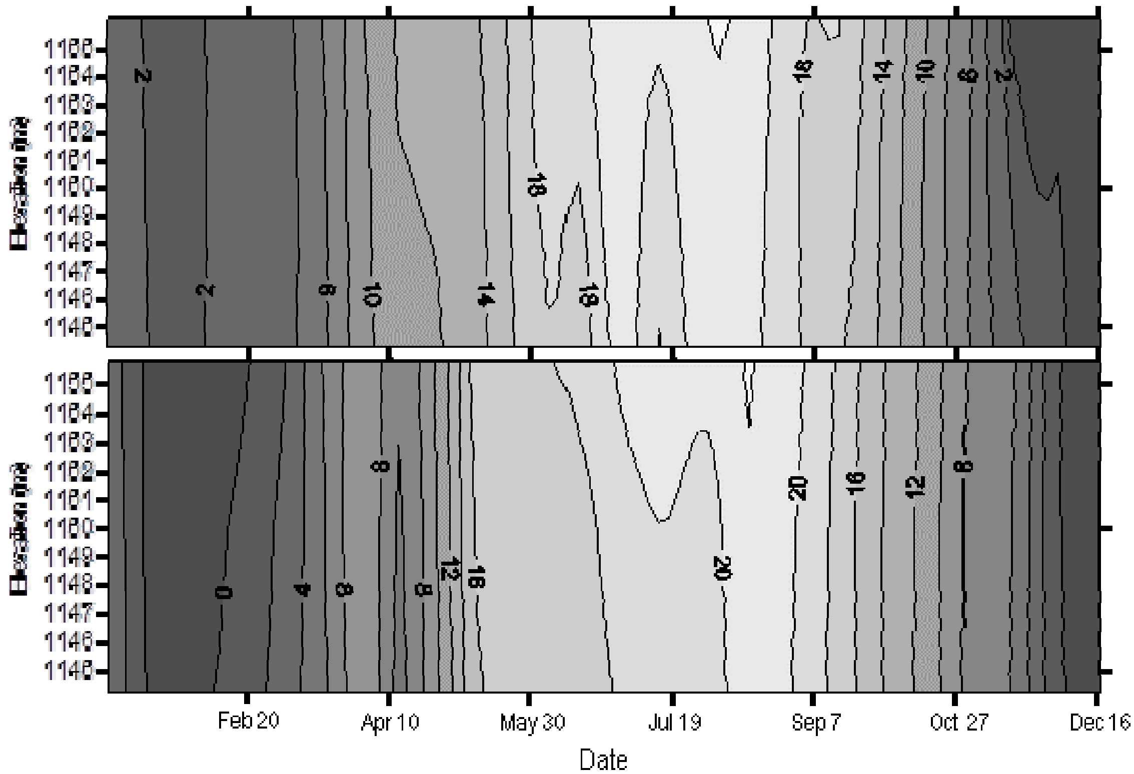

FIGURE 2
J.C. Boyle reservoir water temperature isopleths for 2000 (top) and 2001 (bottom).

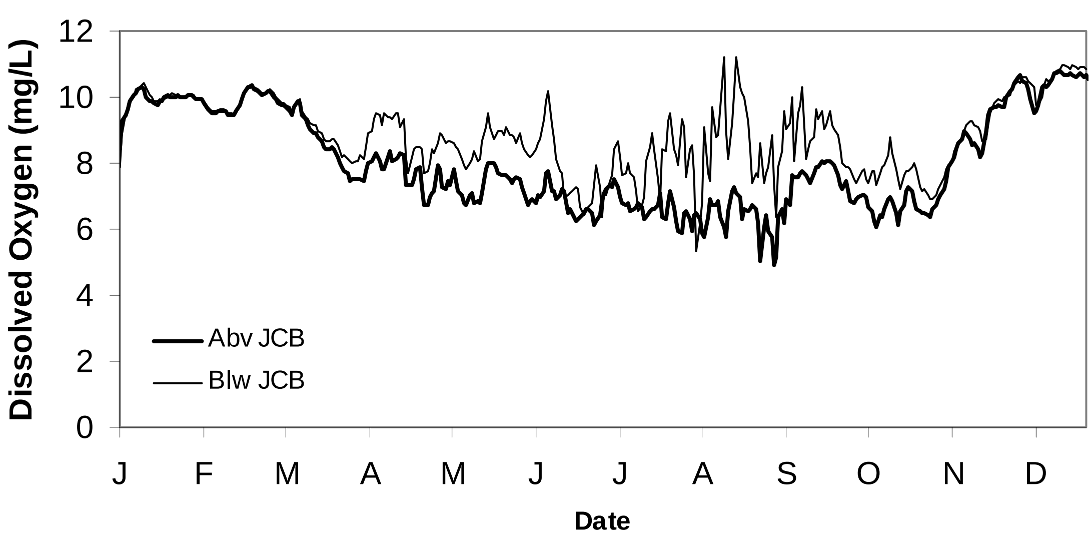

FIGURE 3
Daily average dissolved oxygen concentration in the Klamath River entering J.C. Boyle reservoir and below J.C Boyle dam, based on modeled hourly values for 2000 (PacifiCorp 2008).

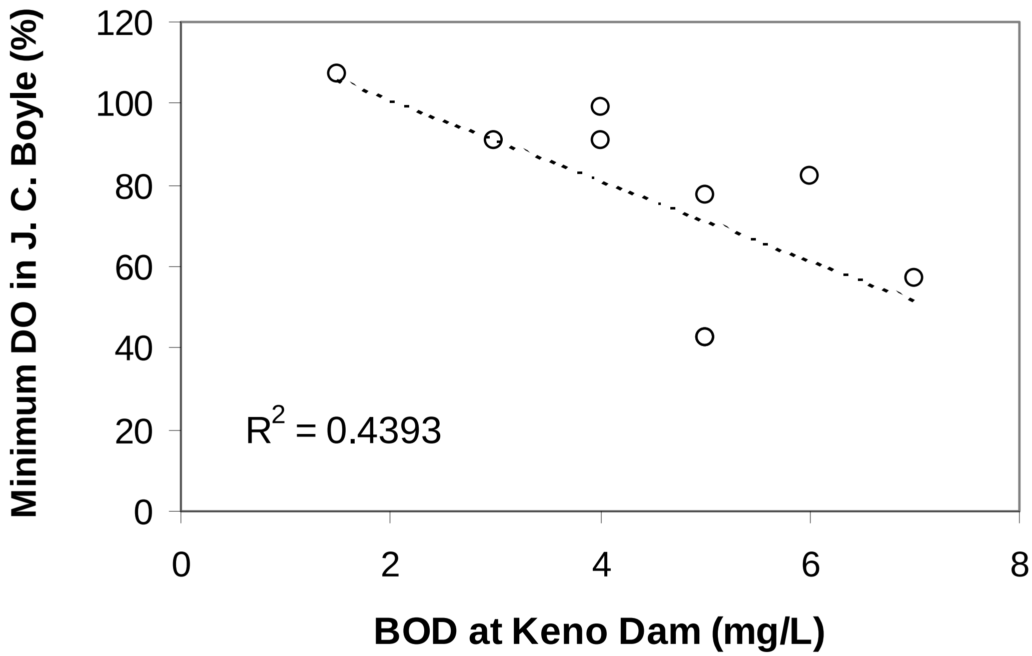

FIGURE 4
Minimum dissolved oxygen measured in J.C. Boyle reservoir compared to BOD measured at Keno dam on the same day. High BOD at Keno dam is associated with low dissolved oxygen in J.C. Boyle reservoir.

The high BOD in the inflow to J.C. Boyle reservoir, combined with the reservoir's short HRT and relatively shallow depth, results in low DO values in the reservoir. However, DO values that are appreciably less than reservoir inflow levels are confined mostly to deeper areas (below 5 m) in the downstream part of the reservoir near the dam. For example, a synoptic survey of DO taken in the reservoir in August 2008 (Figure 5) shows that DO at most locations in the reservoir were generally equivalent to inflow DO levels, except in deeper downstream sampling locations (Figure 6). DO isopleths from the deepest point in the reservoir (near point 32 shown in Figure 5) showed distinct vertical oxygen gradients in the summer of 2000 and 2001 (Figure 7), but the gradients are much smaller in magnitude in J.C. Boyle reservoir than occurs in other reservoir systems with stronger vertical stratification (such as in Copco and Iron Gate reservoirs). The isopleths shown in Figure 7 also confirm that lowest DO values of the year occur in July and August (Figure 7).

To provide additional definition of the temporal character of DO conditions in J.C. Boyle reservoir, two continuously-monitoring probes were deployed in the lower end of the reservoir to measure DO at hourly intervals during several multi-day periods in 2010 and 2011. The probes were deployed at depths of 3 and 7 meters over the deepest point in the reservoir (at the log boom near point 32 shown in Figure 5). The hourly data from the probes were used to assess the diurnal range and variability of DO at the deployment location, and to assess the diurnal range and variability of DO by depth and through the summer-fall seasons.

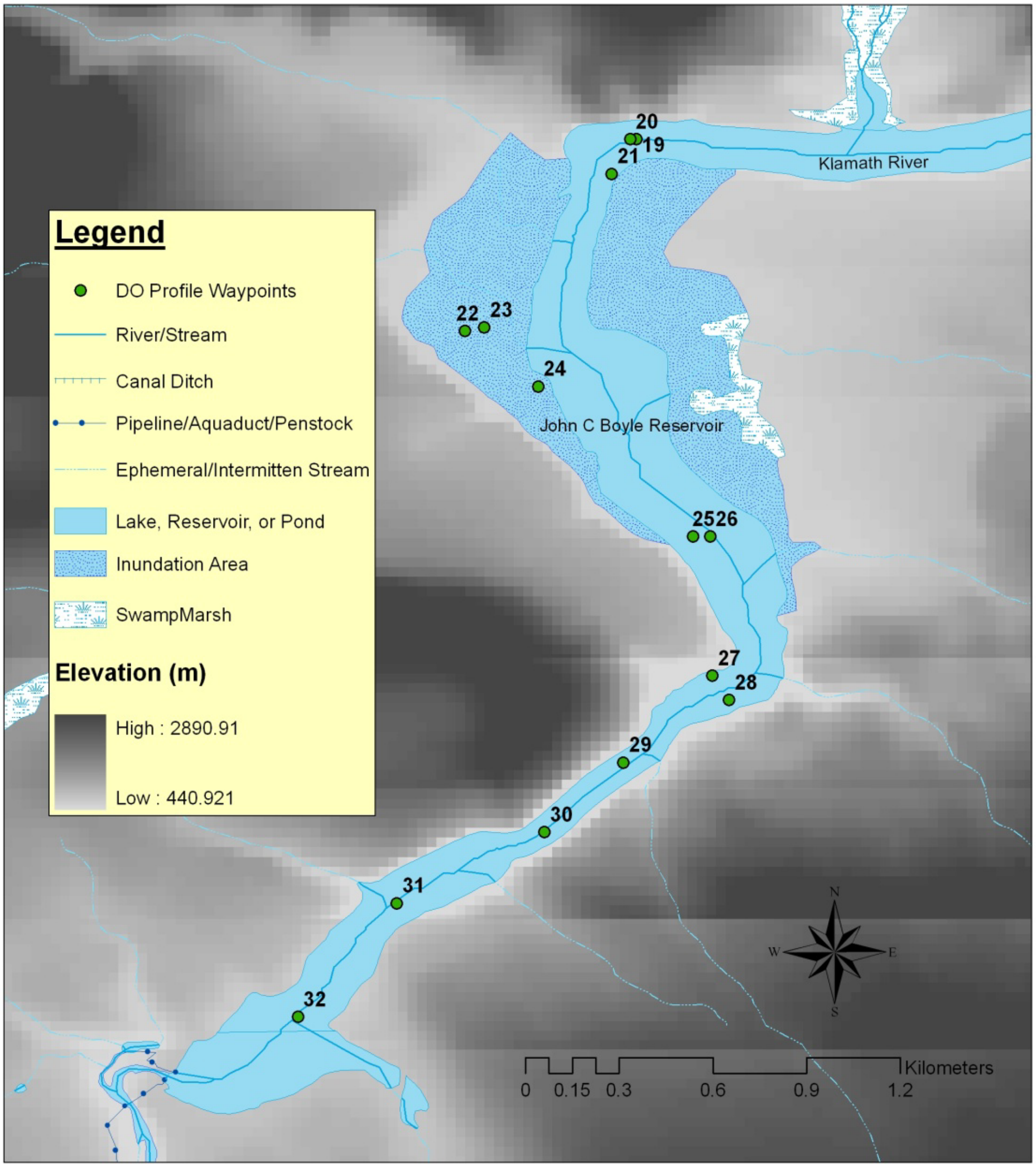

FIGURE 5
Map showing locations of DO profiles taken in J.C. Boyle reservoir on August 28, 2008.

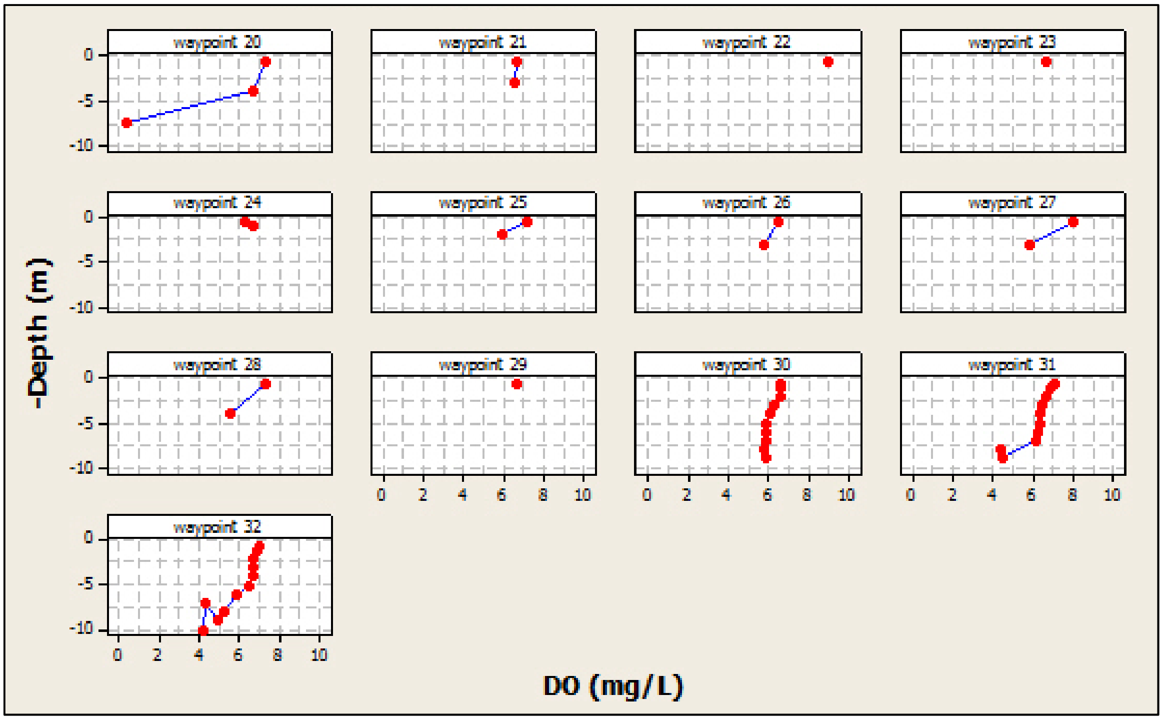

FIGURE 6
Vertical profiles of DO concentration (mg/L) with depth (m) taken in J.C. Boyle reservoir on August 28, 2008.

