Feasibility and Conceptual Design of an Aeration System for Dissolved Oxygen Enhancement in J.C. Boyle Reservoir

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Executive Summary

This report describes the results of a feasibility assessment of potentially implementing an air injection (diffuser) system in J.C. Boyle reservoir to enhance dissolved oxygen (DO). J.C. Boyle reservoir is a narrow, approximately 3.5 mile-long impoundment of 420 surface acres located on the Klamath River from RM 224.7 to RM 228.2 downstream of Upper Klamath Lake (UKL) in Klamath County, Oregon. J.C. Boyle reservoir is classified as "eutrophic" (nutrient-enriched) due to the large inflow loads of nutrients and organic matter from upstream sources, notably UKL. Resulting water quality effects include reduced DO concentrations in J. C. Boyle reservoir – falling to about 3 mg/L – at certain times of the year.

This feasibility assessment was conducted by a team of specialists with expertise in DO enhancement techniques in reservoirs. The team examined water quality data (particularly DO, BOD, and water temperature data and information), performed calculations of oxygen demands and requirements, and estimated system sizing and layouts for an air injection (diffuser) system in J.C. Boyle reservoir.

The team 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).

The most appropriate conceptual design of an air injection (diffuser) system in the deeper, lower portion of J.C. Boyle reservoir would include ten sets of diffuser arrays, with each array consisting of five diffusers on 150-meter lengths of hose. A fine/medium orifice type of diffuser would likely be the best choice of diffuser type to provide most efficient oxygen transfer and water mixing. The entire 1500-meter lineal system of diffuser arrays would be fed by a single 1.5-inch internal diameter (ID) feedline, which would serve compressed air to shorter lateral feedlines to each array. 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 (~ 30 hp) air compressor would be required.

The estimated cost of installation of the conceptual air injection (diffuser) system as described in this report is $300,000 to $500,000. Operation and maintenance (O&M) costs are 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).

Introduction

PacifiCorp Energy (PacifiCorp) owns and operates the Klamath Hydroelectric Project (Project) on the Klamath River and its tributaries in Oregon and California. The Oregon portion of the Project includes the J.C. Boyle dam and reservoir between approximately River Mile (RM) 224 and RM 228 on the Klamath River[1]. The dominant influence on water quality 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 (PacifiCorp 2004a, 2004b, 2006, 2008a). Indeed, the Klamath River is often described as an "upside down" river in which, unlike most large rivers, water quality generally improves—often substantially—as it moves farther downstream.

The nutrients and organic materials from UKL and other upstream sources influence water quality within J.C. Boyle reservoir and in the Klamath River downstream of J.C. Boyle dam (PacifiCorp 2004a, 2004b, 2006, 2008a). J.C. Boyle reservoir experiences reduced dissolved oxygen (DO) concentrations —falling to about 3 mg/L at certain times of the year. The lowest DO levels are restricted to a relatively small volume of water in the deeper portions of the reservoir. Although primary production occurs in the reservoir surface waters, the rates are low, and organic matter input from upstream sources appears to be the primary cause of low DO.

To address the effects of the upstream loading and to otherwise improve DO conditions in J.C. Boyle reservoir, PacifiCorp is considering implementation of an air injection diffuser system for water column mixing and circulation in the reservoir as described in PacifiCorp (2008). This report describes the results of a feasibility assessment conducted by Alex Horne and Associates and CH2M HILL of potentially implementing such an air injection diffuser system 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. The following sections of this report describe limnological features of J.C. Boyle reservoir relevant to DO conditions, potential approaches to DO enhancement in J.C. Boyle reservoir, and a conceptual design of an aeration system in J.C. Boyle reservoir.

[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).

J.C. Boyle Reservoir Features and Conditions

Physical and Limnological Features of J.C. Boyle Reservoir

J.C. Boyle reservoir is a narrow, approximately 3.5 mile-long impoundment of 420 surface acres located on the Klamath River from RM 224.7 to RM 228.2. J.C. Boyle reservoir is located 4.8 miles downstream of Keno dam (RM 233), 21.5 miles upstream of Copco reservoir (river entrance to Copco reservoir is at RM 203.3), and 28 miles upstream of Iron Gate reservoir (river entrance to Iron Gate reservoir is at RM 196.7).

The normal maximum and minimum operating levels of J.C. Boyle reservoir are between El. 3,793 feet and El. 3,788 feet msl, a range of 5 feet. The reservoir has a surface area of 420 acres and 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 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. Much of the upper section contains dense submerged macrophytes. 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.

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 1.2 days at average annual flow of 1,500 cfs, 2.5 days at a typical summer flow of 750 cfs, and 0.6 days 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 (PacifiCorp 2004b, 2006, 2008a). The advected BOD of Klamath River water discharged to J.C. Boyle reservoir represents an enormous amount of oxygen demand in the reservoir. Typically, lakes and streams have a 5-day biochemical oxygen demand (BOD_5) 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 (Doyle and Lynch 2005, Deas and Vaughn 2006), or similar to what is allowed for sewage discharges (EPA 1996). The BOD in UKL likely is mostly due to living and decaying algal biomass that is abundant in UKL (Wood et al. 2006). Even though there are several miles of well mixed river conditions between UKL and J.C. Boyle reservoir, there is insufficient time for oxygenation for these conditions to provide much BOD reduction.

An exact measure of BOD in J.C. Boyle reservoir has not been made, but an approximation of oxygen consumption was made during this assessment using a comparison of closed bottles in J.C. Boyle reservoir and Iron Gate reservoir. The closed bottle comparison showed that up to 3.4 mg/L of DO was lost in five days from surface waters taken from J.C. Boyle reservoir, while only 0.5 mg/L DO was lost from water collected from Iron Gate reservoir. The importance of the high BOD in J.C. Boyle reservoir is that it will create a large demand on DO that will work against management actions to increase DO in the reservoir. Since the water in J.C. Boyle reservoir is replaced so quickly, fresh BOD arrives in the reservoir from upstream faster than DO can be replaced naturally.

The HRT in a reservoir also exerts an important influence on phytoplankton biomass and production levels (Thornton et al. 1990). As in a chemostat, if the HRT is less than the phytoplankton doubling rate, the accumulation of biomass and therefore algae productivity can be limited by advective loss (washout) of cells. Growth rates of algae in laboratory cultures in continuous light and with optimum nutrients range from abut 0.25 to 2.0 days per doubling; however, phytoplankton growth rates in nature are usually much slower (Zison et al. 1978). Westlake (1980) reported a range of phytoplankton doubling rates from 0.12 to 7.5 days at the depth of optimal photosynthesis, which is around 25 percent of I_o (surface light during mid-day in summer). Given that water turbulence stirs phytoplankton over the entire mixed zone of several meters from the water surface, light is normally suboptimal. Therefore, typical doubling rates are more likely in the upper range of those given by Westlake (1980) at about a week. As such, the direct advective effects of the short HRT in J.C. Boyle reservoir (a few days) is a key factor controlling and limiting in-reservoir algal production and biomass accumulation. In effect the algae will be washed out of the reservoir faster than they can grow.

