TECHNICAL MEMORANDUM

Interim Measure 11, Activity 4 – Conceptual Feasibility Study of Oxygenation Systems at Keno Reservoir

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1.0 Introduction

The Klamath Hydroelectric Settlement Agreement (KHSA) includes Interim Measure (IM) 11: Interim Water Quality Improvements, which is intended to address water quality improvement in the Klamath River during the interim period leading up to potential dam removal. Several Interim Measure 11 activities were conducted during 2015 and extending into 2016, which included Activity 4 Conceptual Feasibility Study of Aeration/Oxygenation Systems at Keno Reservoir. Keno reservoir is located on the upper Klamath River from River Mile (RM) 233.0 (at Keno dam) to RM 253.1, and is only 1.2 miles downstream from the outflow of Upper Klamath at Link River dam (RM 254.3)(Figure 1).

This report describes the assessment approach and results of a conceptual feasibility study of oxygenation systems at Keno reservoir. This conceptual feasibility study is an initial analysis that "bounds the problem", after which future more-refined analysis might be further pursued, if feasible and desirable outcomes from this study are evident. For this analysis, CH2M and Watercourse Engineering, Inc. (Watercourse) collaborated to assess the potential use of two technologies for improving dissolved oxygen (DO) concentrations in Keno reservoir: (1) oxygen injection via a linear diffuser (also referred to as "sparging") located in the reservoir; and (2) side-stream oxygenation. The rationale and descriptions of these two technologies are provided in Section 3.1 below.

A draft of this report was circulated to the Interim Measures Implementation Committee (IMIC) for review on April 13, 2016. Comments subsequently received from IMIC members were reviewed by PacifiCorp and the draft report was revised as appropriate; all comments and responses are included in Appendix A.

1.1 Purpose

The purpose of this study is to assess the conceptual feasibility of oxygenation systems for the purpose of enhancing water quality in Keno reservoir through addition of oxygen to increase DO concentrations. In addition, the systems could potentially promote the biological oxidation (and decomposition) of organic matter (OM). The addition of oxygen and resulting enhanced decomposition of organic matter loads emanating from Upper Klamath Lake could provide substantial water quality improvements in Keno reservoir, which is just downstream of Upper Klamath Lake, and possibly further downstream in the Klamath River. In addition, the resulting water quality improvements in Keno reservoir could potentially provide important benefits for endangered suckers found in the reservoir (USFWS 2001) and potentially facilitate anadromous fish passage through the reservoir in the future if downstream dams are removed or fish passage is otherwise established.