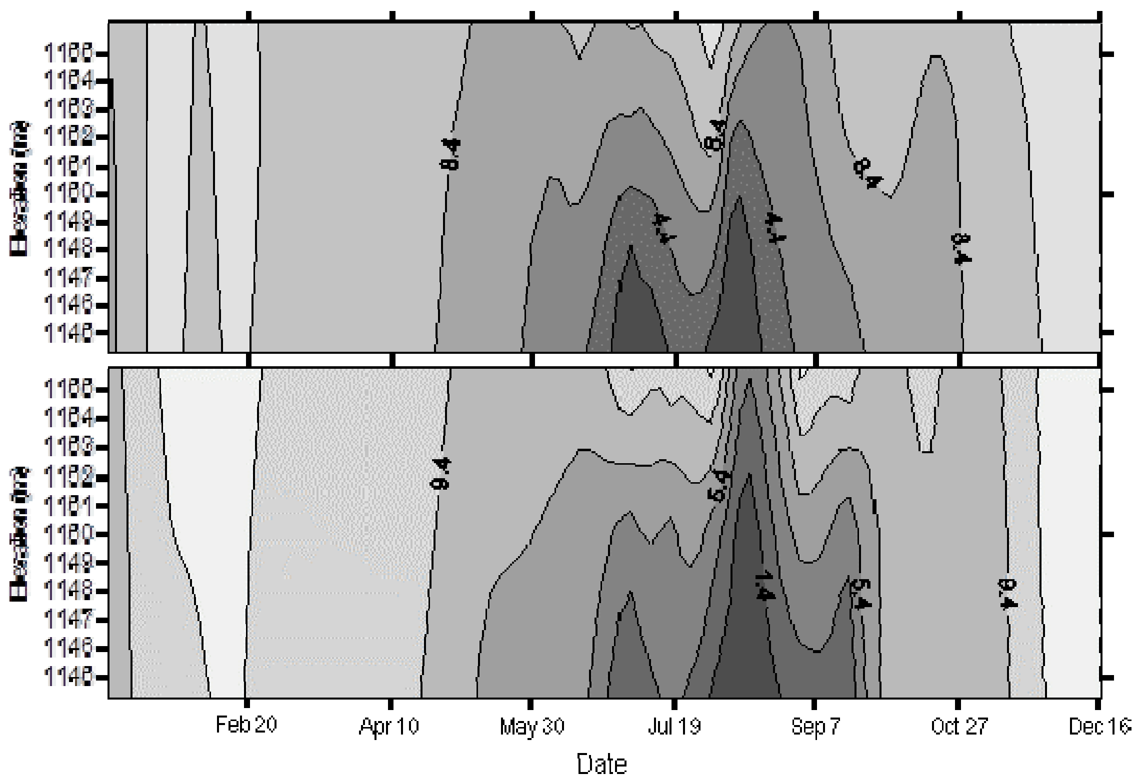

FIGURE 7
J.C. Boyle reservoir dissolved oxygen isopleths for 2000 (top) and 2001 (bottom).

The hourly data from the probes are summarized in Figure 8, which includes vertical bars showing the range in hourly values for each day of probe deployment. Each bar is accompanied by symbols representing the average DO for each day as measured by the probe at 3 meters (indicated by circles) and the probe at 7 meters (indicated by squares). The hourly data summarized in Figure 8 confirm that, from a seasonal perspective, lowest DO values occur in mid-summer (such as also seen in Figure 3 and Figure 7). The relative lengths of the vertical bars shown in Figure 8 are also greatest in July and August, indicating that the greatest daily ranges of hourly values occurs in mid-summer. Greater daily ranges in mid-summer are expected given that algae production and respiration in the river system are at or near peak levels for the year. The daily average values shown in Figure 8 also confirm that DO is consistently higher at shallower than deeper depth levels in the reservoir (such as also seen in Figure 6 and Figure 7).

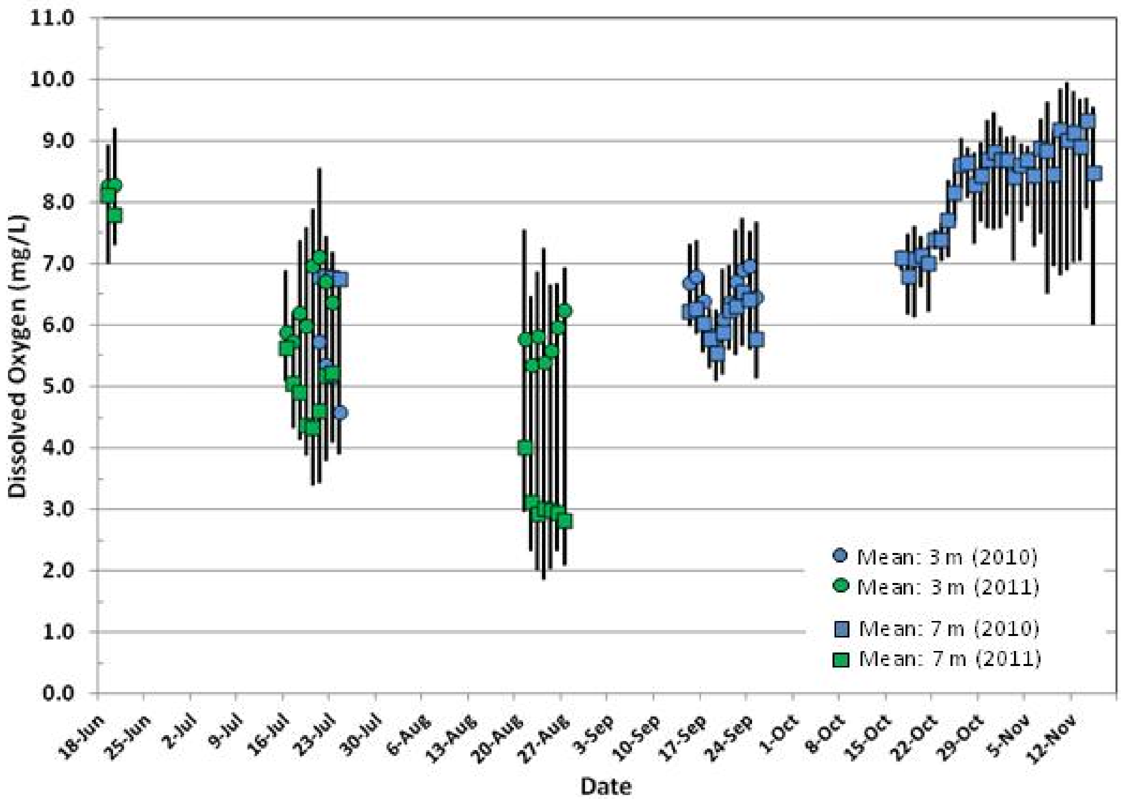

FIGURE 8

High, low, and average hourly DO measurements from probes deployed in J.C. Boyle reservoir (at the log boom) at depths of 3 meters and 7 meters during several multi-day periods in 2010 and 2011.

SECTION 3
Aeration or Air Injection

3.1 Previous Assessment

Horne et al. (2009) previously assessed potential implementation of an air injection diffuser system for water column mixing and circulation in J.C. Boyle reservoir. Air injection diffuser systems are a common technique for enhancing water column circulation and mixing in reservoirs to improve DO by eliminating vertical density gradients that lead to low DO concentrations in the bottom waters.

Horne et al. (2009) determined that the most appropriate system for J.C. Boyle reservoir would be an air injection (diffuser) system located in, and focused on DO enhancement in the deeper, lower portion of the reservoir. A focus on DO enhancement in the deeper, lower portion of the reservoir would be most appropriate because a system in the upper part of the reservoir would lack efficiency and effectiveness for two key reasons: (1) the high inflow load of BOD to the upper end of the reservoir could not be overcome by an air injection (diffuser) system; and (2) the upstream part of the reservoir is too shallow, so that the mixing and air plume effects from a system would be small. In addition, the length of diffuser pipe for a system in the upper part of the reservoir would be long, presenting difficulties of balancing the airflow over long lengths of pipe (although the use of individually regulated diffusers may overcome this drawback).

3.2 Conceptual Design for an Air Injection System in J.C. Boyle Reservoir

The conceptual design developed by Horne et al. (2009) for an air injection (diffuser) system in the deeper part of J.C. Boyle reservoir is shown in Figure 9. The conceptual design is based on a system that would mix and partially aerate the water column by installing a series of 50 individual diffusers over a 1280 meter (m) length of the reservoir up from J.C. Boyle dam. The volume of air needed for the conceptual design for the J.C. Boyle reservoir aeration system was estimated using the generalized method of Cooke et al (2005). The amount of total air flow required was computed as 260 m^3 air/km^2/hr (at atmospheric pressure) to mix an area of about 60 acres (approximately 0.24 km^2) in the deeper part of the reservoir where the proposed aeration system would be located. This particular area is selected because the depth in the center of the reservoir is sufficient (i.e., greater than about 25 ft deep) to allow for effective mixing and oxygen uptake from the diffuse bubble plumes (per the findings of Motarjemi and Jameson 1978).

Horne et al. (2009) recommended that the diffusers to be fitted would be either disc diffusers or tube diffusers fitted with flow regulators. However, the choice of the exact diffuser type would be a subsequent design decision based on more detailed assessment of specific DO enhancement objectives, and associated calculations of mixing and oxygen transfer efficiency calculations (Smith et al. 1975). The literature suggests that with a bubble size of 2-3 mm and with a depth of 10 m, it would be possible to achieve efficient oxygen transfer using a standard disc diffuser with compressed air or oxygen. However, given the additional constraints in J.C. Boyle reservoir of relatively high elevation and high BOD inflow loading, a more sophisticated fine/medium orifice type of diffuser may be the best choice. The fine/medium orifice diffusers would deliver a more controlled bubble size than a simple orifice, giving better oxygen transfer and water mixing. Horne et al. (2009) indicate that minor additional cost implications are involved with the selection of either type of diffuser.

The air would be delivered into the primary system feed line (specially made from 1.5-inch ID hydraulic hose, which is self-sinking in water) as shown in Figure 9. The primary system feed line would be fitted with a manifold, and a non-return valve. The primary system feed line would be located adjacent to the reservoir shoreline in shallow water approximately on the 2 m depth contour to make the system easier to access, install, and maintain. The hose is very tough and heavy, making it virtually vandal proof, but is not so heavy that short sections cannot be brought manually to the surface for maintenance.

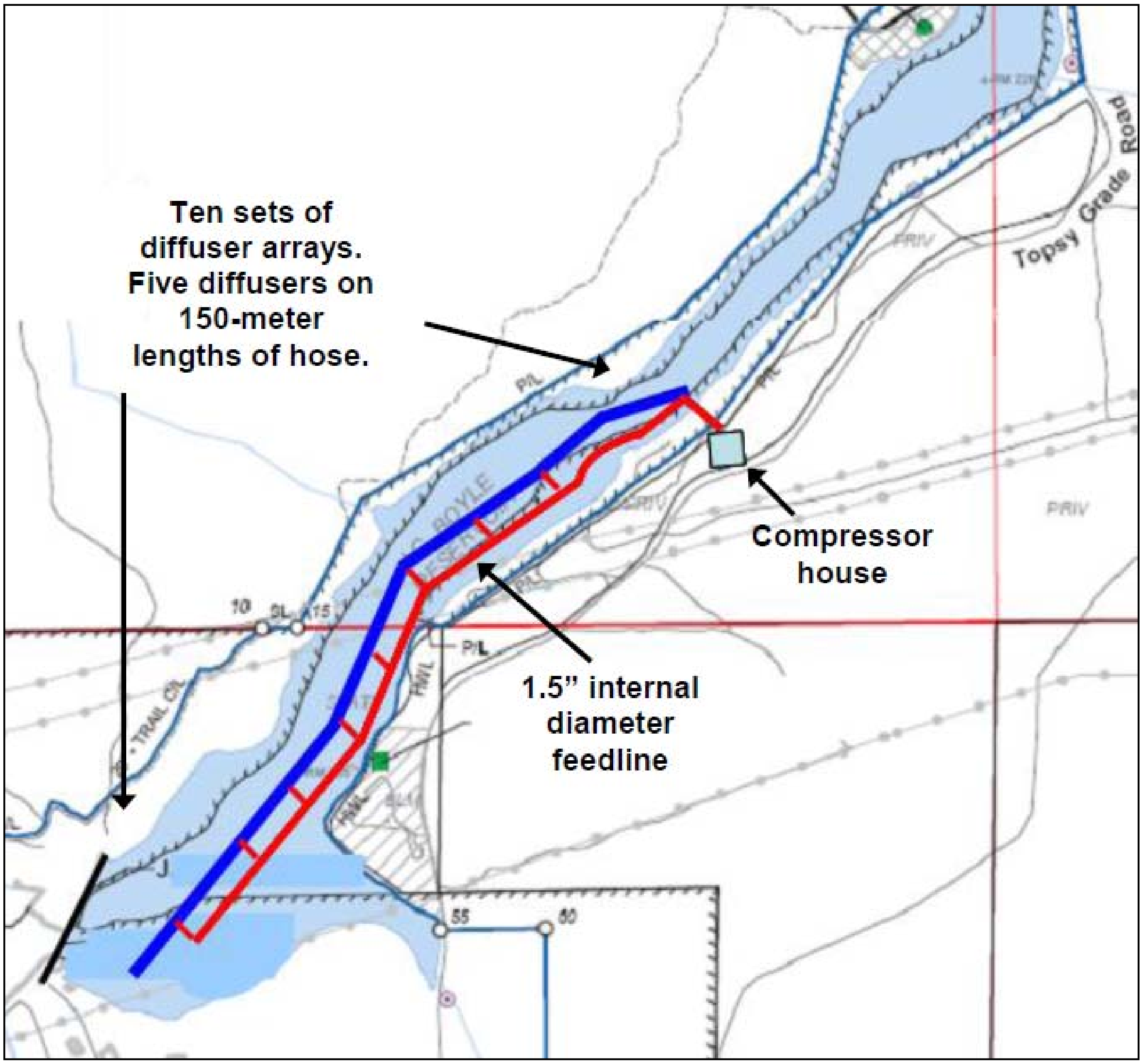

FIGURE 9
Conceptual design layout of an aeration system for J.C. Boyle reservoir (from Horne et al. 2009).

To supply a compressed air flow rate to the air injection (diffuser) system of 260 m^3/hr at atmospheric pressure, a three-phase electrical supply of sufficient size to operate a 22 kW (approximately 30 hp) air compressor would be required. Horne et al. (2009) recommended a location for the compressor and housing as shown in Figure 6. The housing would be located on a constructed concrete base. It may be appropriate to construct a larger base than required and to provide a bigger electrical supply than that stipulated for the present conceptual design; this would allow for expansion of the system either up or down the reservoir should this be needed in the future.

3.3 Estimated Effectiveness of an Air Injection System in J.C. Boyle Reservoir

The effectiveness of this aeration system for enhancing DO in J.C. Boyle reservoir would be limited. In particular, this system would be applicable only in the deeper, lower end part of J.C. Boyle reservoir. Such a system in the upper part of the reservoir would lack efficiency and effectiveness due to: (1) the high advection of BOD in the river inflow to the reservoir from upstream sources; (2) the shallow nature of the upper part of the reservoir so that bubbles generated would have small, if any, DO enhancement effect; and (3) the operation and maintenance difficulties that would be posed by the long lengths of diffuser pipe that would be needed in the upper part of the reservoir.