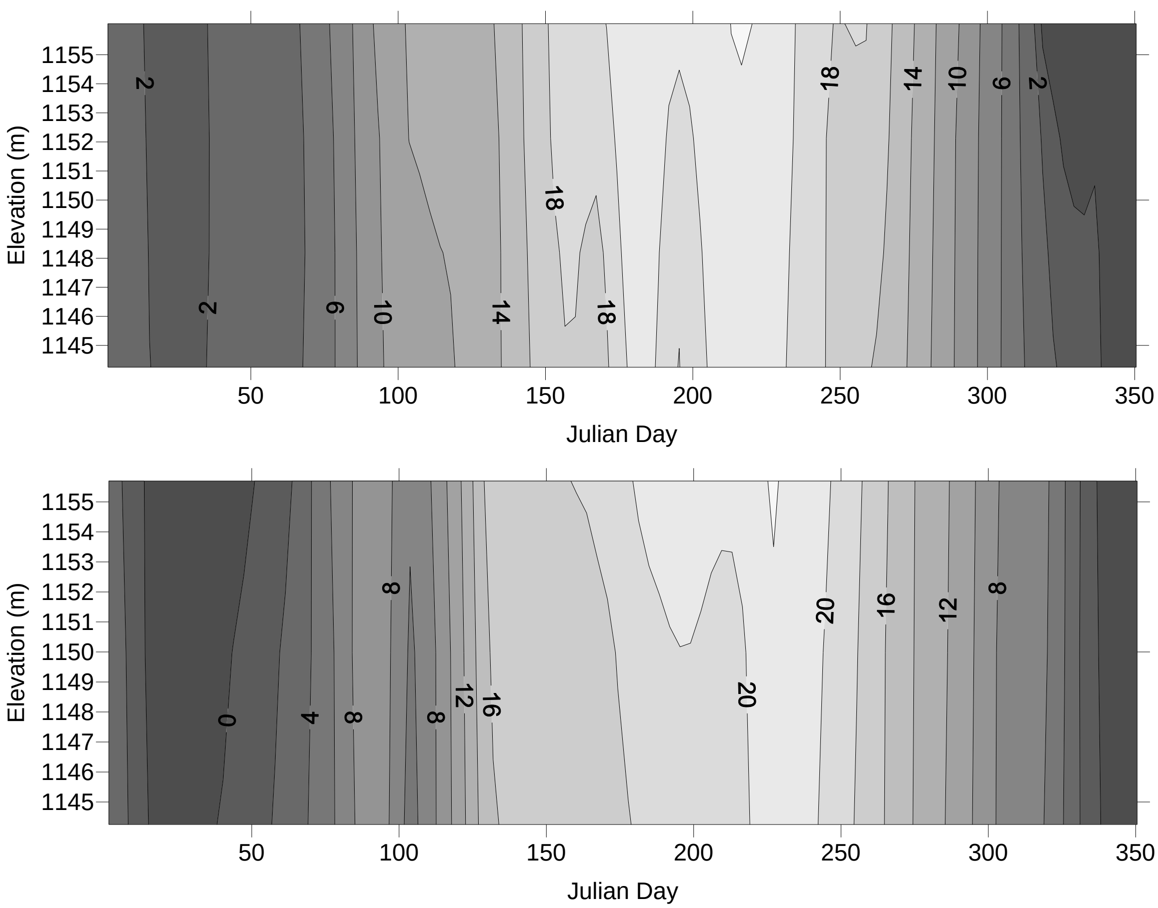

Figure 1. J.C. Boyle reservoir water temperature isopleths for 2000 (top) and 2001 (bottom).

The short HRT and relatively shallow depth of J.C. Boyle reservoir also results in little or no 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 1). During the summer months, cooler water entering the reservoir at night has relatively low DO 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 DO 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 between approximately 20 to 27 ^{o}C (PacifiCorp 2008a). This corresponds to the vertical temperature gradient of about 18 to 22 ^{o}C in J.C. Boyle reservoir (Figure 1).

Dissolved Oxygen Conditions in J.C. Boyle Reservoir

J.C. Boyle reservoir, as well as Copco and Iron Gate reservoirs downstream, is classified as "eutrophic" (nutrient-enriched) due to the large inflow loads of nutrients and organic matter from upstream sources, notably UKL. The nutrients that primarily cause eutrophication in lakes and reservoirs are nitrate, ammonia, and various forms of phosphorus (Thornton et al. 1990, Welch 1992, Horne and Goldman 1994, Holdren et al. 2001, Cooke et al. 2005). In general, eutrophic lakes and reservoirs have high algal biomass and low deep water DO during summer, and are typically characterized by summer-fall blooms of cyanobacteria (Thornton et al. 1990, Welch 1992, Horne and Goldman 1994, Cooke et al. 2005).

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 (Figure 2). These inflow DO conditions, combined with the high BOD as previously described, results in low DO values in J. C. Boyle reservoir, limited mostly to the deeper portion of the reservoir (below 5 m) (Figure 3). Low measured DO values are notably more frequent in the river entering the reservoir than in the reservoir itself (Table 1). Strong vertical oxygen gradients are relatively rare in the reservoir, as shown in Figure 3, suggesting that the effect of the vertical thermal gradient is small.

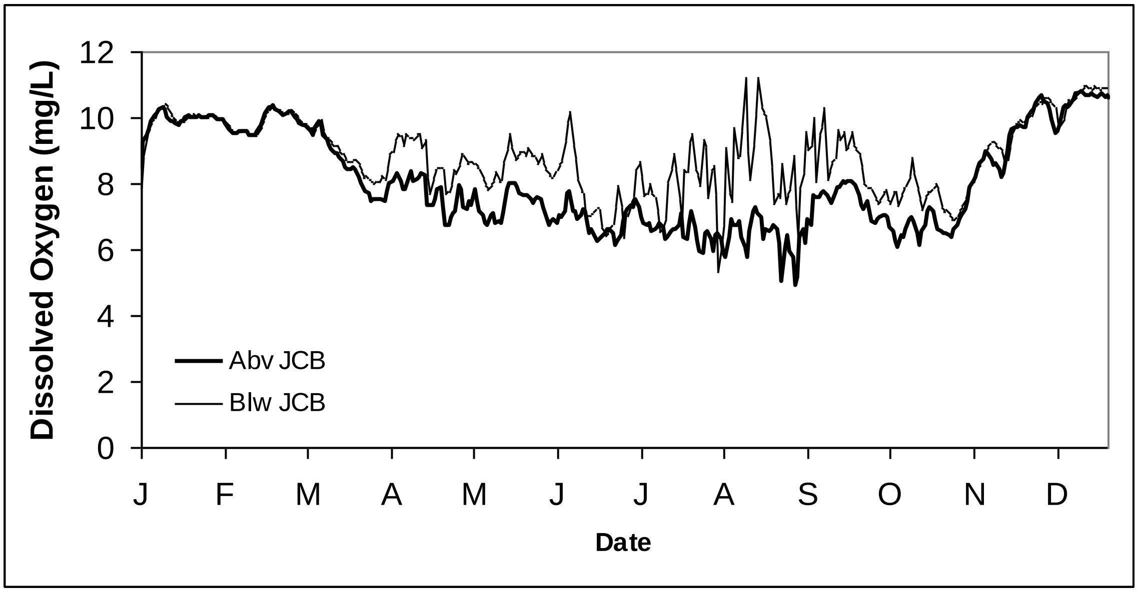

Figure 2. Daily average DO concentration in the Klamath River entering J.C. Boyle reservoir and below J.C Boyle dam, based on modeled hourly values for 2000.