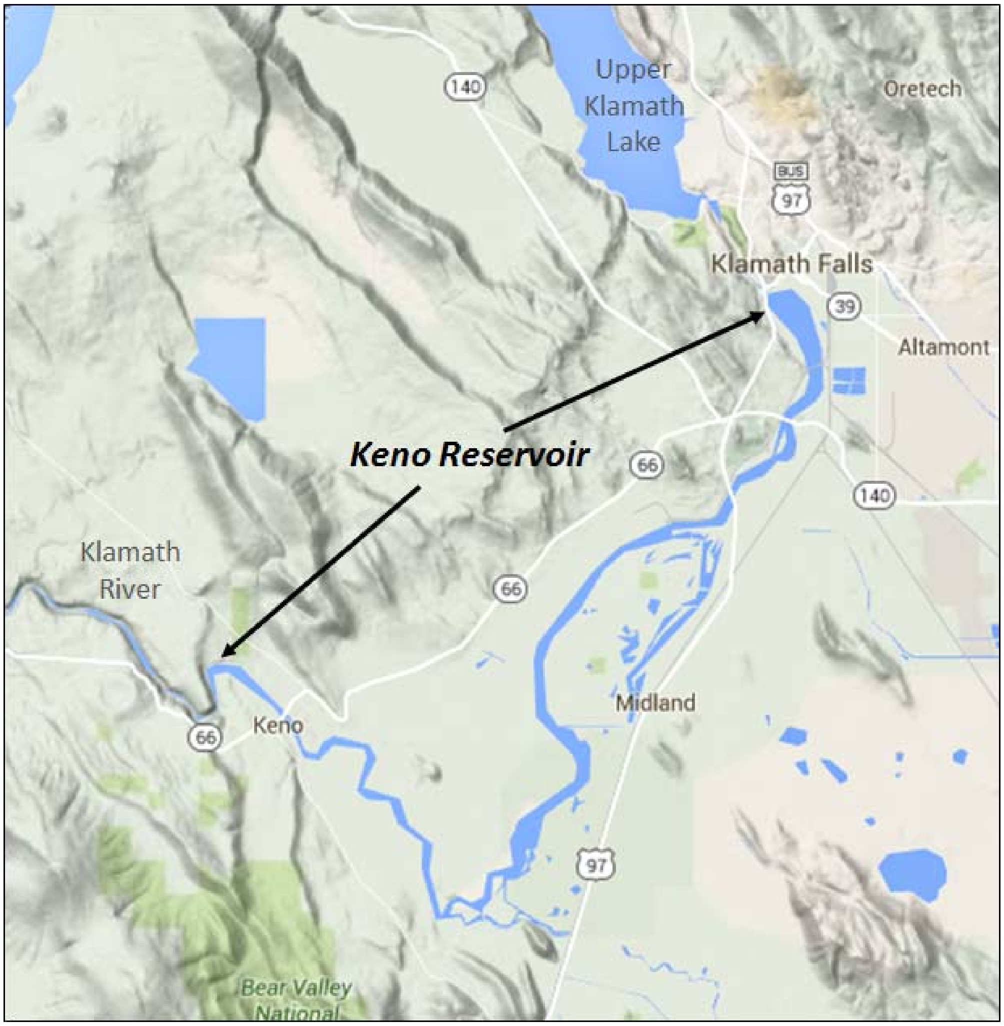

Figure 1. Keno reservoir location.

1.2 Background Context

1.2.1 DO Impairment in Keno Reservoir

Keno reservoir extends 20 miles from the headwaters of Lake Ewauna (RM 253.4) to Keno dam (RM 233.3). The impoundment is generally a broad, shallow body of water. The width of the reservoir in this reach ranges from several hundred feet (ft) to over 1,000 ft, with maximum depths along its length ranging from less than 6 ft to approximately 20 ft (Eilers and Gubala 2003). Municipal, industrial, and agricultural activities are located along this reach (ODEQ 2010).

Currently, Keno reservoir experiences severe seasonal water quality impairment. These impairments include summer and fall anoxia in the reservoir caused primarily by the substantial oxygen demand from the large organic matter loading from Upper Klamath Lake (Sullivan et al. 2010; Sullivan et al. 2011; Sullivan et al. 2013). In addition to the organic matter loading from Upper Klamath Lake, the agricultural return flows from the U.S. Bureau of Reclamation's Klamath Project also contribute loads (although much less) of nutrients, total dissolved solids, and biochemical oxygen demand (BOD; ODEQ 2010).

Sullivan et al. (2010) report that the large organic matter loading causes substantial oxygen demand in Keno reservoir. Sullivan et al. (2010) measured large oxygen demand values in Keno reservoir, including

5-day BOD values ranging from 4.2 to 26.5 milligrams per liter (mg/L) and 30-day BOD values ranging from 13.6 to 55.4 mg/L. Most pristine rivers have a 5-day BOD (BOD_5) below 1 mg/L, and moderately productive rivers generally have a BOD_5 value in the range of 2 to 8 mg/L (Manivanan 2008). Typical treated municipal sewage has BOD_5 values of about 10 to 40 mg/L (Spellman 2013).

The substantial oxygen demand in Keno reservoir has been well-documented. In 1955, the State of Oregon (Oregon State Sanitary Authority et al. 1955) concluded that the large nutrient load and oxygen demand from the Upper Klamath Lake outflow cause severe downstream impacts that are "equivalent to the raw sewage from a population of more than 240,000 persons" but that "94 percent of BOD is derived from natural causes" where the term "natural causes" was referring to algae bloom materials.

DO values in Keno reservoir in summer and fall are typically well below saturation levels and may be near zero (i.e., anoxic). Review of detailed vertical profiles at multiple sites along the longitudinal axis of the reservoir suggests that Keno reservoir experiences something akin to an oxygen sag[1] (Tchobanoglous and Schroeder 1985) in the vicinity of Miller Island. Low DO concentrations persist well into October and may extend into November (Sullivan et al. 2009).