Furthermore, even in the deeper, lower end part of J.C. Boyle reservoir, there are two major constraints that would limit DO improvement from this system. First, the relatively high elevation of J.C. Boyle reservoir (3,790 ft msl) means that the air contains less oxygen than at elevations within 500 feet of sea level where most aeration systems have been installed. The lower oxygen content in the air further reduces the already poor efficiency of oxygen to water transfer in the bubbles. Thus, in J.C. Boyle reservoir, insufficient oxygen can be introduced from atmospheric air uptake at the water surface and from the solubility of the air bubbles to appreciably raise DO levels, especially to 5 mg/L or above. Second, the high and dynamic BOD load to J.C. Boyle reservoir would likely greatly increase the volume of air needed (and the specific oxygen level likely achieved) as calculated based on standard air solubility equations because the efficiency of oxygen transfer decreases as the DO level in the water increases. For example, it would require twice the air volume (hence, double the number of diffusers) to raise the DO level from 3 to 5 mg/L than from 1 to 3 mg/L. The relative effectiveness and approximate costs of an air injection (diffuser) system relative to other technologies for DO improvement in J.C. Boyle reservoir are discussed further below in section 6 *Conclusions*.

SECTION 4

Oxygenation

4.1 Oxygen Demands

The technical feasibility of a particular DO improvement technology depends on whether the technology can meet oxygen demands. BOD in the water column and sediment oxygen demand (SOD) are oxygen sinks in any reservoir. Net dissolved oxygen depletion occurs when atmospheric reaeration and oxygen gain from photosynthesis have a combined value less than the combined value of SOD and BOD. However, SOD is not considered an important element of oxygen demand in J.C. Boyle reservoir because stratification is not the underlying cause of oxygen deficit in the reservoir, and the HRT in the reservoir is short (i.e., about 1 to 2 days at average river flow). Therefore, for J.C. Boyle reservoir, determining water column oxygen demand is the primary step.

CH2M HILL used the BioWin model to derive an initial estimate of water column oxygen demand in J.C. Boyle reservoir. BioWin is a simulator used world-wide in the analysis and design of wastewater treatment plants. BioWin allows for calculation of soluble (filtered) and total carbonaceous BOD for any input element, process unit, or stream. BioWin uses analytical equations to estimate BOD based on rates of degradation of the different components, such as influent biodegradable material (readily and slowly biodegradable). BioWin was used under the assumption that the lower part of J.C. Boyle reservoir is akin to a wastewater reaeration basin. In wastewater treatment, DO is commonly kept between 2 to 4 mg/L for reasons of process efficiency. A reaeration basin is a post-treatment step sometimes required to raise wastewater effluent DO high enough for discharge (typically 5 to 8 mg/L, depending on receiving water conditions).

Based on the BOD values in J.C. Boyle reservoir, and an assumed summer flow of 750 cfs in the Klamath River through the reservoir, the BioWin model estimates the oxygen demand at 4,650 kg/day to raise DO in the lower part of J.C. Boyle reservoir by 2 mg/L (from 3 to 5 mg/L). As discussed in section 2 of this report, measured BOD_5 values in J.C. Boyle reservoir are on the order of 5 to 10 mg/L, which falls within the range (of about 3 to 30 mg/L) of BOD_5 values observed in advanced treated effluents to wastewater reaeration basins. BOD_5 values in J.C. Boyle reservoir of 5 to 10 mg/L equate to oxygen depletion rates of about 2 to 4 mg/L/day. Lorenzen and Fast (1977) report that hypolimnetic oxygen depletion rates in deeper lakes and reservoirs typically range from 0.04 to 0.30 mg/L/day, while oxygen consumption rates in shallow (1 to 2 m deep) aquaculture ponds typically range 1.44 to 20.0 mg/L/day. Therefore, the estimated oxygen depletion rates in J.C. Boyle reservoir are more similar to shallow, well-mixed aquaculture ponds than to deeper lakes and reservoirs as reported by Lorenzen and Fast (1977).

4.2 Potential Oxygenation Technologies

Two types of oxygenation systems considered most suitable for augmenting DO throughout the water column of J.C. Boyle reservoir are: (1) contact chamber or side-stream oxygenation; and (2) linear diffuser oxygenation. For both types of systems, oxygen is typically transported to the site as liquid oxygen (LOx) and stored onshore, or can be generated on-site by a pressure (or vacuum) swing compressor and molecular sieve.

4.2.1 Contact Chamber or Side-Stream Oxygenation

Contact chamber or side-stream oxygenation works by a process of pulling water from the lake, oxygenating it in a saturation chamber, and then returning the water to the lake (Figure 10). An intake is placed in the lake with a screen to prevent debris from damaging the downstream equipment. The process uses a standard centrifugal pump to move the water through the system. The saturation chamber varies for each unit and is described below in the technology specific section. The super-oxygenated water is injected back into the lake via diffusers (or other outlet structure).

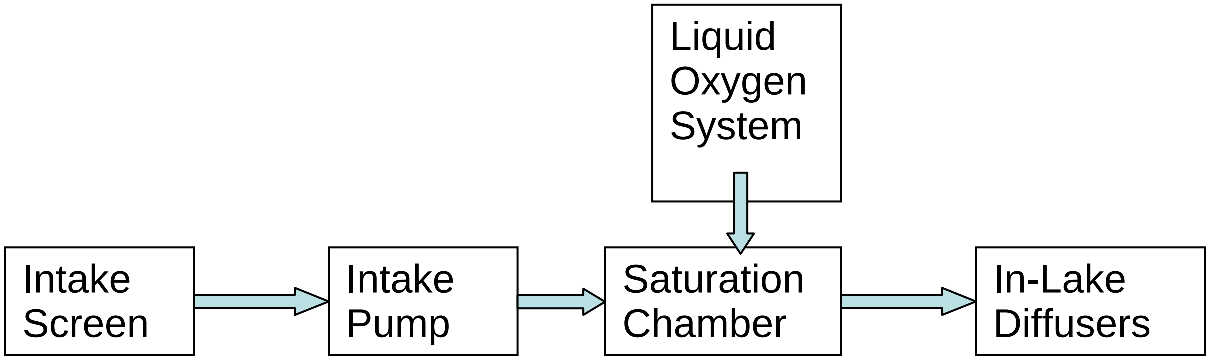

FIGURE 10
Contact chamber or side-stream oxygenation process flow diagram.

There are two types of contact chamber or side-stream oxygenation systems available on the market – Low Pressure and Medium Pressure systems. As the names imply, the primary difference between these systems is the pressure in the oxygen saturation chamber (Table 1). According to Henry's Law, as the partial pressure of oxygen rises in the saturation chamber the oxygen concentration in the water also increases proportionally. At atmospheric pressure, oxygen saturation in freshwater at 25^{o}C in a pure oxygen atmosphere is approximately 40 mg/L. Raising the pressure raises the DO saturation.

TABLE 1
Summary of Side-stream Oxygenation Methods

Method	Description
Low Pressure 1-3 atm (15-45 psi)	Typical pressure of 50 psi with a DO of up to 40- 120 mg/L at 25 °C.
Medium Pressure 3-7 atm (45-150 psi)	Typical pressure of 150 psi with a DO of up to 120-415 mg/L at 25 °C.

Oxygen mass transfer to a reservoir is limited by physics in a contact chamber or side-stream process. Supersaturated water will spontaneously effervesce with pressure drop upon reintroduction into the water column. Under quiescent conditions, oxygen supersaturated water is stable to about 100 mg/L at 25^{o}C. Oxygen comes slowly out of solution. At 1,000 mg/L, depressurized water foams. As a practical matter, a contact chamber or side-stream system needs to instantaneously mix supersaturated water with low DO water to avoid oxygen loss through effervescence. Thus, attention to diffuser design and the hydrostatic head of discharge is a critical design element that would need to be addressed during the design process.

The primary technology that is used for low pressure oxygen transfer is called a "Speece Cone" developed by Dr. Richard Speece. ECO Oxygen Technologies, LLC, headquartered in Indianapolis, Indiana, is the main vendor for these large scale low pressure saturators. The Speece Cone is a downflow bubble contact chamber. Water and oxygen gas are injected into the top of the cone, flow down, and discharge out the bottom (Figure 11). The cone is designed such that the water's downward velocity and the bubble's upward velocity equalize, thus ensuring that the oxygen completely dissolves. Pressure in the Speece Cone is up to 50 psi, but lower pressures are also used. The Speece Cone contains no moving parts and therefore the maintenance is limited to the pump, intake and diffusers. Oxygenated water is discharged through an exit port at the cone bottom and into a diffuser line.

FIGURE 11
Example of a Speece Cone sitting on a barge prior to submergence in Marston Reservoir, Colorado (source: Denver Water).

The primary technology that is used for the medium pressure oxygen transfer is shore-based oxygenation systems, exemplified by the Supersaturated Dissolved Oxygen (SDOX™) system developed and manufactured by BlueInGreen, LLC of Fayetteville, Arkansas. SDOX™ is a patented/patents pending technology that maximizes the delivery of dissolved oxygen and minimizes the footprint of the oxygen delivery system. The SDOX™ operates in a manner whereby oxygen gas is pre-dissolved into a stream of water inside of a pressurized on-shore saturation tank to achieve supersaturated concentrations. The SDOX™ unit sprays water into the saturation chamber though nozzles to increase the surface area for oxygen transfer. The typical operating pressure within the SDOX™ unit is around 100 psi. At a water temperature of 25^{o} C, the discharge oxygen concentration is approximately 290 mg/L. The oxygenated water is then released from the saturation tank and mixed with the larger body of water being treated. A picture of a typical SDOX™ unit is shown in Figure 12. A pilot scale trial of the SDOX™ system was conducted in J.C. Boyle reservoir in September 2011 as discussed below in section 4.3.4.

FIGURE 12
BlueInGreen medium pressure side-stream oxygenation system.

4.2.2 Linear Diffusers

Linear diffusers are another technology for pure oxygen delivery in lakes and reservoirs. This technology has been used throughout the country and has a proven track record. The linear diffuser technology was originally developed by the Tennessee Valley Authority to prevent sulfide formation in reservoirs in the southeastern U.S. In 2008, Mobley Engineering Inc. (MEI) was retained by PacifiCorp to evaluate the feasibility of using linear diffuser systems to place oxygen in the Project's Iron Gate and Copco reservoirs to obtain enhanced DO levels (MEI 2008).

Linear diffusers are of a simple and economical design with the installation typically consisting of three pipes: one for oxygen supply, one for buoyancy, and one containing a porous hose for oxygen diffusion as shown in Figure 13. The porous hose provides a plume of oxygen bubbles that dissolve as they move up through the water column. The buoyancy pipe is used to float the system during installation and for maintenance (these diffusers are installed and retrieved without divers).

Diffusers can be designed to place oxygen at strategic locations in the reservoir to achieve specific design goals such as oxygenation of incoming organic loads or enhancement of hydropower releases as shown in Figure 14. Oxygen transfer efficiency is dependent on the depth of the lake and water temperature. Enhancement of reservoir DO levels using diffusers is best obtained by placing diffusers in deeper waters so that the driving force of the deep water can be utilized to achieve high gas transfer efficiencies. The wide upper section of J.C. Boyle reservoir is probably too shallow for acceptable oxygen transfer efficiency. However, the greater water column depth in the narrow lower section of J.C. Boyle reservoir likely would allow acceptable oxygen transfer efficiency.

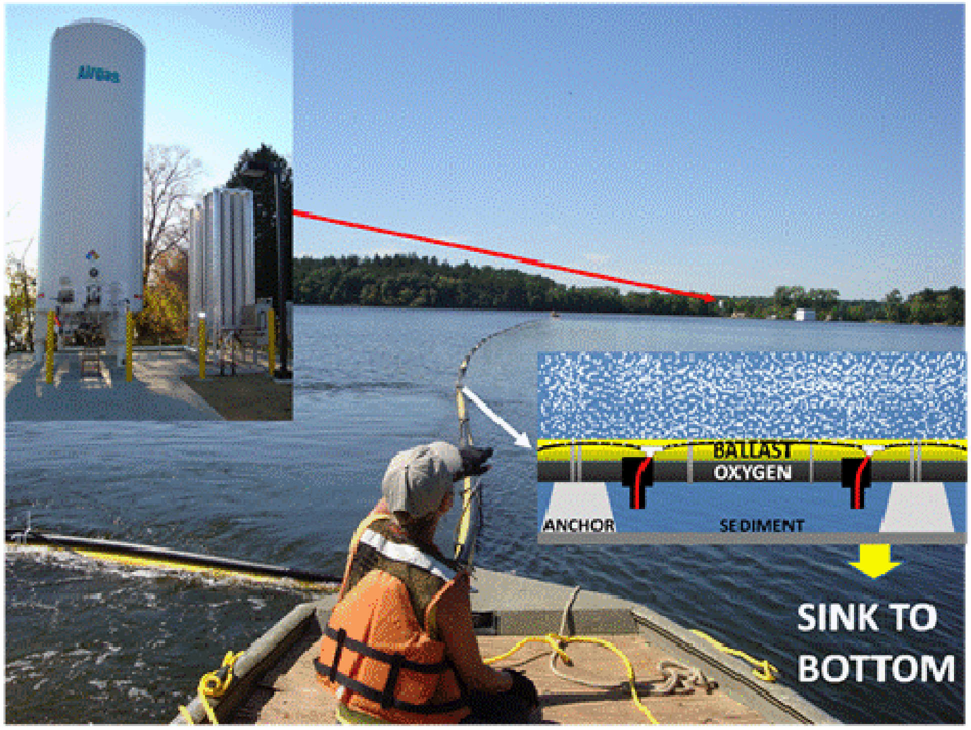

FIGURE 13
Example linear diffuser deployment in Vadnais Lake, Minnesota. Inset in photograph shows a schematic of the diffusers. Diffusers are floated into position and sunk. Note liquid oxygen tank on shore.

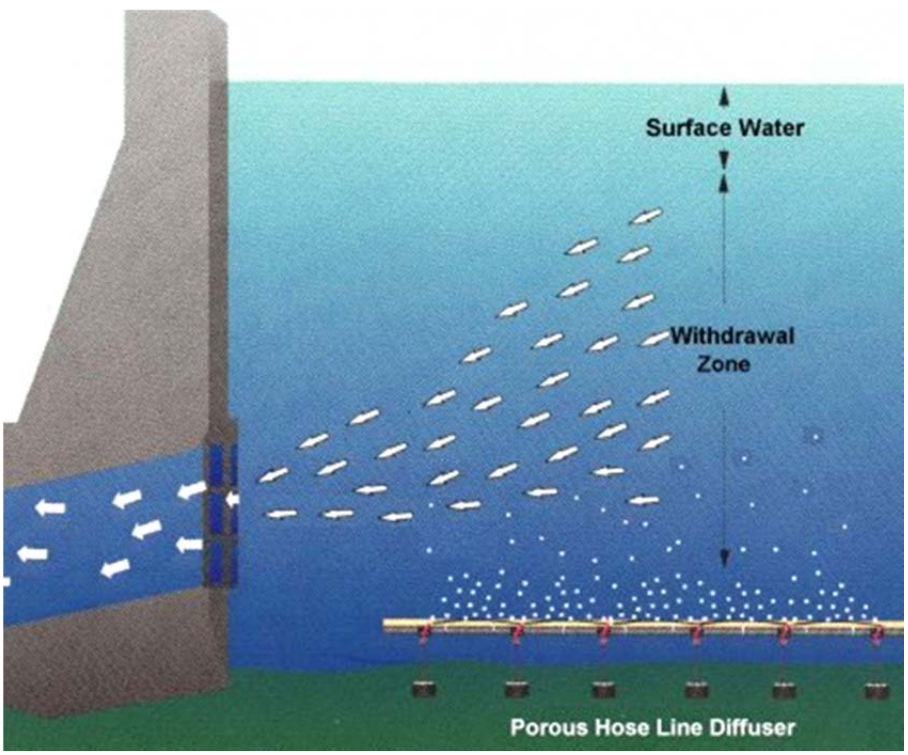

FIGURE 14
Conceptual diagram of linear diffuser deployment in Iron Gate reservoir for enhancement of DO in dam releases (source: MEI 2008).