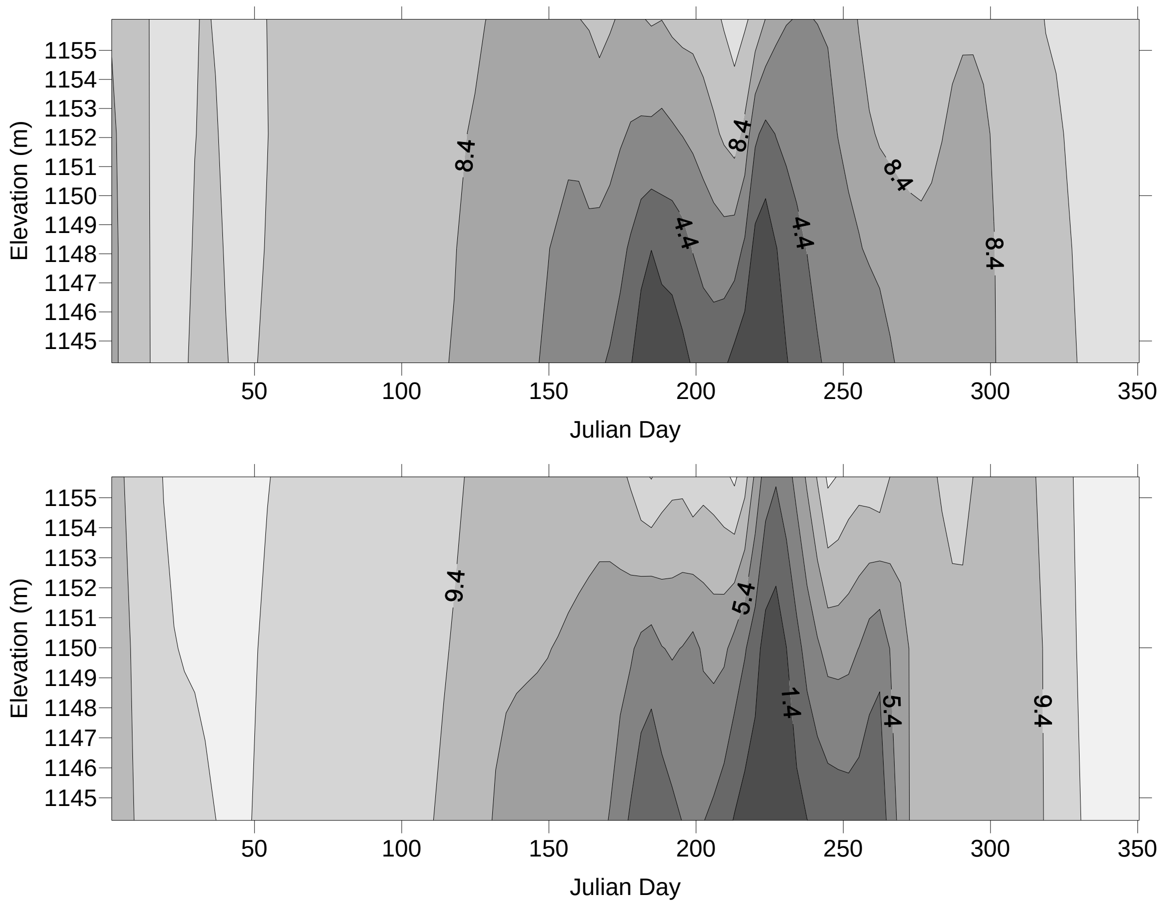

Figure 3. J.C. Boyle reservoir DO isopleths for 2000 (top) and 2001 (bottom).

Table 1. The Number and Percent of Measurements of DO in 2000 through 2002 in J.C. Boyle Reservoir that Were Less Than 8.0 mg/L or, if Conditions of Temperature and Barometric Pressure Precluded Achieving 8.0 mg/L, the Percent Saturation was Less Than 90 percent.

Depth (m)	Number of Measurements*	Number not Meeting Criteria	Percent not Meeting Criteria	Percent of Reservoir Volume in Depth Range
Inlet	365	200	57.8	--
0-3	179	44	24.6	75.4
3-8+	225	108	48.0	24.6

* Values for inlet are based on modeled hourly data for 2000

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 concentrations (Figure 4). This relationship is not specifically an effect of Keno dam, but rather the effect of the loading of organic matter to the Klamath River from sources upstream of Keno dam, notably hypereutrophic UKL.

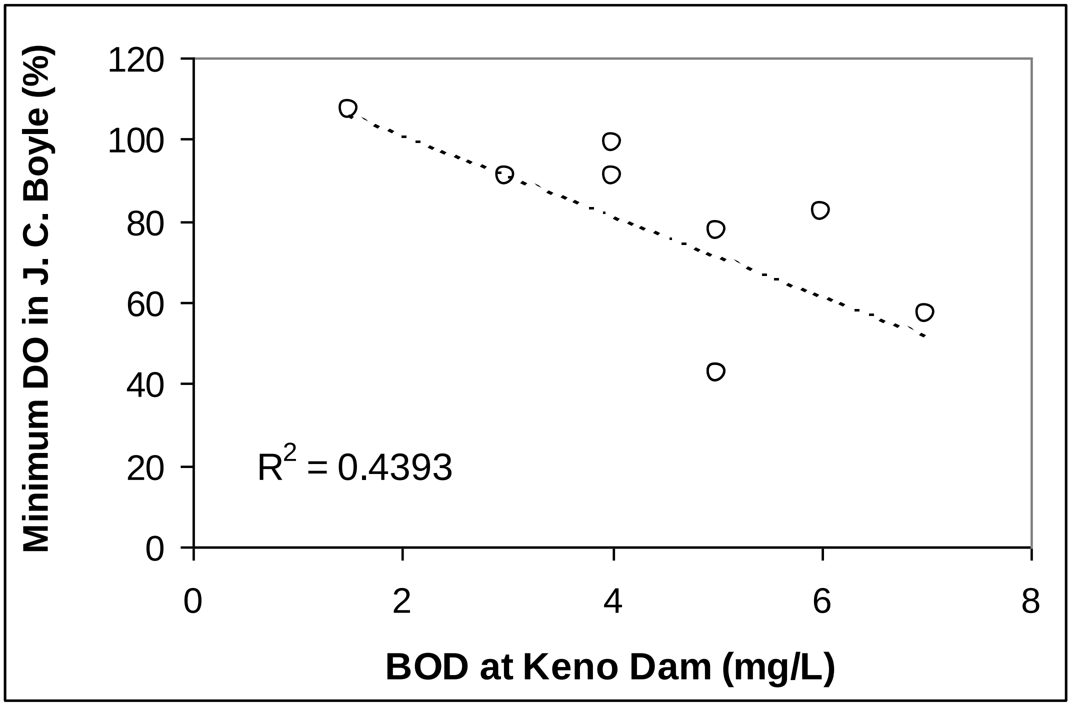

Figure 4. Minimum DO measured in J.C. Boyle reservoir compared to BOD measured at Keno dam on the same day. High BOD at Keno dam is associated with low DO in J.C. Boyle reservoir.

When the upstream Klamath River water enters J.C. Boyle reservoir, it deepens and slows, turbulence decreases, and reaeration decreases, especially for cooler water that flows to the deeper part of the reservoir. The consumption of oxygen from the ongoing processing of organic load is not as readily counteracted. Further, the deeper water keeps phytoplankton out of the photic zone, so that oxygen is consumed rather than produced a greater percent of the time. These effects are counteracted at shallower depths of the upper water column, where there is sufficient light for oxygen to be produced by phytoplankton photosynthesis.

During this study, additional DO data was collected in J.C. Boyle reservoir in July and August 2008 to characterize DO within a wider spatial area of the reservoir than covered in previous data collection (Figures 5 and 6). A large part of the surface area of J.C. Boyle reservoir is located upstream of the Highway 66 bridge. It consists of a large shallow area of about 2 to 3 feet deep bisected by the old river channel thalweg, which is typically a few feet deeper.

On July 29, 2008, a series of surface DO measurements were taken at mid-day at the upstream end of J.C. Boyle reservoir near the thalweg in the middle of the reservoir and within shallower areas between the thalweg and shore (Figure 5). The strong current of the inflowing river at the upstream end of the reservoir ensured that the water was well-mixed and isothermal at 22 ºC, although slightly lesser DO was measured at depths near the bottom (Table 2). The measurement results indicated that DO was variable, with surface DO values ranging from 7.7 to 11.7 mg/L (86 to 134 percent saturation) and DO values at depth ranging from 6.6 to 8.8 mg/L (75 to 100 percent saturation) (Table 2).

On August 28, 2008, another series of surface DO measurements were taken at mid-day in J.C. Boyle reservoir along the thalweg and within shallower areas between the thalweg and shore (Figure 6). As in July, the August measurement results also indicated that DO was variable, with surface DO values ranging from 6.3 to 9.0 mg/L (82 to 115 percent saturation) and DO values at depth ranging from 4.2 to 7.0 mg/L (54 to 91 percent saturation) (Table 3).

Much of the shallow area is occupied by dense growths of submerged or partially emergent macrophytes with smaller amounts of attached filamentous algae. The presence of these dense stands of macrophytes tends to direct the flow of water flow through the thalweg and within the fringes of the macrophyte stands. The amount of photosynthetic biomass in the submerged aquatic vegetation (SAV) is much higher than in the water, so the SAV contributes considerably to the DO increases in daylight and reduction by respiration at night. Examples of the effect of likely SAV-related increase can be seen in Table 2 for sites 8 and 9, and Table 3 for site 23.