4.2.3 Oxygen Supply

Based on design sizes of oxygenation systems used elsewhere (such as discussed further in section 6 of this report), an oxygenation system in J.C. Boyle reservoir would probably involve an oxygen supply system capable of delivering about 1,000-3,000 kg/d of 90 percent purity or greater gaseous oxygen. Such oxygenation systems can be supplied with oxygen from a liquid oxygen (LOx) storage facility, with LOx trucked in by a vendor to the project site. The LOx system would likely need to be sized to provide between 5-8 days of LOx storage based on typical average use. A typical liquid oxygen supply facility is shown in the inset of Figure 13. A liquid oxygen facility would require truck access, concrete foundations, equipment pad, and unloading area.

Alternatively, oxygen can be generated on site via oxygen generation equipment. There are two types of commercial oxygen generators in the market: pressure swing adsorption (PSA) devices and vacuum swing adsorption (VSA) devices. Both devices use a zeolite molecular sieve as the basis for separating oxygen and nitrogen. The PSA pressurizes the air prior to separation compared the VSA, which pressurizes the oxygen after separation. The VSA requires as much as 50 percent less electricity to produce a given amount of oxygen per standard cubic feet per hour[3] (SCFH), but uses more specialized equipment, including a reversible blower and oil-free compressor. Both systems have optional remote monitoring and oxygen purity verification. Commercially available PSAs and VSAs can meet the approximate estimated capacity of 3000-5000 kg/d of oxygen. A picture of a PSA system with a 2,000 SCFH oxygen delivery capacity is shown in Figure 15. Operating costs for PSA systems can be substantially less than on-site LOx supply facilities if wholesale electric power is available at the site.

FIGURE 15
Example of a PSA system with a 2,000 SCFH oxygen delivery capacity.

[3] Standard cubic feet per hour (SCFH) is a volumetric flow rate which is used for gases such as air. Since the volume of gases can change dramatically by pressure, a "Standard" is needed to bring the volume to a commonly known value (at sea level).

4.3 Estimated Effectiveness of Oxygenation Technologies in J.C. Boyle Reservoir

A CE-QUAL-W2 model of J.C. Boyle reservoir (developed by Watercourse Engineering) was used to assess the potential effects of increased oxygen delivery from conceptual oxygenation systems on DO in the reservoir. The model was based on the CE-QUAL-W2 (W2) model presented in PacifiCorp (2005), with updated geometry and code version 3.6 and beta version 3.7 (the latter to assess diffuser operations). Two conceptual oxygenation systems were modeled to explore the effects on DO levels in J.C. Boyle reservoir:

1. A side-stream oxygenation system at a specific location adjacent to the reservoir, wherein water was assumed withdrawn from the reservoir, oxygen added, and waters returned at a higher oxygen concentration; and
2. A linear diffuser oxygenation system in the deeper portions of the reservoir, which is assumed to be placed at depths of 8 to 10 meters to provide effective oxygen transfer.

The W2 model representation of J.C. Boyle reservoir included 39 longitudinal segments, with each segment consisting of 0.5 meter layers (maximum of 25 layers). Hydrodynamic and water quality was simulated for each layer and segment. Year 2002 meteorological and hydrological conditions were selected for model simulations because 2002 conditions were already an available part of the W2 model as presented in PacifiCorp (2005).

4.3.1 Side-stream Oxygenation Model Simulations

4.3.1.1 Side-stream Oxygenation Modeling Approach

A side-stream flow oxygenation system consists of a diversion facility, and a contact chamber where liquid oxygen and water are combined to create supersaturated conditions (often in excess of 100 mg/L). These oxygenated waters are subsequently discharged to the reservoir at a specific location. For the W2 modeling, two locations were selected to assess and illustrate the potential efficacy of a side-stream system:

1. Upstream location: withdraw from J.C. Boyle reservoir model segment 13 and inject DO saturated flow at model segment 14 at a point 3.15 km upstream from J.C. Boyle dam.
2. Downstream location: withdraw from J.C. Boyle reservoir model segment 28 and inject DO saturated flow at model segment 29 at a point 1.12 km upstream from J.C. Boyle dam.

Withdrawal was assigned explicitly to two of the model's vertical layers (a 1-meter vertical distance), akin to a screened pipe intake. The return flow was assigned to 10 vertical layers to represent a diffuser distributing oxygen over a 5-meter vertical region in the reservoir. The lateral average representation in W2 distributes oxygen laterally and is a limitation of the analysis.

For this W2 application, model assumptions were made for flow rates and oxygen concentrations of "treated" water discharged back to the reservoir from the side-stream oxygenation system. CH2M HILL consulted with commercial vendors on pumping rates and oxygen treatment concentrations on commercially-available systems associated with these scenarios. Side-stream oxygenation systems typically operate at pressures between 1 to 3 atm. Commercially-available Speece Cone equipment (as described above in section 4.2.1) operating at 1 to 3 atm can achieve treated water delivery rates of 5,700 to 8,500 gpm at supersaturated DO levels of 50 to 150 mg/L (2,350 kg/d O_2 to 4,710 kg/d O_2) (source: ECO Oxygen Technologies, LLC).

The W2 modeling assumed three pressure regimes within this commercially-available range as example side-stream oxygenation system alternatives. These assumed pressure regime alternatives may exceed what would actually be needed in J.C. Boyle reservoir pending determination of appropriate DO improvement objectives for system design. However, modeling of these particular alternatives allows us to conservatively assess the relative effectiveness of the potential use of side-stream oxygenation technology in the reservoir.

Table 2 lists the model simulation scenarios (or runs) for side-stream oxygenation analysis taking into account the two locations and three pressure regimes. All model run scenarios were set to start on June 1 (Julian day 152) at 0:00 hrs. Oxygenation input was tested for continuous flow of side-stream oxygenation for a simulation period of seven days. This model simulation period of seven days (i.e., the first week of operation) conservatively assumes that equilibrium for the effects of the continuous side-stream oxygenation on DO levels in J.C. Boyle reservoir would be attained at approximately three times the HRT of the reservoir[4]. To assess the relative effectiveness of these scenarios on DO in J.C. Boyle reservoir and its outflow, the model results from these scenarios were compared to a baseline model simulation that assumes no oxygen augmentation (i.e., no oxygenation).

For each of the run scenarios, water was assumed to be withdrawn at a constant rate (per flow rates as listed in Table 2) from the specified segment of the reservoir. The DO of the withdrawn water was then assumed to be increased to a specified concentration (per DO design specifications as listed in the model scenario descriptor in Table 2), and the same flow rate of treated water subsequently released to the downstream segment. Aside from DO, the W2 modeling assumed other water quality constituents (e.g., water temperature, nutrients, organic matter, and phytoplankton) were unchanged during transit of withdrawn water through the side-stream system.

TABLE 2
Summary of Model Scenarios (Runs) for Assessing J.C. Boyle Reservoir Side-Stream Oxygenation Systems

Model Scenario		Segment Number (Distance from Dam, km)	Return Flow Elevation Range (m)	Assumed DO Added in System (mg/L)	Assumed System Flow Rate (gpm)
Number	**Descriptor[1]**				
1	Seg 14, DO 150, Q5700	14 (3.15)	1,153.75 – 1,155.75	150	5,700
2	Seg 14, DO 111, Q7800	14 (3.15)	1,153.75 – 1,155.75	111	7,800
3	Seg 14, DO 51, Q8500	14 (3.15)	1,153.75 – 1,155.75	51	8,500
4	Seg 29, DO 150, Q5700	29 (1.12)	1,148.25 – 1151.25	150	5,700
5	Seg 29, DO 111, Q7800	29 (1.12)	1,148.25 – 1,151.25	111	7,800
6	Seg 29, DO 51, Q8500	29 (1.12)	1148.25 – 1,151.25	51	8,500

1: Descriptors as used in the legends of Figures 16 and 17.

4.3.1.2 Side-stream Oxygenation Model Results

Simulated Effects of Side-stream Oxygenation on In-Reservoir DO Conditions

Modeling results for the side-stream oxygenation scenarios at the upstream site (Segment 14) and downstream site (Segment 29) are shown in Figures 16 and 17, respectively. The results of the model simulations show notable improvements in reservoir DO levels under all modeled scenarios.

For the upstream system (Figure 16), in-reservoir DO concentrations are increased with the exception of a small volume near the bottom of the reservoir – a small stagnant zone behind a relatively short remnant coffer dam left from the original construction of J.C. Boyle dam. There is little benefit to DO levels upstream of the return point (3.15 km) for this system because the upstream area is dominated by inflows from the Klamath River. The model results indicate that the upstream system location (Segment 14) would result in more overall DO benefit than the downstream system location (Segment 29). The upstream system would provide oxygen to a larger portion of the reservoir, while taking advantage of the proximity to the river-dominated (and usually higher DO) that occurs in the upper reservoir reach. With regard to the lower DO in the small stagnant zone behind the remnant coffer dam, this could be remedied with a small, separate system (e.g., pump) that would circulate water from shallower depths (thus containing more DO) through the small stagnant zone.

[4] As described in section 2, the HRT of J.C. Boyle reservoir is approximately 1 to 2 days at average annual flow of 1,500 cfs, and 2 to 3 days at a typical summer flow of 750 cfs.

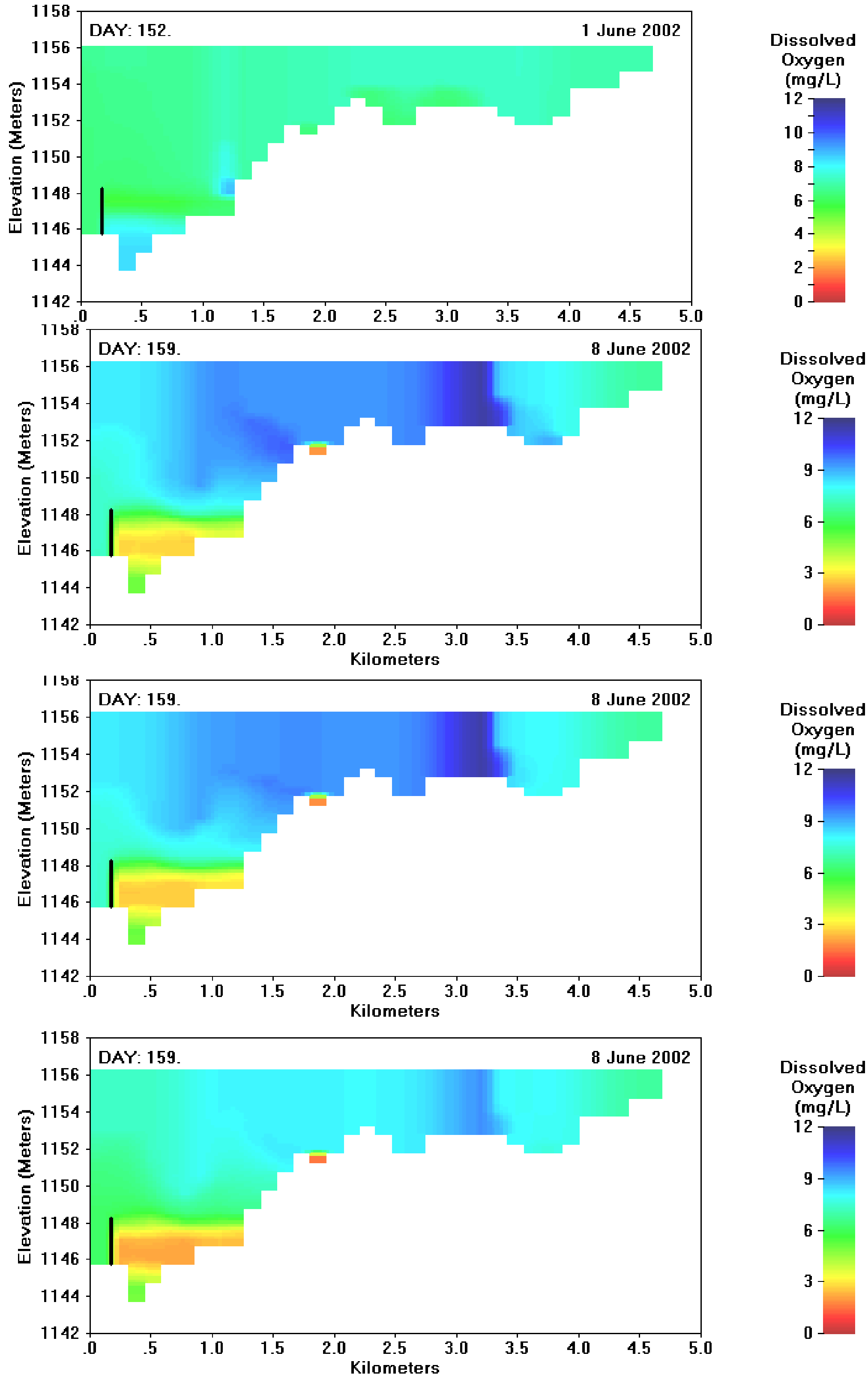

FIGURE 16

J.C. Boyle reservoir longitudinal and vertical DO concentrations under "upstream" (Segment 14) side-stream oxygenation scenarios for (top to bottom): baseline (no oxygenation); Scenario 1; Scenario 2; and Scenario 3.

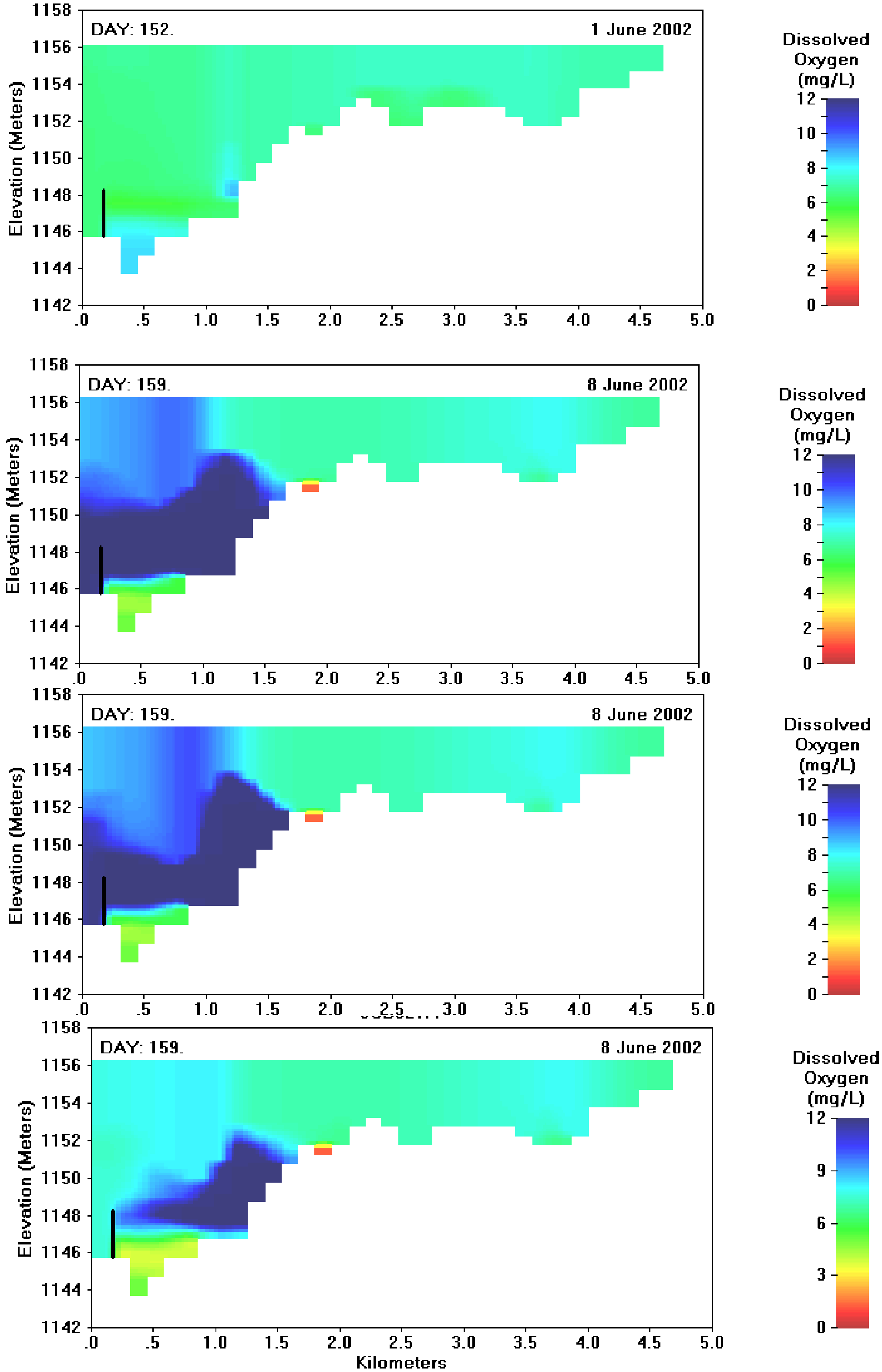

FIGURE 17

J.C. Boyle reservoir longitudinal and vertical DO concentrations under "downstream" (Segment 29) side-stream oxygenation scenarios for (top to bottom): baseline (no oxygenation); Scenario 4; Scenario 5; and Scenario 6.

For the downstream system (Figure 17), in-reservoir DO concentrations are increased with the exception of the small stagnant zone behind the remnant coffer dam (but which could be remedied as suggested above for the upstream system). Also, the model indicates that reservoir waters for a distance of about 0.4 km upstream of the downstream system's return point (1.12 km) would also receive benefit from this input of oxygen. The reason for this benefit is that hydropower peaking operations at J.C. Boyle dam produce dynamic mixing in the lower portion of the reservoir as the operations vary between peaking and non-peaking periods (Figure 18). During peaking periods, velocities are uniformly towards the dam. However, during non-peaking periods, velocities can reverse, resulting in mixing upstream of Segment 29. Under these conditions, the side-stream oxygenation discharge could increase DO concentrations in the reservoir for a distance of about 0.4 km upstream of the discharge.

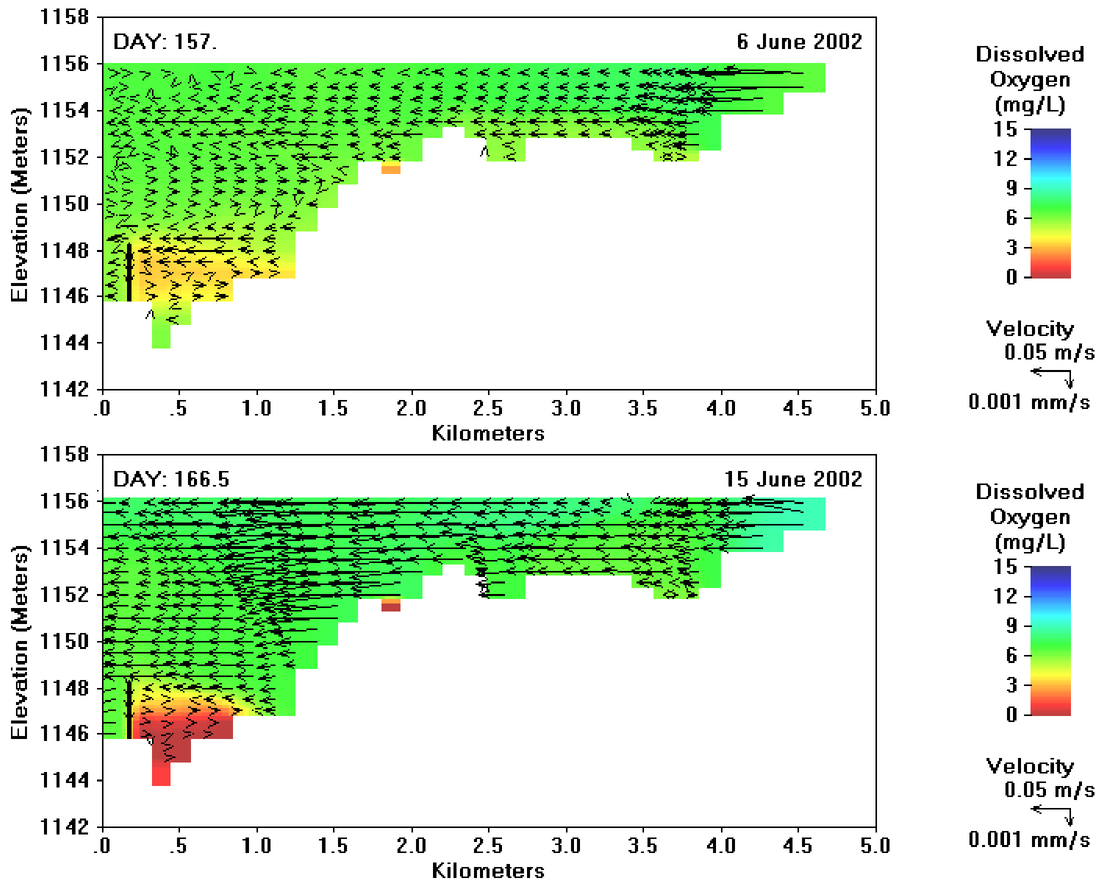

FIGURE 18
J.C. Boyle reservoir longitudinal and vertical velocity profiles during non-peaking operations (top) and peaking operations (bottom).

Simulated Effects of Side-stream Oxygenation on DO Conditions in Reservoir Outflows

Modeling results for side-stream oxygenation scenarios at the upstream site (Segment 14) and downstream site (Segment 29) are shown in Figures 19 and 20, respectively. The results of the model simulations show appreciable improvements in reservoir outflow DO levels under all modeled scenarios. Such simulated improvements in DO are expected given that modeled scenarios involve pressure regimes that likely exceed what would actually be needed in J.C. Boyle reservoir (pending determination of appropriate DO improvement objectives for system design). However, modeling of these particular scenarios allows assessment of the effectiveness of the potential use of this technology on a relative basis.

For the side-stream oxygenation system at the upstream site (Segment 14), reservoir outflow DO concentrations are generally in the 8 to 9 mg/L range and approximately 2 mg/L greater than the baseline case (no augmentation) under Scenarios 1 and 2, which assume added DO concentrations of 111 and 150 mg/L, and oxygenation system flow rates of 7,800 and 5,700 gpm, respectively (Figure 19). Reservoir outflow DO concentrations are typically above 7 mg/L and approximately 1 mg/L greater than baseline under Scenario 3, which assumes an added DO concentration of 51 mg/L and an oxygenation system flow rate of 8,500 gpm (Figure 19). The similar results between Scenarios 1 and 2 suggests that there may be a particular combination of DO concentrations and flow rates for a side-stream oxygenation system that would most efficiently yield enhanced DO concentrations in reservoir outflows.

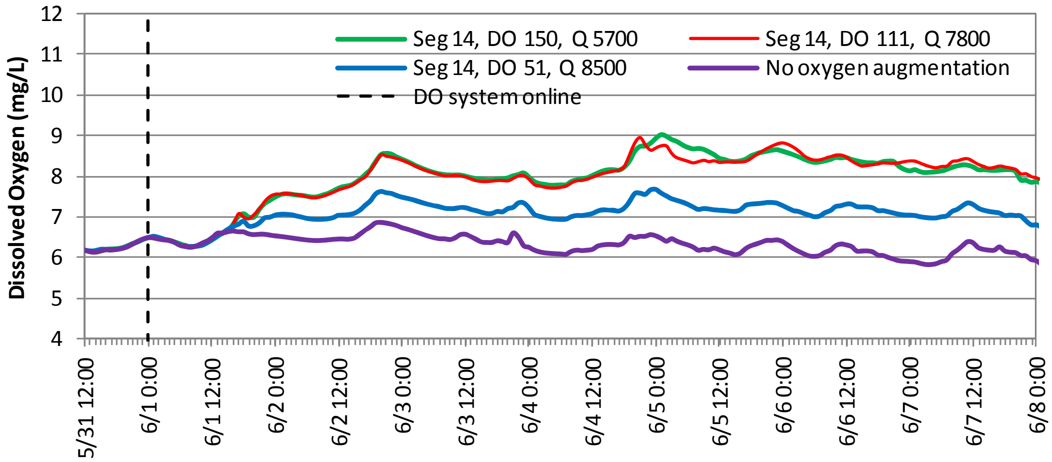

FIGURE 19
J.C. Boyle reservoir outflow DO concentrations for Scenarios 1, 2, and 3, which simulate the effects of continuous side-stream oxygenation at the upstream location (i.e., withdraw at segment 13 and return saturated flow at segment 14). Also plotted are reservoir outflow DO concentrations for the baseline condition of no oxygen augmentation.

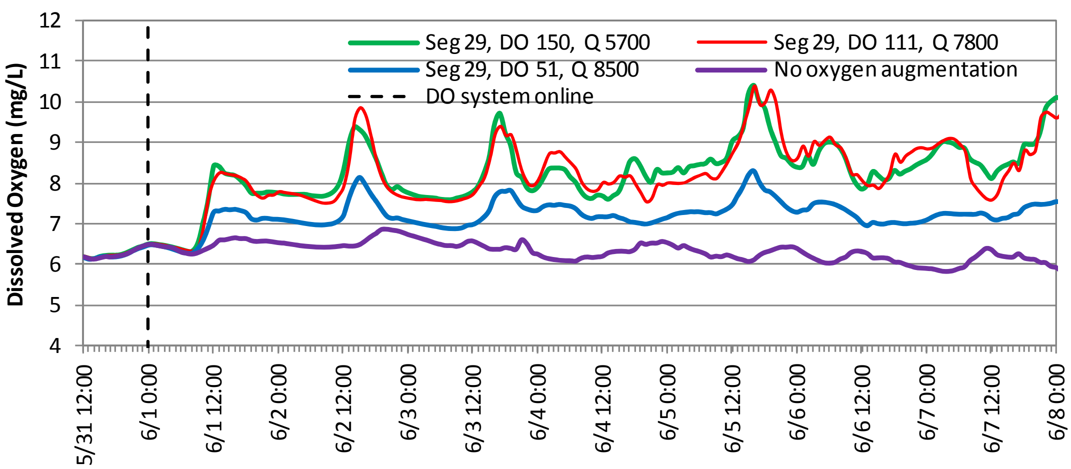

FIGURE 20
J.C. Boyle reservoir outflow DO concentrations for Scenarios 4, 5, and 6, which simulate the effects of continuous side-stream oxygenation at the downstream location (i.e., withdraw at segment 28 and return saturated flow at segment 29). Also plotted are reservoir outflow DO concentrations for the baseline condition of no oxygen augmentation.

Modeling results indicate that after DO augmentation begins at the upstream site, there is an approximately 15-hour time lag for the oxygenated waters to reach J.C. Boyle dam. Also, the results indicate that the variability in DO level is less for the upstream location (compared to the downstream location) because it is farther from the dam, and peaking operations would have a relatively smaller effect on outflow DO concentrations if augmentation occurs at the upstream location.

For the side-stream oxygenation system at the downstream site (Segment 29), reservoir outflow DO concentrations are generally greater than 8 mg/L and are 1 to 4 mg/L higher than the baseline case (no augmentation) under Scenarios 4 and 5, which assume added DO concentrations of 111 and 150 mg/L, and oxygenation system flow rates of 7,800 and 5,700 gpm, respectively (Figure 20). Reservoir outflow DO concentrations are mostly above 7 mg/L and are about 0.5 to 2 mg/L greater than baseline under Scenario 6, which assumes an added DO concentration of 51 mg/L and an oxygenation system flow rate of 8,500 gpm (Figure 20).

Modeling results indicate that after DO augmentation begins at the downstream site, there is an approximately 10-hour time lag for the oxygenated waters to reach J.C. Boyle dam. Also, as with Scenarios 1 and 2 for the upstream site, the similar results between Scenarios 4 and 5 suggests that there may be a particular combination of DO concentrations and flow rates for a downstream side-stream oxygenation system that would most efficiently yield enhanced DO concentrations in reservoir outflows.

4.3.2 Linear Diffuser Model Simulations

4.3.2.1 Linear Diffuser Modeling Approach

Oxygenation via linear diffusers was also modeled using the W2 model to explore the effects on DO levels in J.C. Boyle reservoir using a linear diffuser oxygenation system. This approach would require 8 to 10 meters of depth for acceptable/efficient levels of oxygen transfer to the water column. Thus, location of a diffuser line in the model was restricted to the deeper portions of the reservoir as illustrated in Figure 21 in the vicinity of model segment 29 at a point 1.12 km upstream from J.C. Boyle dam.

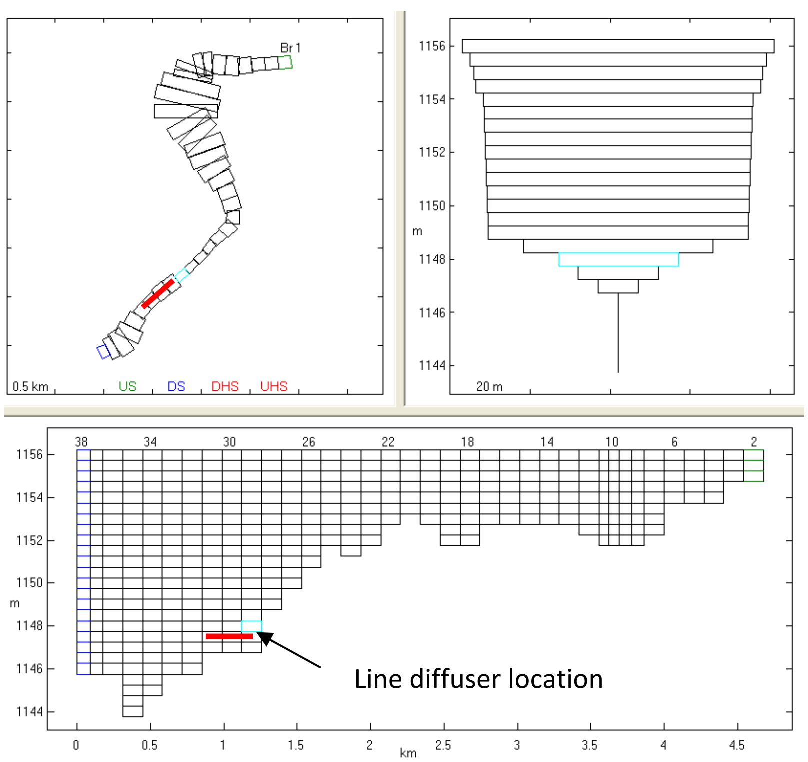

FIGURE 21
W2 reservoir representation showing line diffuser location in the vicinity of Segment 29 approximately 1.1 km upstream from dam. Top left – plan view; top right – segment 29 cross section; bottom – longitudinal profile of reservoir.

Oxygen flow rates of 50 and 100 standard cubic feet per minute (SCFM) of oxygen were modeled, which corresponds to 2,920 and 5,840 kg/d. The W2 model assumed these two oxygen flow rates as example linear diffuser oxygenation system alternatives. These particular flow rates may exceed what would actually be needed in J.C. Boyle reservoir pending determination of appropriate DO improvement objectives for system design. However, modeling of these particular flow rates allows us to conservatively assess the relative effectiveness of the potential use linear diffuser oxygenation technology in J.C. Boyle reservoir.