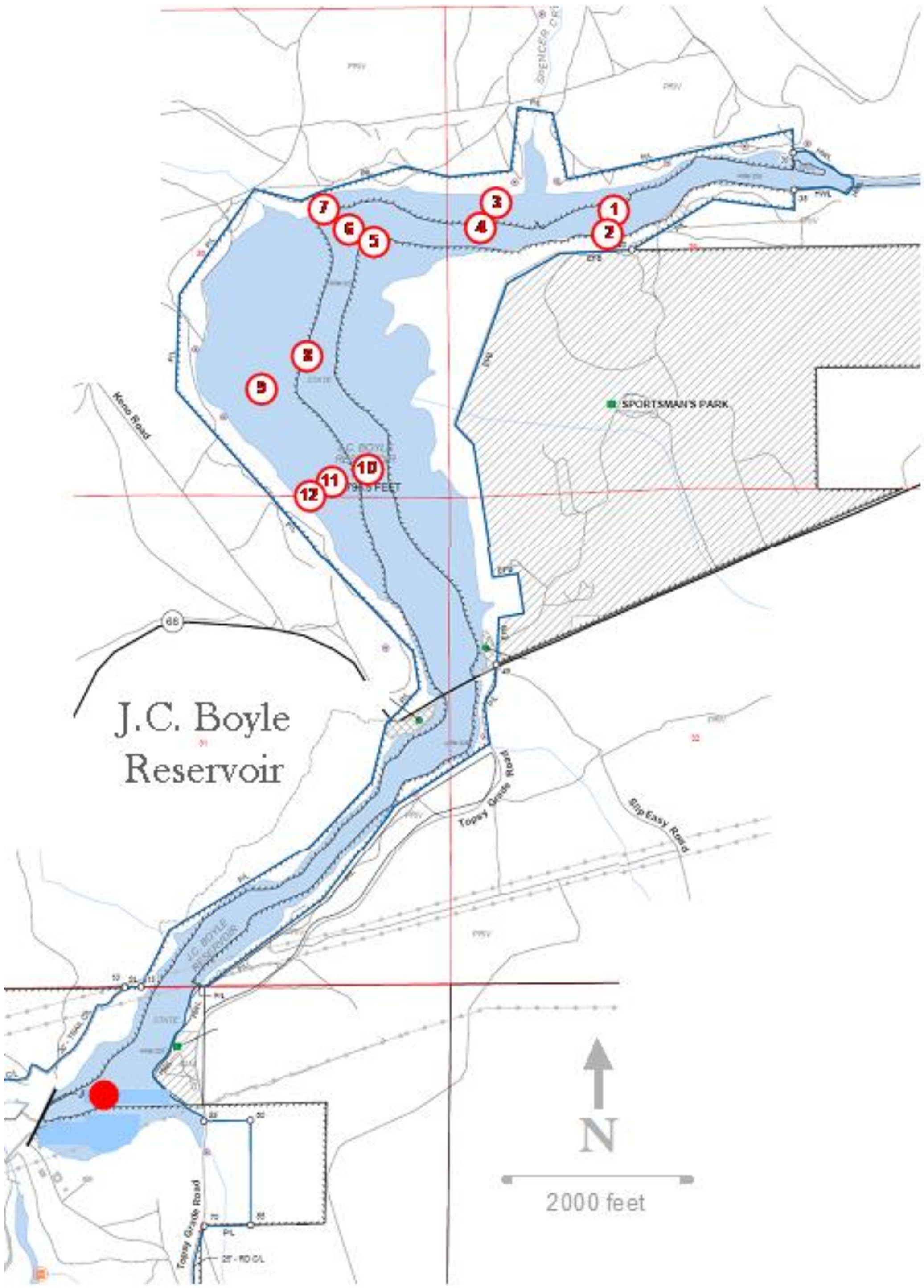

Figure 5. Locations of measurements of DO in J.C. Boyle reservoir taken on July 29, 2008. Circles with numbers correspond to Site Numbers listed in Table 2. The solid circle indicates the routine monitoring site over the deepest point in the reservoir upstream of J.C. Boyle dam.

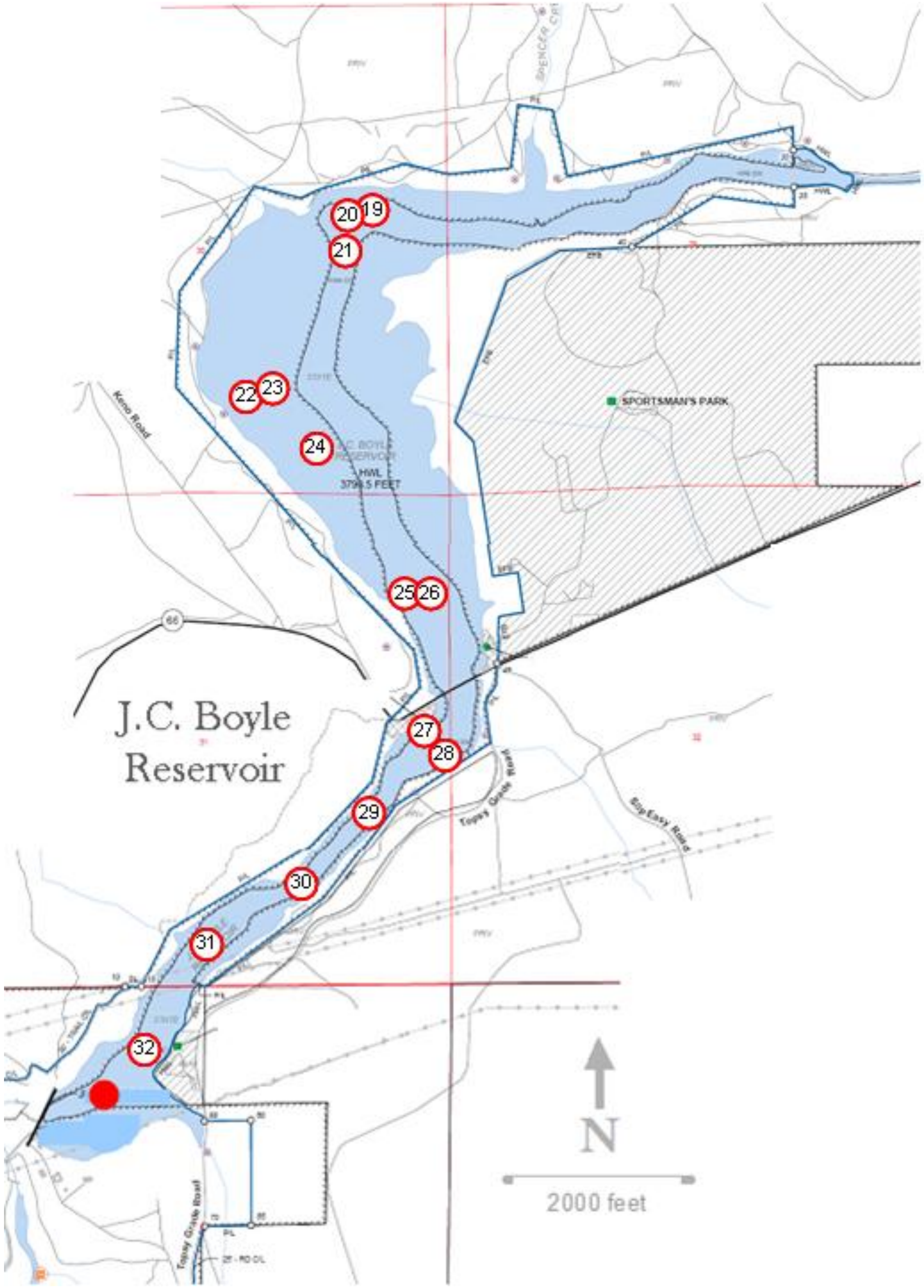

Figure 6. Locations of measurements of DO in J.C. Boyle reservoir taken on August 28, 2008. Circles with numbers correspond to Site Numbers listed in Table 3. The solid circle indicates the routine monitoring site over the deepest point in the reservoir upstream of J.C. Boyle dam.

Table 2. Measurements of DO at Various Sites in J.C. Boyle Reservoir Taken on July 29, 2008. Site Numbers Correspond to Locations Shown on Figure 5.