An aeration option is available in W2 version 3.7 (Beta)[5] and was used to simulate linear diffuser operations for the two flaw rate scenarios. To assess the effects of these linear diffuser scenarios on DO in J.C. Boyle reservoir and its outflow, the model results from these simulations were compared to a baseline model simulation that assumes no oxygen augmentation (i.e., no oxygenation). Diffuser location (in terms of segment number, top and bottom layer numbers), along with oxygen mass flow rate and vertical mixing coefficient multiplier (DZFACT) are required input. DZFACT is intended to increase vertical mixing induced by fine-bubble plumes rising out of an aeration or oxygenation system (i.e., a surrogate for explicit modeling of a fine bubble rising in the water column). This vertical mixing coefficient was set to 20 for this application.

4.3.2.2 Linear Diffuser Model Results

Simulated Effects of Linear Diffuser Oxygenation on In-Reservoir DO Conditions

Results of model simulations of in-reservoir DO conditions during operation of the linear diffuser oxygenation scenario at an assumed 50 SCFM delivery rate[6] are shown in Figures 22 and 23[7]. Figure 22 shows DO conditions shortly after inception of diffuser operation, and Figure 23 shows conditions six days later. In addition to DO, Figures 22 and 23 also show the results of water temperature simulations because intermittent thermal stratification appears to play a role in simulated DO concentrations using the aeration option in this version of W2.

Modeling results shown in Figure 22 indicate that, shortly after inception of diffuser operation, DO concentrations of reservoir waters were approximately 6 mg/L. The results shown in Figure 23 indicate that DO concentrations were on the order of 8 mg/L six days later. This level of increase in DO conditions in the reservoir is similar to that indicated in the model results with the side-stream system located at Segment 29 as discussed above.

Weak thermal stratification is evident in Figure 23, which could reduce vertical mixing (even with the DZFACT coefficient increased to 20). Even so, DO is clearly distributed vertically in the simulation results. Also evident in these results is the small stagnant zone behind the remnant coffer dam in the deepest portion of the reservoir, which was also seen in the model results of the side-stream systems as discussed above.

[5] Because the model used for assessing linear diffusers is still in the beta stage, the results should be understood as preliminary. As such, this modeling assessment is not definitive, but is useful for context and perspective on potential effectiveness of linear diffusers in the reservoir.

[6] Only the 50 SCFM delivery rate was used in the modeling to assess in-reservoir conditions because modeling of the 100 SCFM delivery rate shows much higher outflow DO concentrations (as discussed further in the next section below).

[7] Due to a software incompatibility with the W2 Beta 3.7 version, the longitudinal and vertical concentrations in Figures 22 and 23 have reversed axis orientation from Figures 16 and 17 in this report.

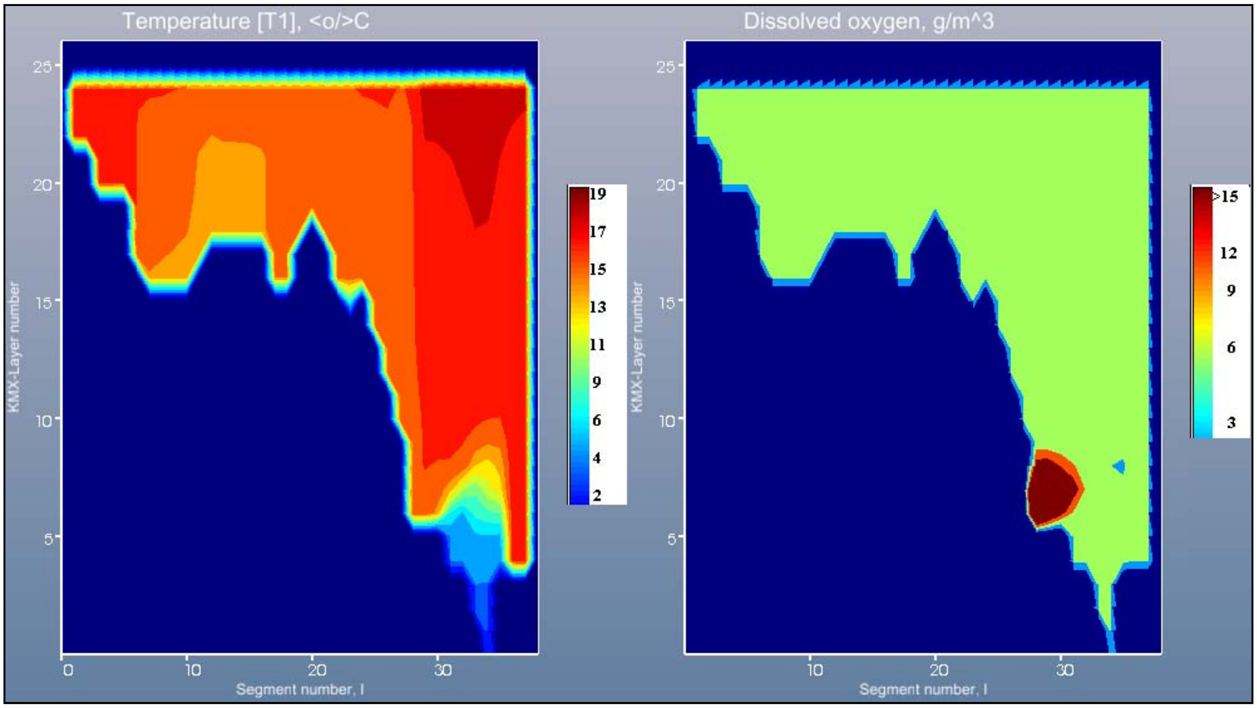

FIGURE 22
J.C. Boyle reservoir longitudinal and vertical water temperature (left plot; °C) and DO concentrations (right plot; mg/L) with operations of a linear diffuser at a delivery rate of 50 SCFM located in the vicinity of Segment 29 (1.12 km upstream of dam). The time depicted is June 1 (Julian Day 151), shortly after system is assumed to be turned on.

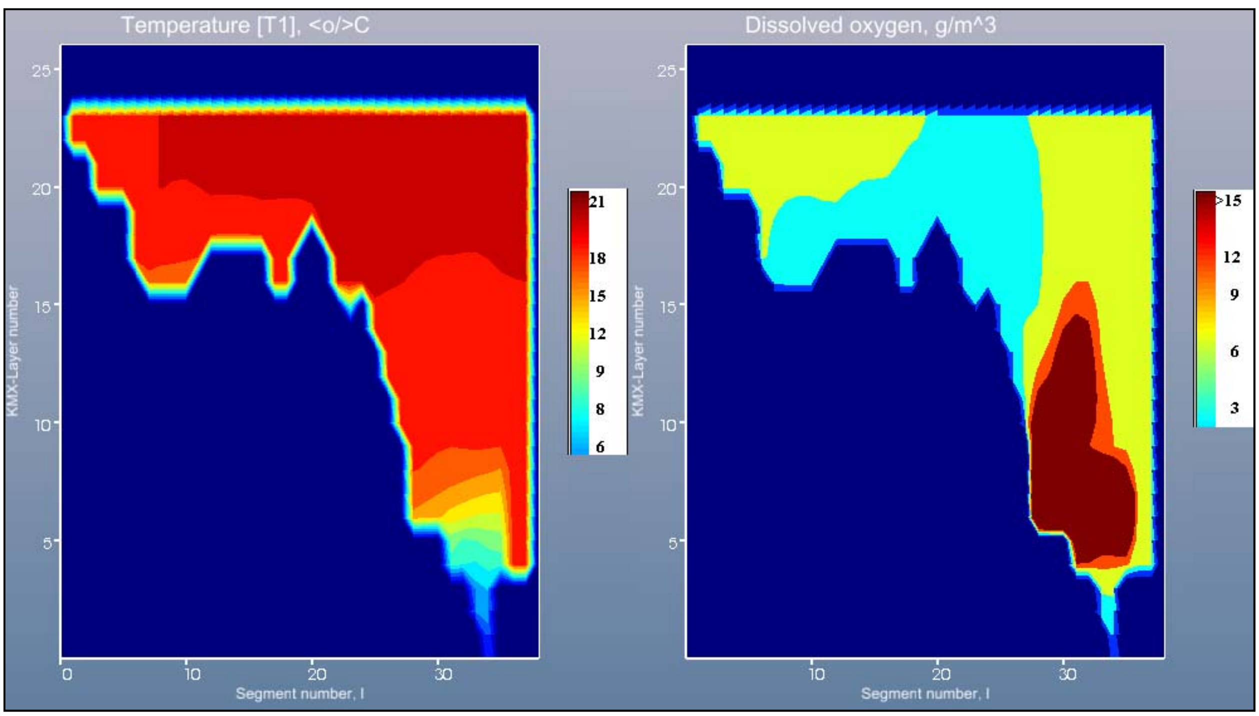

FIGURE 23
J.C. Boyle reservoir longitudinal and vertical water temperature (left plot; °C) and DO concentrations (right plot; mg/L) with operations of a linear diffuser at a delivery rate of 50 SCFM located in the vicinity of Segment 29 (1.12 km upstream of dam). The time depicted is June 6 (Julian Day 157), 6 days after system is assumed to be turned on.

Simulated Effects of Linear Diffuser Oxygenation on DO Conditions in Reservoir Outflows

Results of model simulations of reservoir outflow DO conditions during operation of the linear diffuser oxygenation scenario are shown in Figure 24. The results indicate appreciable improvements in reservoir outflow DO levels under both delivery rate scenarios. Such simulated improvements in DO are expected given that assumed delivery rates likely exceed what would actually be needed in J.C. Boyle reservoir (pending determination of appropriate DO improvement objectives for system design). However, modeling of these delivery rates allows assessment of the effectiveness of the potential use of this technology on a relative basis.

Both delivery rates provide improved oxygen conditions over baseline (no augmentation) conditions at DO levels sufficient to maintain 7 mg/L to 8 mg/L in reservoir outflow water. However, simulated DO levels in the reservoir outflow are notably higher under the 100 SCFM delivery rate than the 50 SCFM rate, indicating that the nominal delivery rate would be an important and sensitive factor in the actual implementation of a linear diffuser system, depending on location (proximity to the dam) and the desired reservoir volume to be treated.

The modeling results shown in Figure 24 also indicate high variability in simulated DO concentrations in reservoir outflow under linear diffuser oxygenation simulations. Similar high variability was shown with the side-stream system simulations (as discussed above), due to the dynamic mixing that can occur in the vicinity of the assumed location of the system in the lower portion of the reservoir from peaking operations at the dam (see Figure 18).

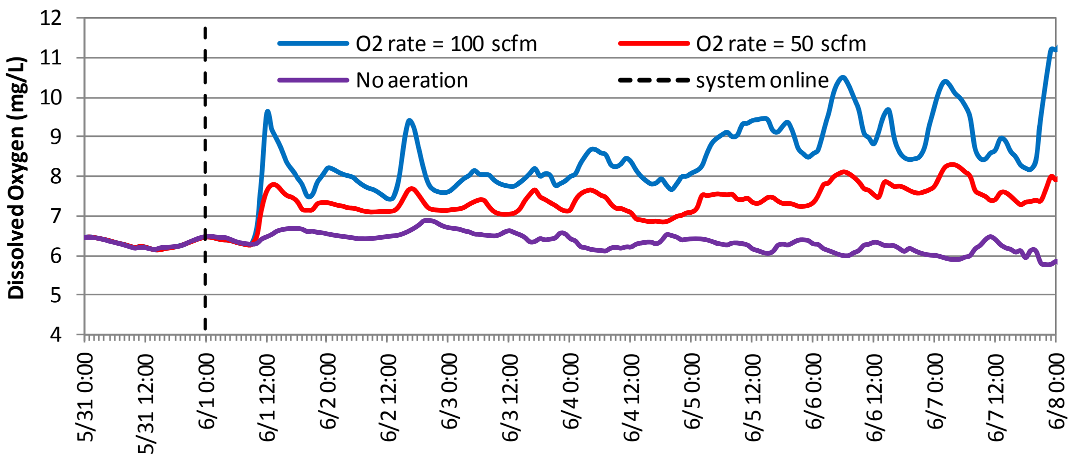

FIGURE 24
Comparison of J.C. Boyle reservoir outflow DO levels with different assumed oxygen delivery rates.

4.3.3 Conclusions from Model Simulations and Vendor Inquiries

The W2 model results indicate that either side-stream or linear diffuse oxygenation systems could be effective in enhancing DO conditions in J.C. Boyle reservoir. Regarding side-stream oxygenation, the model results indicate that the three pressure regimes assumed for side-stream systems could offer DO improvement in J.C. Boyle reservoir, with the level of improvement increasing as delivery DO concentrations increase. The W2 model results also indicate that locating the side-stream system discharge further away from J.C. Boyle dam would have the effect of oxygenating a larger portion of J.C. Boyle reservoir and dampening the variance in reservoir outflow DO. Locations further upstream provide more reservoir volume to be treated. If potential implementation of a side-stream oxygenation system in J.C. Boyle reservoir is pursued further, additional modeling and assessment of system attributes is recommended to verify these results and determine the appropriate size and equipment requirements for such a system.

Contacts with commercial vendors indicate that side-stream or contact chamber oxygenation equipment options are available that would be sufficient to achieve DO improvements as indicated in this analysis. Examples of such equipment options include: (1) an SDOX™ saturation chamber in the range of a 7-foot diameter tank with 9-foot seam heights, such as available from BlueInGreen (as described above in section 4.2.1); and (2) an 8-foot to 12-foot diameter Speece Cone, such as available from ECO Oxygen Technologies (as described above in section

4.2.1). Intake and discharge aspects of these side-stream systems would need to be designed to minimize head loss and prevent fish or other solids from entering the oxygenation systems.

Regarding linear diffuser oxygenation, the model results indicate a fine bubble diffuser system could be an effective means for enhancing DO in J.C. Boyle reservoir. However, the requirement of 8 to 10 meters of minimum depth would limit the placement location of a linear diffuser system to the deeper, lower section of the reservoir, leaving the shallower, upper section of the reservoir without oxygen augmentation. Based on the standard flux rates for linear diffusers systems, a diffuser length of 1,660 to 3,330 feet would be needed to deliver the sorts of flow rates assumed in this analysis (i.e., 50 and 100 SCFM). The length of 3,330 feet and a flow rate of up to 100 SCFM are within the current design range of existing Mobley systems (as described above in section 4.2.2). A diffuser of this length in J.C. Boyle reservoir would likely need to fit between 0.5 km and 1.25 km upstream of the dam in a zigzag pattern to achieve the necessary length and depth.

Finally, the W2 model results indicate that, with use of either side-stream or linear diffuser systems, a small stagnant zone in the deepest portion of the reservoir behind the original coffer dam would likely continue to occur. However, this stagnant zone comprises a small volume and can be remedied through mixing (e.g., pumping) oxygen rich waters from higher in the reservoir through this zone.

The relative effectiveness and approximate costs of oxygenation relative to other technologies for DO improvement in J.C. Boyle reservoir are discussed further below in section 6 *Conclusions*.

4.3.4 Pilot Scale Trial of the SDOX™ System in J.C. Boyle Reservoir

During September 26-30, 2011, BlueInGreen, LLC conducted a pilot test of the SDOX™ system in J.C. Boyle reservoir. For this pilot test, a trailer-mounted SDOX™ 400 system (Figure 25), which has a full-rated capacity to deliver 1,540 pounds of dissolved oxygen per day (lbs/day), was deployed adjacent to the shoreline near the upper end of the reservoir. The SDOX™ system operated nearly continuously over the five-day test period, delivering an estimated total of 5,175 lbs of dissolved oxygen to the reservoir at an average rate of approximately 1,150 lbs/day. The pilot demonstration showed formation of a dissolved oxygen plume mainly along the southern portion of the reservoir downstream of the injection point, and a rise in dissolved oxygen levels within the plume area of at least 0.5-1.5 mg/L. The data collected in the pilot was sufficient to allow sizing for a larger system to effectively treat a larger portion of the reservoir. More detailed information on this pilot test is available in BlueInGreen's final report on the test (BlueInGreen 2011).

FIGURE 25
Trailer-mounted SDOX™ 400 system at J.C. Boyle reservoir.

SECTION 5
Mechanical Mixing

5.1 Available Mixing Technologies

Mixing (also referred to as "destratification") of lakes and reservoirs to improve DO has predominantly been done with two different technologies: (1) aeration or air injection (also referred to as "bubble plume mixing"); and (2) axial flow pumps (also referred to as "propeller mixing"). Aeration or air injection diffuses compressed air at multiple points near the lake bottom. The resulting bubble plume provides mixing by entraining and moving water through the water column under buoyancy forces. Axial flow pumps use propeller-driven mechanical force to move and mix water in lakes or reservoirs. This is typically done by submerging the axial flow pump from a floating platform just below the water surface. The pump is then oriented to move naturally-oxygenated water downward from the surface into the deeper portions (e.g., hypolimnion) of the lake to mix with (or lift to the surface) water that may be low in DO.

5.1.1 Aeration or Air Injection

Aeration or air injection is not discussed further in this section of the report. As described above in section 3, an aeration system has already been evaluated for use in J. C. Boyle reservoir and a conceptual design has been completed (Horne et. al. 2009). Details and analysis of the aeration system can be found above in section 3 and in the Horne et al. (2009) report.

5.1.2 Axial Flow Pumps

Axial flow pumps ("propeller mixing") promote mixing (reduce stratification) by producing a similar circulation pattern to that produced by aeration or air injection ("bubble plume mixing"), except that axial flow pumps are a top-down approach, which moves water downward from the surface into the deeper portions (e.g., hypolimnion) of the reservoir to mix with (or lift to the surface) water. By contrast, aeration or air injection ("bubble plume mixing") is a bottom-up approach of releasing a stream of buoyant gas at the bottom that carries cold water towards the surface. Axial flow pumps can be used as a direct replacement for bubble plume systems by locating the pump at the bottom of the water column and pumping the water vertically upwards, which in fact may result in enhanced mixing efficiencies of 6 to 12 percent for destratification (Stevens and Imberger 1993). However, the typical axial flow pump configuration has been the surface-mounted top-down approach, which is substantially more advantageous in terms of the logistics of access, deployment, operation, and maintenance of the axial flow pumps and associated equipment.

Use of axial flow pumps is a well-documented lake and reservoir mixing technique, but has had varying degrees of success (Punnett 1991, Lawson 2007). Punnett (1991) observed that that in Beech Fork Lake, a 35 foot deep 750-acre reservoir in northwestern West Virginia, four pumps capable of pumping 18,000 to 33,600 gpm successfully destratified the reservoir. The destratification successfully prevented anoxia at the dam, but overall DO was reported to be low. This is in contrast to a detailed assessment of 20 axial flow pumps installed in Lake Elsinore (Lawson and Anderson 2007). Lawson and Anderson (2007) observed that axial flow pumps did not dramatically alter the DO conditions in the water column or significantly change percent of the area of anoxic sediments. Stratification persisted despite pumping with little observed lateral transmission of mixing energy. Rather, mixing occurred in localized cells around the mixers.

The WEARS Australia line of axial pump mixers appears to be the most commercially viable mechanical mixing system. WEARS is a primary manufacturer of pre-engineered axial flow pumps specifically for use in lakes or reservoirs (Figure 26). The WEARS line of ResMix™ mixers range in reported pumping capacities from 9,000 to 140,000 gpm (Table 3). The ResMix™ 1000 unit can be run from on-board solar panels or through the electrical grid. The larger ResMix™ 3000 and ResMix™ 5000 units must be run on the grid. Also, two ResMix™ units can also be coupled together to double their pumping capacity.

FIGURE 26
WEARS ResMix™ system pictures. Left box includes wire frame representation showing overall structure (top left), and representation showing system submerged in water (bottom left). Right box shows ResMix™ pump with flexible shroud (shown in green) shown prior to in-reservoir deployment. (Source: WEARS ResMix Systems literature.)

TABLE 3
WEARS ResMix™ Pump Capacities and Sizes

Unit	Pumping Capacity (m^3/s)	Pumping Capacity (cfs)	Pumping Capacity (gpm)	Motor Size (KW)
ResMix™ 1000	0.57	20	9,000	1
ResMix™ 3000	2.83	100	45,000	3
ResMix™ 5000	8.83	312	140,000	5

Another commercially viable line of mixers are the SolarBee™ solar-powered circulators manufacturer by Medora Corporation (Dickinson, ND). The SolarBee™ circulators use an impeller of about 3 feet in diameter that rotates at less than 100 rotations per minute (rpm) to produce a combination of both axial flow and positive displacement characteristics. The pumping action creates about 0.2 inch of lift above the reservoir surface and, due to the physical configuration of the machine, causes the pumped water to flow 360-degrees radially outward across the surface of the reservoir.

The flow rates generated by the commercially-available models of SolarBee™ circulators range from 1,250 gpm to 10,000 gpm, which are substantially less than produced by the WEARS ResMix™ pumps (Table 3). By design, the SolarBee™ circulators produce a lower-energy laminar flow circulation to create mixing, which differs from the turbulent mixing approach produced by the WEARS ResMix™ pumps. This lower-energy approach has the advantage of substantially lower energy costs for operations, but has the disadvantage of less energetic mixing that may not be adequate in certain applications. The SolarBee is primarily designed to disrupt algal growth by increasing lateral surface velocity and is not really intended for use in the destratification of lakes or reservoirs.

PacifiCorp previously deployed 12 SolarBee™ circulators (Model SB10000v12 with flow rates rated at 10,000 gpm) in the upper portion of Copco reservoir from April through October 2008. PacifiCorp's interest in testing these particular circulators was not for direct DO enhancement, but to potentially reduce blooms and accumulations of cyanobacteria (blue-green algae) in the reservoir, such as *Microcystis aeruginosa* (MSAE) and *Aphanizomenon flos-aquae* (APFA). The concept behind the use of the circulators is to create enough mixing and agitation in surface layers of the reservoir to reduce cyanobacteria by reducing their light exposure and disrupting the generally quiescent conditions that may contribute to cyanobacteria bloom formation.

Carlson and Foster (2009) describe the results of water quality monitoring in Copco reservoir during the SolarBee™ deployment to assess whether the circulators improved water quality in the "treated" upper portion of Copco reservoir relative to other "untreated" areas. The monitoring data indicates that the solar-powered circulators did not act to discernibly improve water quality, and in particular did not act to reduce cyanobacteria blooms. The monitoring data showed that algae production and densities generally remained high throughout the reservoir during the monitoring period. Carlson and Foster (2009) indicated that the observed differences in water quality conditions between sites could be explained on the basis of reservoir spatial heterogeneity – that is, even if it is assumed that the solar-powered circulators provided circulation in the "treated" portion of Copco reservoir, such mixing was evidently overridden by the stronger influence of other reservoir processes, such as advection and stratification.

5.2 Axial Flow Pump Estimates for J.C. Boyle Reservoir

5.2.1 Basis of Estimates

Water pumped through an axial flow pump will propagate as a jet over a vertical length to a specific depth at which the momentum of the jet is balanced by a resisting pressure force arising from the density change between the source water and the water at the specific depth. This specific depth varies according to predictive equations that have been developed for jet plume hydraulics (Fischer et al. 1979).

Punnett (1991) derived equations from field tests specifically designed to determine the best depth penetration predictions for axial flow pumps. The equations of Punnett (1991) are applied below to approximate potential axial flow pump requirements applicable to conditions representative of J.C. Boyle reservoir. The resulting estimates from these equations are for preliminary assessment ("ball park") purposes only. If the potential application of axial flow pumps is pursued further, a more thorough evaluation of pump requirements would be necessary. This would include analysis of other factors not considered here that would influence pump requirements, such as the specific volume, size, and shape of the reservoir area to be treated, pump locations, wind action, and timing of operations.

Several equations were developed by Punnett (1991) to predict the depth of plume penetration for axial flow pumps, the best non-dimensional form of which is:

$$\frac{H_p}{D} = 0.176\frac{V^2}{g(\frac{\Delta\rho}{\rho_o})} + 0.756\frac{H_e}{D}$$

Where:

H_p = length (vertical) of plume, m

D = pump propeller diameter, m

V = initial jet velocity, m/sec

g = gravitational constant (9.81 m/sec^2)

$\Delta\rho$ = difference in density between surface and desired depth of penetration, kg/m^3

ρ_o = average density of pumped water

H_e = length (vertical) from pump to thermocline, m

The plume created by the axial flow pump must penetrate to the desired depth (represented in the equation by H_p) in order to be effective. For example, the desired depth would be the reservoir bottom if complete water column mixing is the objective or to the dam intake invert if more localized surface water mixing is the objective. As surface water is pumped downward, a plume of warmer (lighter-density) water is formed within the lower layers of cooler (heavier-density) water. Buoyant forces acting upon the plume impede the downward velocity of the plume until a relatively stable mixing depth is established.

In the above equation, the first term on the right side accounts for plume penetration into dissimilar density strata. The second term on the right side accounts for penetration within the surface layers where little buoyant resistance is encountered. In the above equation, the depth of the thermocline is considered to be from the pump propeller to the depth at which the first major increase in density (or temperature) occurs. In a case where no apparent thermocline exists but there is a thermal gradient, Punnett (1991) recommends using the midpoint between the pump and the desired depth of penetration. Because J.C. Boyle reservoir has a modest thermal gradient with no thermocline, this midpoint approach is used in the analysis discussed further below.

To find the associated pump flow rate, Punnett (1991) used the following equation:

$$Q = 0.785D^2V$$

Where:

$Q =$ pump flow rate, m^3/sec

$D =$ propeller diameter, m

$V =$ initial jet velocity, m/sec

To determine the approximate flow rate necessary for complete water column mixing (often referred to as "destratification"), Punnett (1991) determined on the basis of field tests that the required flow rate is about equal to pumping the volume of the hypolimnion every 8 days. Because J.C. Boyle reservoir has a modest thermal gradient with no distinct hypolimnion, a volume proportionate to the midpoint depth approach is used in the analysis discussed further below.

Table 4 lists the pertinent assumptions of conditions in J.C. Boyle reservoir used in the equations as discussed further below. These conditions represent conservative mid-summer conditions when vertical gradients of water temperature and associated water densities are at maximum.

TABLE 4
Pertinent Data for J.C. Boyle Reservoir

Parameter	Value (metric)	Value (English)
Surface Area (Total)	170 ha	420 ac
Surface (Lower Reservoir)	24.3 ha	60 ac
Maximum Depth	12.2 m	40 ft
Mid Depth	6.1 m	20 ft
Reservoir Volume (Total)	4,311,019 m^3	3,495 ac-ft
Reservoir Volume (Lower Reservoir)	703,085 m^3	570 ac-ft
Maximum Thermal Conditions:		
Surface	24°C	75°F
1 m Depth	22°C	72°F
2 m Depth	21°C	68°F
Bottom	18°C	64°F
Corresponding Density Conditions:		
Surface	997.3 kg/m^3	62.25 lb/ft^3
1 m Depth	997.8 kg/m^3	62.28 lb/ft^3
2 m Depth	998.0 kg/m^3	62.30 lb/ft^3
Bottom	998.6 kg/m^3	62.33 lb/ft^3

5.2.2 Estimated Pump Requirements for J.C. Boyle Reservoir

The above formula was used to estimate pump requirements (associated with the WEARS ResMix™ pumps as listed in Table 3) to achieve mixing of the entire water column in J.C. Boyle reservoir. These estimates were made assuming mid-summer conditions when the maximum vertical $\Delta\rho$ occurs in J.C. Boyle reservoir, with water temperatures conservatively bracketed at about 24°C at the surface and 18°C near the bottom at a depth of about 40 ft (Table 4).

For mixing of the entire water column in J.C. Boyle reservoir, the pump plume should penetrate to the reservoir bottom at the pump site. For calculation purposes, the pump site is assumed to be located over the deepest point in the reservoir, which would require that the pump plume penetrates to the maximum reservoir depth of 12.2 m.

Assuming a propeller diameter (D) of 2 m, the above equation is solved for velocity (V) by assuming that the length of the plume (H_p) is equal to the maximum reservoir depth of 12.2 m:

$$\frac{12.2}{2} = 0.176\frac{V^2}{9.81(\frac{1.3}{997.9})} + 0.756\ \frac{6.1}{2}$$

Therefore, $V = 0.52$ m/sec.

Using the second equation above (per Punnett 1991) the associated pump flow rate is solved as:

$$Q = 0.785(5)^2(0.52)$$

Therefore, $Q = 10.21$ m^3/sec.

Based on pump capacities listed in Table 3, this estimate of pump flow rate suggests that one to two ResMix™ 5000 unit or three to four ResMix™ 3000 units would likely be needed to provide mixing of the entire water column in J.C. Boyle reservoir over the deepest point in the reservoir.

To determine the approximate flow rate necessary for mixing of the entire volume of the lower portion of J.C. Boyle reservoir, a flow rate is calculated that is equal to pumping the volume of the lower portion of the reservoir every 8 days (per the approach of Punnett 1991). Assuming a volume in the lower portion of the reservoir of 703,085 m^3 (Table 4), a flow rate of about 1.02 m^3/sec is required. This calculation suggests that the number of ResMix™ units as estimated above for water column mixing would be more than adequate to pump at the rate of about 1.02 m^3/sec. However, it should be noted that the HRT in J.C. Boyle reservoir under typical mid-summer flow conditions is about 2 to 4 days (Figure 27), which indicates that the volume of the lower portion of the reservoir is already replaced in less than 8 days under existing conditions. Therefore, if axial flow pump technology is further considered for use in J.C. Boyle reservoir, the desired depth penetration (water column mixing) of the pump plume, rather than volume replacement, should probably be the primary consideration for pump sizing and siting.

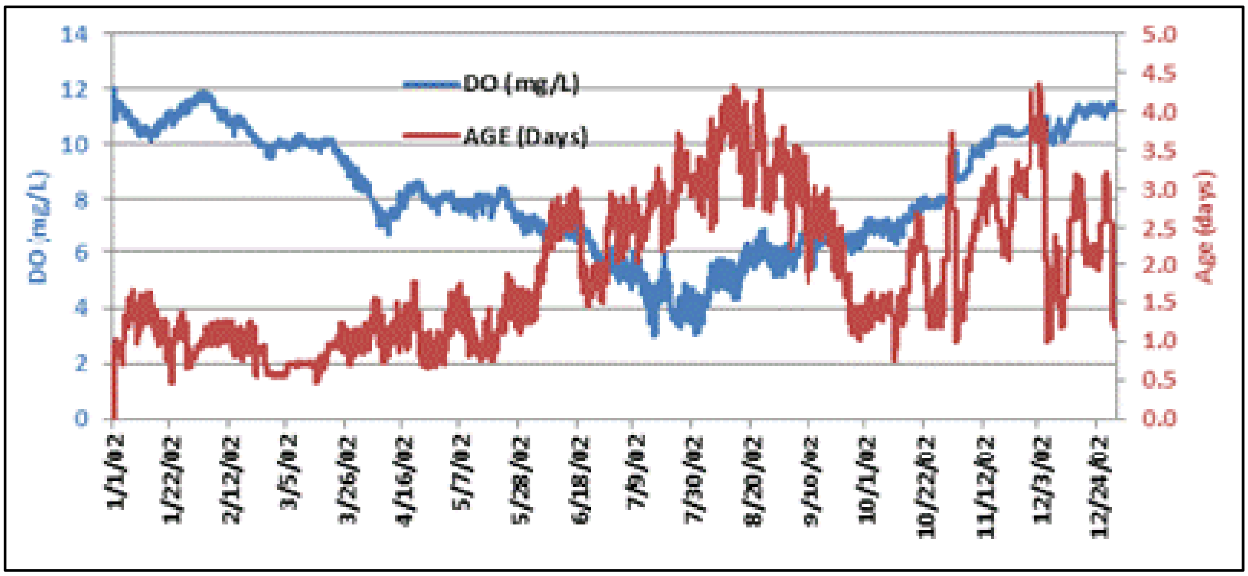

FIGURE 27
CE-QUAL-W2 model of DO and HRT in the lower J.C. Boyle reservoir.