Site Number	DO at the Surface		DO at Depth		
	mg/L	Percent Saturation	mg/L	Percent Saturation	Depth (m)
1	8.8	100	8.1	94	1.3
2	8.7	99			
3	8.3	94	8.8	100	2.0
4	8.3	94	8.8	100	2.0
5	7.7	86			
6	8.4	95	7.8	87	0.9
7	8.1	92	6.9	80	5.1
8	11.6	130			
9	11.7	134			
10	10.3	115	6.6	75	4.0
11	9.7	109			
12	11.3	128			
Min	7.7	86	6.6	75	
Max	11.7	134	8.8	100	

Table 3. Measurements of DO at Various Sites in J.C. Boyle Reservoir Taken on August 28, 2008. Site Numbers Correspond to Locations Shown on Figure 6.

Site Number	DO at the Surface		DO at Depth		
	mg/L	Percent Saturation	mg/L	Percent Saturation	Depth (m)
20	7.3	93	6.7	84	4.0
21	6.7	86	6.6	83	3.0
22	9.0	115			
23	6.6	84			
24	6.3	82	6.7	86	1.0
25	7.2	95	5.9	75	2.0
26	6.5	85	5.8	73	3.0
27	7.9	105	5.8	73	3.0
28	7.3	96	5.6	71	4.0
29	6.7	88			
30	6.7	88	6.7	87	1.0

Table 3. Measurements of DO at Various Sites in J.C. Boyle Reservoir Taken on August 28, 2008. Site Numbers Correspond to Locations Shown on Figure 6.

Site Number	DO at the Surface		DO at Depth		
	mg/L	Percent Saturation	mg/L	Percent Saturation	Depth (m)
30 cont.			6.6	86	2.0
			6.3	82	3.0
			6.1	79	4.0
			5.9	76	5.0
			5.9	76	6.0
			5.9	75	7.0
			5.8	75	8.0
			5.8	75	9.0
31	7.0	92	6.8	89	1.0
			6.6	85	2.0
			6.4	82	3.0
			6.4	82	4.0
			6.3	81	5.0
			6.2	81	6.0
			6.1	78	7.0
			4.4	56	8.0
			4.4	56	9.0
32	7.0	92	7.0	91	1.0
			6.8	87	2.0
			6.7	87	3.0
			6.7	87	4.0
			6.5	79	5.0
			5.9	76	6.0
			4.4	56	7.0
			5.2	67	8.0
			5.0	64	9.0
			4.2	54	10.0
Min	6.3	82	4.2	54	
Max	9.0	115	7.0	91	

Figure 7 shows the results of vertical profile measurements for water temperature and DO taken at the routine monitoring site in J. C. Boyle reservoir in 2008 (location indicated by solid circles in Figures 5 and 6). The water temperature and DO profiles taken on July 29, 2008 – the concurrent date of the additional spatial measurements listed in Table 2 – are highlighted in Figure 7 with larger square symbols (in red). The water temperature and DO profiles taken on August 26, 2008 – two days before the additional spatial measurements listed in Table 3 – are highlighted in Figure 7 with larger square symbols (in green). These profile measurements at the routine monitoring sites in J. C. Boyle reservoir in 2008 are discussed in more detail, along with other water quality parameters, in Raymond (2009).

The DO values presented in Tables 2 and 3, and Figure 7 indicate that DO in J.C. Boyle reservoir is variable on a spatial basis. As previously described, the high BOD in the Klamath River flowing into J.C. Boyle reservoir results in low DO values in the deeper portion of the reservoir below about 5 m (as shown in Figure 3 and Figure 7). DO values at or near the surface of the reservoir are variable, but generally higher than at depth (as indicated in Tables 2 and 3, and Figure 7).

The spatial variability likely is explained by variations in the processes that affect DO, including the DO production processes of algae photosynthesis and air-water surface reaeration, and the DO consumption processes of respiration and decomposition. DO production occurs in the top portion of a lake or reservoir, where the photosynthetically-active algae reside. Because it requires sunlight, DO production from photosynthesis occurs during daylight hours and is greatest between mid-day and mid-afternoon. DO production from air-water surface reaeration is particularly important where the river enters the reservoir or when wind stirs the water, which creates conditions for efficient diffusion to occur.

Decomposition and respiration are DO consumption processes that counter the production of oxygen through photosynthesis and air-water surface reaeration. DO consumption typically is greatest near the bottom of a lake or reservoir, where sunken organic matter decomposes. As previously described, the decomposition of the high load of organic matter from the Klamath River to J.C. Boyle reservoir likely is the key process that explains low DO values in the deeper portion of the reservoir (as shown in Figure 3 and Figure 7). Respiration is the cellular process in which algae use oxygen and release carbon dioxide. Basically, it is the reverse of photosynthesis because carbon dioxide, water and energy are released in the process.

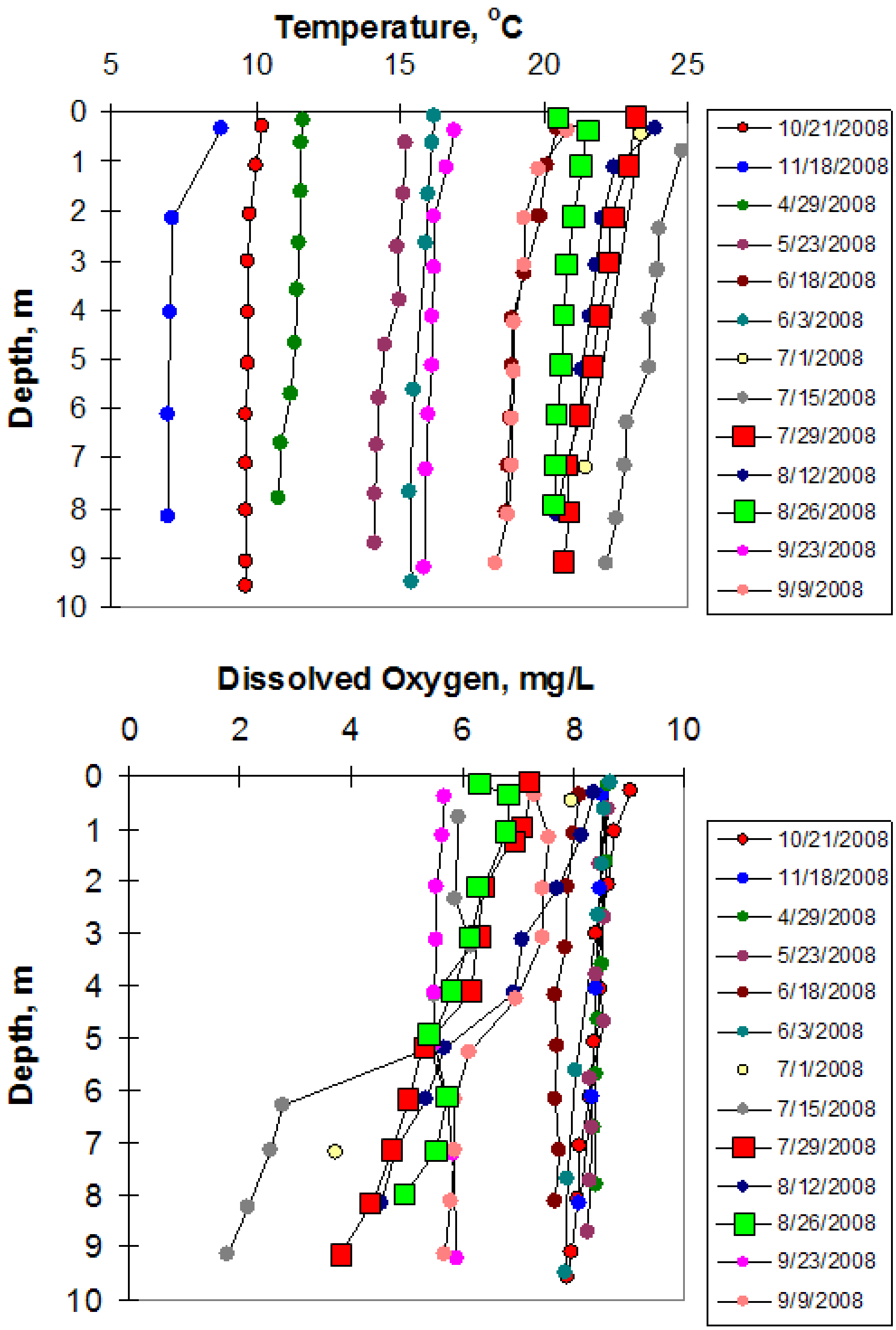

Figure 7. Vertical profile measurements for water temperature and DO taken at the routine monitoring site in J. C. Boyle reservoir in 2008 (location indicated by solid circles in Figures 5 and 6).

Approaches to Dissolved Oxygen Enhancement in J.C. Boyle Reservoir

Assessment Methods

This feasibility assessment was conducted by a team of specialists with expertise in DO enhancement techniques in reservoirs. Reconnaissance visits of the Project vicinity, particularly J.C. Boyle reservoir, were carried out by the team in summer 2008. During the site reconnaissance, the team discussed potential DO enhancement systems in J.C. Boyle reservoir, which included opportunities and constraints of potential techniques. In addition, the team brainstormed on conceptual layouts of potential systems in J.C. Boyle reservoir.

Following site reconnaissance visits, the team examined water quality data (particularly DO, BOD, and water temperature data and information), performed calculations of oxygen demands and requirements, and estimated system sizing and layouts for an aeration diffuser system in J.C. Boyle reservoir. The team also derived a rough order-of-magnitude estimate of costs for aeration diffuse system construction. The following sections describe the results of the feasibility assessment.

Approaches to Dissolved Oxygen Enhancement in Reservoirs

PacifiCorp previously prepared *Reservoir Management Plans* (RMPs) in 2007 and 2008 to evaluate the effectiveness and feasibility of various technologies and measures to more effectively control water quality conditions in J.C. Boyle reservoir (PacifiCorp 2008a), as well as in Copco and Iron Gate reservoirs (PacifiCorp 2008b). The technologies and measures assessed in the RMPs focused on improving water quality conditions in the reservoirs that result from significant loads of organic and nutrient matter originating from upstream sources, notably UKL.

The J.C. Boyle reservoir RMP identified several potential techniques for DO enhancement in lakes and reservoirs as described by Cooke and Kennedy (1989), Cooke et al. (1993), NALMS (2001), Price and Meyer (1992), and Thornton et al. (1990). Of these techniques, three targeted at improving DO and pH were further evaluated in the RMP development process: (1) water column circulation, (2) epilimnion methods, and (3) hypolimnetic methods. In the following sections, these techniques are defined and summarized. Advantages and disadvantages of each are described with regard to application to J.C. Boyle reservoir, particularly for improving DO conditions in the reservoir.

As noted above, J.C. Boyle reservoir does not strongly stratify during summer, but only experiences gradual and transient vertical gradients of water temperature and DO. Therefore, the terms "hypolimnetic" and "epilimnetic" are used herein mostly for consistency with terminology as used elsewhere in the literature on reservoir water quality management. In the case of J.C. Boyle reservoir, the terms "hypolimnion" and "epilimnion" approximately correspond to the lower (deeper) half and upper (shallower) half of the water column, respectively.

Water Column Circulation

Water column circulation is targeted at mixing the entire water column, whereas epilimnetic or hypolimnetic aeration involves mixing only shallower or deeper layers of the reservoir, respectively. Water column circulation is a technique intended to improve water quality by mixing the oxygen produced by algae out of the euphotic zone (i.e., the surface zone with sufficient light for algal growth), thus introducing oxygen to the bottom waters of the reservoir. A second mechanism, applicable in deeper lakes, is by elevating 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 into darker water. The circulation also minimizes intermittent vertical gradients that can lead to the dominance of low DO processes in bottom waters. Water column circulation uses aeration-driven circulation to mix the entire vertical water column to prevent or interrupt vertical stratification. As used in this plan, water column circulation is differentiated from epilimnetic (or surface) aeration, and hypolimnetic (or bottom) aeration by the extent of reservoir waters to be mixed.

The two most common techniques for water column circulation (destratification) are air injection and mechanical mixing. Air injection (diffuser) systems are the most common water column circulation (destratification) method. A compressor on shore 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.

Mechanical mixing is accomplished using axial flow pumps in a "top-down" approach to set up a circulation pattern. 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 a vertical circulation pattern. Oxygen-poor water from the lake bottom is circulated to the reservoir surface, where oxygenation from the atmosphere can then occur.

Both techniques for water column circulation have strengths and weaknesses. The primary strengths are simplicity and relatively low cost. The first weakness is that there must be enough oxygen produced by algal photosynthesis in the upper waters to load the waters with oxygen to be mixed down to the bottom sediments. The second weakness is that there remains a layer of dense lower-DO water over the sediments that is less affected by mixing directed from the surface because the less dense warmer surface water tends to rise before it finally reaches the sediments.

Epilimnetic Methods

Surface or epilimnetic circulation is performed to mix water and minimize quiescent conditions in surface layers of the reservoir. In some reservoirs, mixing is used to directly control algae growth by mixing the algae out of the euphotic zone (i.e., the surface zone with sufficient light for algal growth), and as an indirect control on elevated pH. However, if the wrong mixing regime is used, algae may increase since they will also be mixed out of the two unfavorable zones (high surface light and low deep water light) and pass through the intermediate optimal light zone.

Mixing also appears to tip the competitive balance between some nuisance forms, such as blue-green algae (cyanobacteria), and other groups, such as diatoms, but the exact mechanism remains uncertain. The surface mixing and agitation caused by this circulation is expected to reduce algae production by also disrupting the generally quiescent conditions they prefer for bloom formation. However, in J.C. Boyle reservoir, algae bloom formation is limited primarily due to washout as discussed earlier.

Several types of aerators and circulators are available for potential application for surface or epilimnetic circulation and aeration. Examples include low-powered (e.g., solar-powered) water "circulators" that claim to spread a very thin layer of deeper water horizontally across surface water of the reservoir at a manufacturer-estimated rate of up to 10,000 gallons per minute. Other examples include traditionally-powered mixers, such as those used in wastewater treatment or industrial processes.

For J. C. Boyle reservoir, circulation of the deep water to the surface and surface water to the bottom would most effectively be performed with a conventional large bubble system that promotes vertical circulation motion with larger air bubbles, which can move large amounts of water to give the required mixing of the layers of water of different densities and temperature. Such systems have been frequently used in other lakes and reservoirs throughout the world.

Hypolimnetic Methods

Hypolimnetic aeration is a technique that increases the concentration of oxygen in the deeper part of the reservoir by injecting compressed air into the hypolimnion. The addition of oxygen to the hypolimnion is used to prevent low oxygen from occurring in the bottom layer. An advantage of this method is that thermal stratification is preserved for most of the season although in some waters the fall turnover or destrafication event may arrive earlier than normal.

Hypolimnetic aeration supplies air containing 20 percent oxygen to the hypolimnion. In most systems, one or more large compressors are installed near the reservoir and compressed air is piped to several deep locations. The most common methods for delivering compressed air to the hypolimnion include full airlift or partial airlift systems.

In a full airlift approach, compressed air is injected into the base of a vertical pipe that lifts both air bubbles and some entrained bottom water to the surface. During the lifting process some oxygen from the air dissolves in the water. The water emerges into a floating box where the majority of the added air escapes to the atmosphere. The partially aerated water then sinks back to the bottom via another pipe. This simple system was originally popular but has been replaced in most places by partial lift systems that do not have large boxes floating on the water surface. The partial airlift system is similar to the full airlift aerator except that the cylinder is capped below the water surface and gas is released via a pipe to the surface.

Hypolimnetic (or bottom water) aeration provides the following advantages: (1) counteracts low DO in deeper waters of the reservoir, thereby improving conditions for organisms that may prefer the deeper waters of the reservoir, and (2) provides oxic conditions that retard the buildup of undecomposed organic matter and compounds (e.g., ammonium) in deeper waters of the reservoir. Successful reduction of blue-green algae or reversal of eutrophication has not been shown with full or partial lift aeration, although some improvements in other water quality parameters, such as increased DO, have occurred in some cases. The main drawback to any full mixing system is that the sediments become heated and bacterial action is increased, which results in more flux of nutrients from the sediments. In addition, any cool water aquatic habitat is lost.