5.2.3 Estimated Effectiveness for Mechanical Mixing in J.C. Boyle Reservoir

It is not expected that mechanical mixing would solve the principal cause of DO decline in J.C. Boyle reservoir. As described above in section 2, the oxygen demand and decline in the reservoir, particularly during summer, is driven primarily by the large loading of organic matter advected to the reservoir from the Klamath River inflow. The modest thermal gradient in J.C. Boyle reservoir during summer is only a secondary and minor exacerbating factor. Mechanical mixing would only help to address this less-consequential factor.

In the case of J.C. Boyle reservoir, which has both high inflow BOD and relatively short HRT (of 2 to 4 days in summer), mechanical mixing would only reasonably affect DO as a result of physically mixing the water column, and not by oxygen uptake from aeration or oxygenation, such as would occur from the other technologies discussed above. Physical mixing of the water column could reduce the vertical gradient of DO in the lower portion of J.C. Boyle reservoir, and in so doing cause the DO concentrations in the bottom waters of the reservoir to increase through the downward mixing and entrainment of higher DO water that was present higher in the water column. For example, physical mixing of the water column could increase DO concentrations in the bottom waters of the reservoir by as much as 1 to 2 mg/L if it is conservatively assumed that mixing is sufficient that DO in bottom waters achieves a concentration equal to the water-column average condition.

Axial flow pumps have had a mixed record of success in increasing DO concentrations in lakes and reservoirs elsewhere. Lawson and Anderson (2007) conducted a three-year study to quantify the effectiveness of a system of 20 axial flow pumps in weakening thermal stratification and increasing DO levels in Lake Elsinore, a hypereutrophic lake with a surface area of about 3,000 acres in southern California. The system had an estimated pumping capability of 600,000 gpm (each unit pumps 30,000 gpm) and a total pumping rate of 2,000 AF/day. Lawson and Anderson (2007) concluded that the system had little effect on stratification and DO levels in the lake. Stratification and a large area of anoxic sediments persisted despite pump operation in the summers of 2004 and 2005. Acoustic Doppler current profiler (ADCP) measurements showed that mixing energy was not being efficiently transmitted laterally into the water column.

Garton (1976) evaluated operation of a 27,000-gpm axial flow pump in Ham's Lake, a relatively small 100-acre lake in Oklahoma. The water had zero DO below a depth of 5 m and DO was in excess of 8 mg/L above 4 m when pumping started. After four days, DO ranged from 7.2 mg/L at the surface to 2.9 mg/L at the bottom. A 10°C vertical difference between the top and bottom was reduced to 1.2°C difference in four days. The temperature at a depth of 9 m increased 8.50°C.

Garton et al. (1979) found that a cluster of 16 axial flow pumps installed in Arbuckle Lake, a 2,350-acre eutrophic lake in Oklahoma, caused a decrease in the volume of anoxic water in the lake. The cluster had an estimated pumping capability of 416,000 gpm. The improved oxygen levels in the lake were observed by comparing the percent of the volume maintained above 2 mg/L with the percent in normal year, during the two weeks in August an average of about 85 percent of the lake DO was as above 2 mg/L during the two mixing years compared to about 63 percent during the 1976 control summer.

Axial flow pumps have also been installed for more localized mixing in the vicinity of dam intakes for the purpose of improving water quality in dam release waters. In 1987, a series of localized mixing tests were conducted at J. Percy Priest Reservoir in Tennessee (Price and Sneed 1989 as cited in Price and Meyer 1992). These tests were designed to investigate the feasibility of direct-drive mixers to improve release quality from the hydropower project. Results of these tests indicated that three pumps generating 45 cfs each improved the release DO by 1 mg/L (release discharge of 4,600 cfs). These tests also demonstrated that the location of the jet relative to the intake structure had a significant impact on the efficiency of the localized mixing application.

Robinson et al. (1982) evaluated the effectiveness of an axial flow pump to improve release water quality during thermal stratification from Lake Texoma, a large eutrophic reservoir (surface area of 89,000 acres) on the Red River in Oklahoma and Texas. The pump was mounted on a floating support platform and operated directly over the intake structure to pump higher quality epilimnion water down to the outlet. Water quality parameters were monitored with and without pumping at several release rates to determine pump effectiveness. The maximum observed improvements for turbidity, sulfides, manganese, total iron, phosphorous, and ammonia nitrogen were 83, 68, 49, 21, 53, and 37 percent, respectively (Robinson 1982). However, improvements in DO were not observed or were inconsistent.

The relative effectiveness and approximate costs of an axial flow pump system relative to other technologies for DO improvement in J.C. Boyle reservoir are discussed further below in section 6 *Conclusions*.

SECTION 6

Conclusions on Relative Effectiveness and Costs

6.1 Relative Effectiveness of Approaches for DO Improvement

Based on the information presented in this report, the relative effectiveness of technologies for DO improvement in J.C. Boyle reservoir are ranked as follows (in order of most to least effective): (1) oxygenation, either via linear diffuser, contact chamber, or side-stream oxygenation; (2) aeration or air injection; and (3) mechanical mixing.

The principal reason that oxygenation would be most effective of the technologies is that, as discussed earlier, the large BOD loads in inflowing water is the primary cause for oxygen deficits in J.C. Boyle reservoir, and transferring or injecting pure oxygen to the water is the most direct and surest means to address such oxygen deficits. Different oxygenation techniques are commercially-available (i.e., linear diffuser, contact chamber, or side-stream oxygenation), each of which are potentially applicable to J.C. Boyle reservoir. As described in section 4 of this report, specific oxygen quantities can be determined for use in design of an oxygenation system that could address in-situ oxygen demands (e.g., BOD, SOD) and raise DO levels by specified amounts. On this basis, oxygenation systems allow for a greater degree of design and operational control over the improvements in DO that would be achieved.

Aeration or air injection also could provide DO improvement, but effectiveness would be less than oxygenation. J.C. Boyle reservoir (3,790 ft msl) is located at relatively high elevation, where air contains less oxygen than at elevations within 500 feet of sea level where most aeration systems have been installed. The lower oxygen content in the air further reduces the already lesser efficiency of air compared to pure oxygen for DO enhancement.

In addition, an aeration or air injection system would only be applicable in the deeper, lower section of J.C. Boyle reservoir. Such a system in the upper section of the reservoir would lack effectiveness due to the high advection of BOD in the river inflow to the reservoir from upstream sources. Moreover, there is not enough depth in the upper section of the reservoir so that air bubbles from diffusers would dissolve and provide an oxygenating effect to the water. Horne et al. (2009) did not perform detailed modeling of DO in J.C. Boyle reservoir under aeration system configurations, but estimated on the basis of preliminary calculations that an aeration diffuser system in the lower section of the reservoir could raise DO by up to 2 mg/L if total concentrations of DO were less than 5 mg/L. However, the aeration diffuser system would not be capable of raising DO above 5 mg/L due to constraints on air solubility at the reservoir's relatively high elevation.

Mechanical mixing is considered the least effective of the three potential technologies for DO improvement in J.C. Boyle reservoir. Because BOD of the water is the primary cause for oxygen deficits in J.C. Boyle reservoir, and water column stratification is a minor factor related to DO deficits in the reservoir, mixing would be much less effective at addressing DO deficits. Mechanical mixing systems can only improve DO by transferring oxygen via mixing of the water column. As described in section 5 of this report, the physical mixing of the water column could increase DO concentrations in the bottom waters of the reservoir by as much as 1 to 2 mg/L if it is conservatively assumed that mixing is sufficient that DO in bottom waters achieves a concentration equal to the water-column average condition. However, this would presumably come with a counter reduction in DO concentrations in surface waters. The lower ranking of mechanical mixing is further supported by inconsistent results of mechanical mixing to improve DO in other similar reservoirs.

6.2 Relative Costs of Approaches for DO Improvement

From a cost perspective, the relative rankings of the technologies are reversed from the above effectiveness rankings (in order of least to most costly): (1) mechanical mixing; (2) aeration or air injection; and (3) oxygenation. It is noted that costs were not estimated or assessed in detail for this report, and in any event would depend on specific features and specifications for these technologies that would emerge from future planning and design efforts to meet a specific yet-to-be-defined DO objective for the reservoir. However, for rough comparative purposes, general cost information is provided below based on previous estimates developed for Project reservoirs (i.e., Horne et al. 2009, MEI 2008), or as obtained from the literature for other similar lake and reservoir systems. Table 5 includes a comparative summary of costs of aeration, oxygenation, and mixing systems for several example projects. Table 6 includes a comparative summary of the sizes of the lakes or reservoirs cited in Table 5.

The information in Table 5 indicates that oxygenation systems are more costly then aeration or mixing systems for capital costs as well as annual operations and maintenance (O&M) costs. For example, MEI (2008) estimated capital costs of about $2.8M to $3.2M and O&M costs of $1.2M to $2.7M for conceptual oxygenation diffuser systems in Copco and Iron Gate reservoirs. However, these systems would be considerably larger than needed for J.C. Boyle reservoir.

Vadnais Lake (MN) is most like J.C. Boyle reservoir in size (Table 5, Table 6). The Vadnais Lake oxygen diffuser system was designed by CH2M HILL and constructed in 2011. Because J.C. Boyle is slightly larger than Vadnais Lake and has a higher inflow BOD load that may also require higher oxygen transfer rates, we roughly estimate that an oxygenation system for J.C. Boyle reservoir could be twice the size of the Vadnais Lake system, including a longer diffuser. Using Vadnais Lake construction and design unit costs, the capital costs of the comparable system in J.C. Boyle would be about $1.25M, and annual O&M costs would be approximately $270,000 (assuming a 4 to 5 month operating period).

The cost of a Speece Cone oxygenation system is expected to be higher than an oxygen diffuser system based on recent quotes received by CH2M HILL on other projects. In round terms, the added cost of the intake screens, pump station, diffusers, and ancillary equipment would be on the order of twice the capital costs as an oxygen diffuser system, although O&M costs (including liquid oxygen supply) would probably be comparable. It is noted that the Camanche Reservoir Speece Cone costs as included in Table 5 are in 1995 dollars (Horne 1995).

The information in Table 5 indicates that aeration systems are generally intermediate in costs between oxygenation systems and mechanical mixing systems. Horne et al. (2009) estimated a capital cost of $300,000 to $500,000 for installation of the conceptual air injection (diffuser) system in J.C. Boyle reservoir as described above in section 4. This range in estimated cost depends on the cost of specialized fittings, the details of the compressor shed and sound proofing, and the distance over which electrical power is needed. O&M costs were estimated at $40,000 to $60,000 annually, assuming a 4 to 5 month operations period (during the late spring, summer, and early fall time frame when DO is lowest and BOD is highest in the reservoir and its inflow). These cost estimates are comparable to aeration system costs reported by PACE (2004) for Canyon Lake (CA) and Lake Elsinore (CA) after roughly adjusting for differences in the sizes of the respective aeration systems and host lakes (Table 5, Table 6).

Finally, mechanical mixing – assumed in this assessment as provided by an axial flow pump system – is the least costly of the technologies considered in this report. As described above in section 5, two to four axial flow pump units (depending on unit sizes selected within the range of 45,000 to 140,000 gpm) would likely be needed to provide mixing of the water column in J.C. Boyle reservoir over the deepest point in the reservoir. At capital costs of about $35,000 to $75,000 per unit (depending on size) and O&M costs of about $5,000 to $7,500 per unit, a two to four-unit system would run about $70,000 to $300,000 in capital costs and $6,000 to $30,000 annually in O&M costs. These cost estimates are comparable to axial flow pump system costs reported by Fast (2002a, 2002b) for Canyon Lake (CA) and Lake Elsinore (CA) after roughly adjusting for differences in the sizes of the respective systems and some inflation (Table 5, Table 6).

TABLE 5
Comparative Summary of Costs of Aeration, Oxygenation, and Mixing Systems.

Location / (Data Source)	Type of System	System Features & Sizes	Capital Costs (Total $)	O&M Costs (Annual $)
Copco reservoir (CA) (MEI 2008)	Oxygen diffuser system	Diffuser length: 18,440 ft LOx: 23 tons/day ave. usage Two 20,000-gal. LOx storage tanks Two 1,400-SCFH PSA units	$3,160,000	$1,216,000 - $2,710,000
Iron Gate reservoir (CA) (MEI 2008)	Oxygen diffuser system	Diffuser length: 15,600 ft LOx: 17 tons/day ave. usage One 20,000-gal. LOx storage tank Two 1,800-SCFH PSA units	$2,800,000	$1,623,000 - $2,413,000
Vadnais Lake (Reservoir) (MN) (CH2M HILL 2011)	Oxygen diffuser system	Diffuser length: 3,000 feet LOx: 1.5 tons/day design usage One 9,000-gal. LOx storage tank	$780,000	$150,000
Camanche Reservoir (CA) (Horne 1995)	Speece Cone oxygenation system	Speece Cone: 23-ft high; 12-ft dia. LOx: 9 tons/day ave. usage One 13,000-gal. LOx storage tank	$1,500,000	$120,000 - $150,000
Norfolk Dam tailwaters (AR) (Osborn and Thompson 2008)	SDOX™ oxygenation system	LOx: 10 – 20 tons/day usage (a) Design: treat 1000 cfs for 3 mg/L DO rise (b) Design: treat 1000 cfs for 6 mg/L DO rise	(a) $1,700,000 (b) $3,400,000	(a) $200,000 – $300,000 (b) $400,000 - $600,000
J.C. Boyle reservoir (OR) (Horne et al. 2009)	Aeration diffuser system	Diffuser length: 5,000 ft Five diffuser manifolds Air flow rate: 260 m^3/hr 22 kW (30 hp) compressor	$300,000 - $500,000	$40,000-$60,000
Canyon Lake (CA) (PACE 2004)	Aeration diffuser system	Diffuser length: 5,750 ft Six diffuser hoses Compressed air flow rate: 50 psi One 100-hp compressor	$230,000	$65,000
Lake Elsinore (CA) (PACE 2004)	Aeration diffuser system	Diffuser length: 30,000 ft 12 diffuser hoses Compressed air flow rate: 50 psi Two 200-hp compressors	$1,060,000	$260,000 – 330,000
Lake Elsinore (CA) (Fast 2002a)	Axial flow pump mixing system	16 axial flow pumps in 4 clusters 6-ft dia. Propeller units Each unit pumps 30,000 gpm Total pumping rate: 2,000 AF/day	$586,000	$46,000
Canyon Lake (CA) (Fast 2002b)	Axial flow pump mixing system	Two axial flow pumps 6-ft dia. Propeller units Each unit pumps 30,000 gpm Total pumping rate: 250 AF/day	$75,000	$5,000

TABLE 6
Comparative Summary of Sizes of Lakes or Reservoirs Cited in Table 5.

Lake or Reservoir	Surface Area	Total Volume	Max. Depth
	acres	**AF**	**ft**
J.C. Boyle reservoir (OR)	420	3,495	42
Vadnais Lake (MN)	383	3,179	55
Canyon Lake (CA)	525	11,920	40
Copco reservoir (CA)	1,000	46,867	116
Iron Gate reservoir (CA)	944	58,794	163
Lake Elsinore (CA)	3,452	89,000	42
Camanche Reservoir (CA)	7,770	417,120	150

SECTION 7

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