Hypolimnetic oxygenation is a relatively new technique aimed at preventing hypolimnetic anoxia. The first systems were only installed in the 1980s primarily in very large reservoirs in the Southwest. Hypolimnetic oxygenation systems are similar to hypolimnetic aeration systems (as described above) except that pure oxygen rather than air is used. Oxygen is often provided as liquid oxygen and stored lake-side, and also can be generated on site by a pressure swing compressor and molecular sieve. Oxygen is delivered using one of two primary approaches: a bubble system or a bubble-free system. The bubble systems consist of pipes with small holes laid throughout 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 efficiency of fine bubble oxygenation varies with water depth, but can be over 80 percent in deep cold reservoirs. The bubble-free systems consist of a pressuring device into which the deep water is pumped to compress the oxygen for an efficiency of almost 100 percent.

Two popular types of bubble oxygenators are the unconfined fine bubble diffuser and the unconfined and diffuse bubble curtain. The fine bubble diffuser sends oxygen to the bottom at a few sites using discrete diffusers. The bubble curtain uses long arrays of hoses that emit fine bubbles over the entire length of the hose. Large bubble curtain systems, supplying up to 100 tons of oxygen a day, are currently in use in several reservoirs in the United States – the larger systems in current use are mostly used to oxygenate water as it passes through turbines and downstream, but a few smaller systems have been installed for water quality improvements within reservoirs.

The bubble-free oxygenator systems (Submerged Downflow Contact Oxygenators or Speece Cones) send oxygen into a pressurized container where the gas mixes with water pumped from the reservoir. The pressurized container can be situated at the bottom of the lake, taking advantage of the natural pressure of deep water. The oxygenated water is then dispersed over the sediments via a short manifold or sometimes with a few direct pipes. As with the bubble aerators, various sizes of bubble-free oxygenator systems are currently in use in reservoirs in the U.S., both for downstream oxygen regulations and to reduce nutrient recycling and eutrophication in the reservoirs themselves.

Hypolimnetic oxygenation would not be a prudent choice for J.C. Boyle reservoir, since the weak stratification in J.C. Boyle reservoir would make the regulation of the deeper DO difficult. In addition, the relatively short HRT of J.C. Boyle reservoir would ensure that much of the more-expensive pure oxygen added would be lost soon after discharge from the reservoir to the Klamath River downstream.

Preferred Approach to Dissolved Oxygen Enhancement in J.C. Boyle Reservoir

Based on the physical and limnological features of J.C. Boyle reservoir and the techniques reviewed, the most appropriate oxygen enhancement system for J.C. Boyle reservoir would be an air injection (diffuser) system that mixes the entire vertical water column to keep oxygen circulating through the deeper waters of the reservoir. This system would also minimize intermittent vertical gradients that can otherwise lead to low DO conditions in bottom waters. The air injection (diffuser) system in J.C. Boyle reservoir be located in, and focus on DO enhancement in the deeper part of J.C. Boyle reservoir in the lower end of the reservoir. Circulation of the water column in the deeper section of J.C. Boyle reservoir would provide an even (isothermal) distribution of temperatures and uniform distribution of DO with depth. J.C. Boyle reservoir is essentially well-mixed or at most “weakly” stratified; that is, it does not exhibit the classic distinct summer stratification of a deeper reservoir, such as occurs in Iron Gate and Copco reservoirs. Thus, less energy is needed to induce and maintain the desired isothermal conditions for a given level of solar heating.

A focus on DO enhancement in the deeper, lower end part of J.C. Boyle reservoir is preferred since the shallow reaches of J.C. Boyle reservoir near its upstream end cannot be improved by any aeration or oxygen enhancement technique for three primary reasons. First, a system in the upper part of the reservoir would lack efficiency and effectiveness due to the high advection of BOD in the river inflow to the reservoir from upstream sources (notably from Upper Klamath Lake and Keno reservoir). Second, a system in the upper part of the reservoir would be shallow, so that bubbles generated would have small direct oxygenation effect. In addition, the mixing effect would be small since the zone of influence of an air plume is related to its depth, with shallow water being the most difficult to mix. Third, 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).

Conceptual Design of an Air Injection (Diffuser) System for J.C. Boyle Reservoir

A conceptual design for an air injection (diffuser) system in the deeper part of J.C. Boyle reservoir is shown in Figure 8. The conceptual design is based on a system that would mix and partially aerate the water column by installing a series of individual diffusers over a 1280 meter (m) length of the reservoir up from J.C. Boyle dam. 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).

Early aeration-mixing systems designs in the 1970s used pipes with small holes drilled in them to produce the bubbles (Horne 1976). Some systems still use this older approach, but the method can result in inefficient operation and maintenance (Horne 2008). The diameter of the hole in the pipe must be designed with a depth consideration since the greater hydraulic head in the deeper sections reduces the ability of the air to be released. For example, the holes in diffusers of an aeration system in Lake Elsinore, Riverside County, California were discovered to be the wrong size requiring retrofitting of several thousand feet of diffuser pipe. Commercially-made diffusers are now available for attachment to air hoses, and the use of these commercially available diffusers is recommended for the air injection (diffuser) system in the deeper part of J.C. Boyle reservoir.

Key System Design Components

Volume of Air Needed

The volume of air needed for the conceptual design for the J.C. Boyle reservoir aeration system was initially estimated using the generalized method of Cooke et al (2005) based on the total surface area to be mixed. The amount of air required was computed as 550 m^3 air/km^2/hr. For J.C. Boyle reservoir, the area-based estimate requires adjustment due to the reservoir's extensive amount of shallow area; in shallow or narrow lakes and reservoirs, it is inefficient to extend the area of mixing much beyond the immediate area of location of the diffusers (O'Hara and Horne in preparation). The total surface area of J.C. Boyle reservoir is 420 acres (approximately 1.70 km^2), and the surface area of the deeper part of J.C. Boyle reservoir in the immediate area of the proposed aeration system is 60 acres (approximately 0.24 km^2).

The restricted area adjustment yields a revised estimate of approximately 132 m^3 air/hour for the adjusted reservoir area under consideration, which for each diffuser would be approximately 11 m^3 air/hour. It is possible to pass 11 m^3 air/hour through each diffuser, but is not optimal for the amount of water lifted per diffuser. Smith et al. (1975) indicate that it is better to put less air per diffuser (obviously within limits, as commercially manufactured diffusers are optimized for a certain airflow), and so an air flow of 5.5 m^3 air/hour per diffuser is considered more appropriate. An air flow rate of 5.5 m^3 air/hour per diffuser would require an estimated 24 total diffusers with individual feed lines (more on these design features is described below).

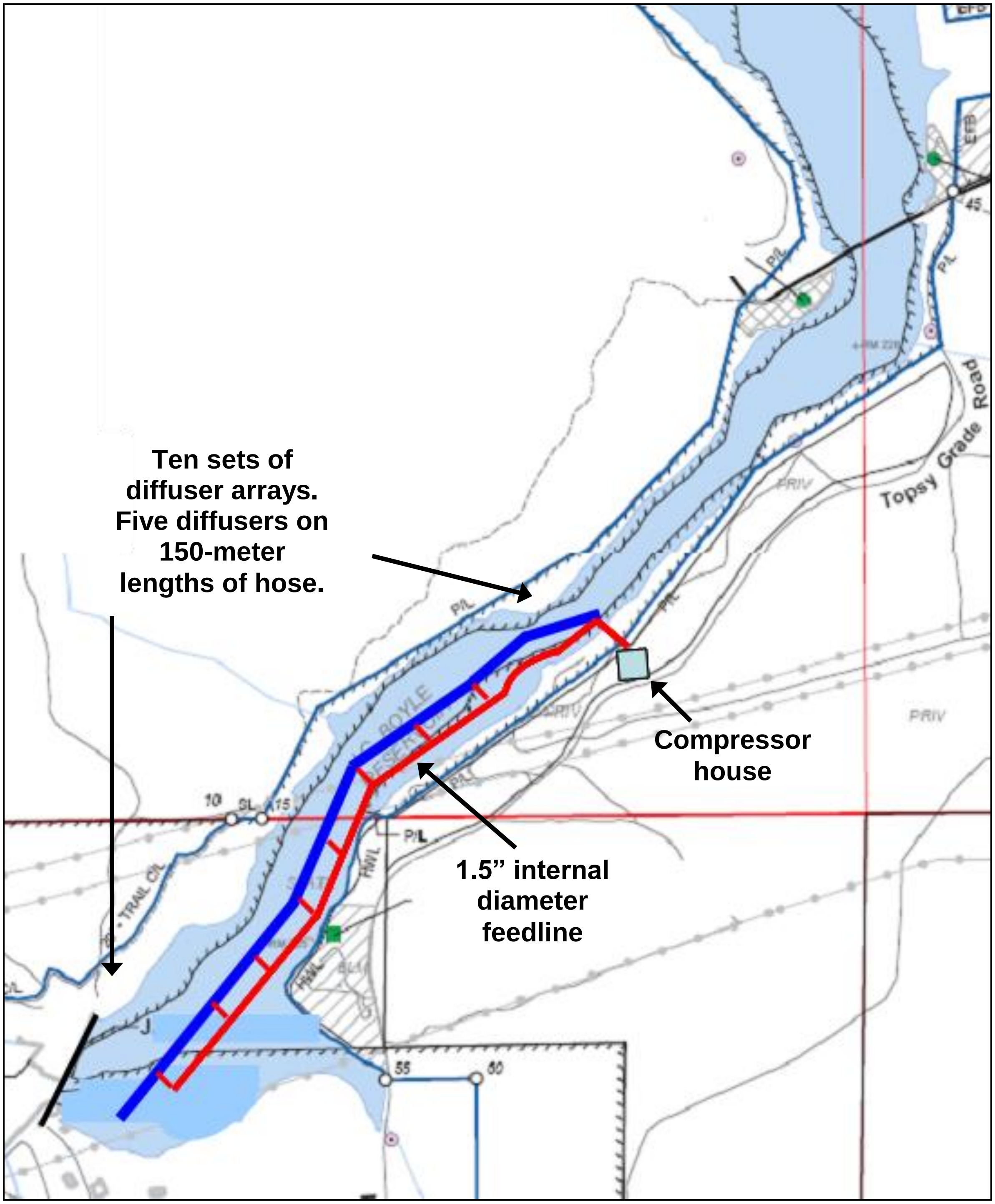

Figure 8. Conceptual design layout of an aeration system for J.C. Boyle reservoir.

In the case of J.C. Boyle reservoir, there are two major design constraints with respect to the volume of air needed. First, the relatively high elevation of J.C. Boyle reservoir (3,790 ft msl) means that the air contains considerably less oxygen than at elevations within 500 feet of sea level where most aeration systems have been installed. The low 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 air atmospheric uptake at the water surface and from the solubility of the bubbles to raise the oxygen level to 5 mg/l and above. As was mentioned earlier, the oxygen produced by photosynthesis in J.C. Boyle reservoir is low due to washout of algae. Photosynthetic oxygen is normally more important than any gas transfer from bubbles in reservoir aeration. The elevation effect can be overcome somewhat by the use of more diffusers, essentially increasing the total equivalent water column depth.

The second major design constraint with respect to the volume of air needed is the high and dynamic BOD load to J.C. Boyle reservoir, particularly during the summer-early fall period. The high and dynamic BOD load to J.C. Boyle reservoir makes for variable DO conditions in the reservoir. These variable DO conditions make the calculation of the volume of air needed (and the specific oxygen level likely achieved) challenging using standard air solubility equations because the efficiency of oxygen transfer decreases as the DO level in the water increases. For example, it requires more air to raise the oxygen level from 3 to 5 mg/L than from 1 to 3 mg/L. Therefore, the number of diffusers for the conceptual aeration system for J.C. Boyle reservoir would be doubled from 24 (as calculated above) to 50, and the total airflow thus increased to approximately 260 m^3/hr (at atmospheric pressure).

Air Diffusers, Supply Piping, and Manifold

As described above, a total number of 50 diffusers is suggested for this design. There are a number of commercially available diffuser systems for use in lake and reservoir environments. These systems usually rely on having an individual air line to feed each diffuser to enable the airflow to each diffuser to be balanced (Cowell et al. 1987). Typical past designs have relied on individual feed lines for each diffuser, with no more than about six lines practical for most aeration manifolds. For 50 diffusers in the conceptual design of the J.C. Boyle reservoir aeration system, it would be impractical to install the number of individual air lines and balance the flow from a manifold fitted with individual regulating taps. However, this potential problem can be solved by the use of a patented design, which automatically balances the airflow to each diffuser even when all of the diffusers are connected to a single airline. The system was developed in the United Kingdom by Ken O'Hara (one of the authors of this report) and has also been successfully used in mainland Europe and the U.S. As shown in Figure 8, the conceptual design of the J.C. Boyle reservoir aeration system includes ten sets of diffuser arrays, with each array consisting of five diffusers on 150-meter lengths of hose. The entire 1500-meter lineal system of diffuser arrays would be fed by a single 1.5-inch internal diameter (ID) feedline, which serves compressed air to shorter lateral feedlines to each array.

The air would be delivered into the primary system feedline (specially made from 1.5-inch ID hydraulic hose, which is self-sinking in water). The primary system feedline would be fitted with a manifold, a non-return valve, and a connection where an additional oxygen supply could be fitted to the system, if desired. The primary system feedline would be located adjacent to the reservoir shoreline in shallow water approximately on the 2 m depth contour. Experience has shown that the main air supply feedline is best placed along the shoreline 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. The spacing of the diffusers would require T-fittings at 125 m intervals to permit connection of 1-inch ID hose of sufficient length to reach the deepest point of the channel. Five diffusers would be individually fitted at 25 m intervals to the 1-inch hose. (See Figure 8; more detailed drawings of the system can be provided at a later stage of the design process).

The diffusers to be fitted would be either disc diffusers or tube diffusers; this would depend on which is most appropriate for the bed sediment conditions and the maximum flow velocities that are likely to pass through the reservoir. Each diffuser would be fitted with flow regulator, it is this device and concept that is patented and which permits the automatic balancing of the diffusers from a single primary feedline as shown in Figure 8. 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.

At this conceptual design level, a specific recommendation is not made on which type of diffuser to use. The choice of the diffuser type would be a subsequent design consideration to be made based on more detailed assessment of specific DO enhancement objectives, and associated calculations of mixing and oxygen transfer efficiency calculations (Smith et al. 1975). However, minor additional cost implications are involved with the selection of either type of diffuser.

Air Supply Compressor

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 (~ 30 hp) air compressor would be required. The compressor and all ancillary equipment, including housing, can be provided as a purpose-designed package. 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.

The compressor and housing would be located at the point shown in Figure 8. Although the compressor would be very quiet in operation, it is appropriate, given the relatively quiet, rural nature of the environment, to site the equipment at a considerable distance from nearby houses, campgrounds, or day use areas.

Cost Estimate

The estimated cost of installation of the conceptual air injection (diffuser) system as described above (and shown in Figure 8) is $300,000 to $500,000. 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. Operation and maintenance (O&M) costs are 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).

Conclusions

The key conclusion of this feasibility assessment is that the most appropriate system for enhancement of DO in J.C. Boyle reservoir would be an air injection (diffuser) system located 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 three 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; and (3) 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).

The most appropriate conceptual design of an air injection (diffuser) system in the deeper, lower portion of J.C. Boyle reservoir would include ten sets of diffuser arrays, with each array consisting of five diffusers on 150-meter lengths of hose. The entire 1500-meter lineal system of diffuser arrays would be fed by a single 1.5-inch internal diameter (ID) feedline, which would serve compressed air to shorter lateral feedlines to each array. 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 (~ 30 hp) air compressor would be required.

Given the constraints in J.C. Boyle reservoir of high BOD inflow loading and relatively high elevation, a fine/medium orifice type of diffuser would likely be the best choice of diffuser type to provide most efficient oxygen transfer and water mixing. The choice of the diffuser type would be a subsequent design consideration made based on more detailed assessment of specific DO enhancement objectives, and associated calculations of mixing and oxygen transfer efficiency calculations.

The estimated cost of installation of the conceptual air injection (diffuser) system as described in this report is $300,000 to $500,000. Operation and maintenance (O&M) costs are 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).

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