Some recovery in DO levels occurs by the time waters reach the downstream end of Keno reservoir at Keno dam. This may be a function of residence time (e.g., processing time and settling), physical reaeration aided by windy conditions in the Keno area, primary production, or other factors (Sullivan et al. 2010; Sullivan et al. 2011; Sullivan et al. 2013). Conditions downstream of Keno dam are generally improved by reaeration of releases from the dam because the configuration of radial gates and the sluice discharge from the dam can act to reaerate releases to some degree, and from natural mechanical aeration in the high-gradient riverine environment downstream of the dam.

The large organic matter and nutrient loading to Keno reservoir also has important implications for processing of nutrients and growth of algae in the reservoir (Sullivan et al. 2010). The organic matter takes on one of several forms (labile, refractory, particulate, and/or dissolved), and includes organic forms of nutrients (nitrogen and phosphorus). These nutrients are transported downstream and upon decay of the organic matter are released and available for uptake by local phytoplankton and benthic algae populations (Sullivan et al. 2010; Sullivan et al. 2011). One of the most notable aspects of the reach is the large amount of inorganic nutrients present during periods of anoxia. During anoxic conditions total inorganic nitrogen (nitrate and ammonia) is in excess of 1 mg/L and orthophosphate values can be excess of 0.5 mg/L (Deas 2008).

Under anoxic conditions in Keno reservoir, internal nutrient cycling from the sediments has been identified (Eilers and Raymond 2003; Raymond and Eilers 2004). When the entire water column is anoxic, processes that are otherwise typically restricted to the bed (such as release from sediments of phosphorous and ammonia bound to organic or inorganic particles) can occur throughout the water column as anoxic conditions result in release of nutrients from suspended sediments (Sullivan et al. 2011).

During summer and early fall, Keno reservoir can experience extensive algal standing crop. This large standing crop is driven by in-reservoir processing of nutrients, as well as wash-in of algae from Upper Klamath Lake. Maximum concentrations of chlorophyll *a* at Link River can reach 250 micrograms per liter (µg/L), while concentrations in the Klamath River downstream of Keno dam are generally well under 100 µg/L. However, at times of severe anoxia the reservoir has limited primary production, apparently as a result of the lack of available oxygen to meet algal respiratory demands (Deas 2008).

[1] Oxygen sag is the characteristic fall and recovery in the amount of DO in a body of water downstream from a significant organic matter pollution source. When such pollution waste is introduced into a body of water, bacteria will begin to consume the waste. As they consume the waste, the bacteria use up oxygen, causing the overall amount of oxygen in the water to drop. In some cases, the waste itself will consume oxygen without a bacteria.

1.2.2 Previously-developed Studies and Concepts

This study draws on previously-developed studies and concepts for water quality improvement in Keno reservoir, or Link River upstream, that address DO conditions and OM loads emanating from Upper Klamath Lake. For example, extensive modeling work by the U.S. Geological Survey (USGS) has shown that Keno reservoir experiences seasonal anoxia due to the processing of OM loads from Upper Klamath Lake, and that conditions may be improved through load reductions (Sullivan et al. 2011; Sullivan et al. 2012; Sullivan et al. 2013; Sullivan et al. 2014). From 2011 to 2014, studies were conducted under IM 11 to assess the potential efficacy of reducing OM from Klamath River water (at or near Link River dam) using a hydrodynamic separation technology that is employed in stormwater treatment (Watercourse Engineering 2013, 2014a, 2014b). In 2013, as a result of the Klamath Basin Nutrient Reduction Workshop (held in September 2012 in Sacramento, California), Stillwater et al. (2013) reported on the potential concept of using oxygenation in combination with injection of buffered alum micro-floc to reduce oxygen demand and sequester or inactivate phosphorus in the water column and sediments in Keno reservoir. Stillwater et al. (2013) make clear that potential use of buffered alum dosing and oxygenation in Keno reservoir would first be predicated on the successful outcome of bench-scale water quality and toxicity tests. Alum micro-floc and oxygen would then be injected into a pilot site in Lake Ewauna to assess effects before implementing any broader use of this technology in Keno reservoir.

2.0 Assessment Approach and Methods

2.1 Criteria and Assumptions

The Activity 4 study concepts (i.e., potential oxygenation/aeration system components) were discussed with the IMIC and included in the 2015 IM 11 Study Plan (PacifiCorp 2015). A Technical Advisory Committee (TAC) subgroup of the IMIC was convened to provide additional input on the study, including on specific goals and objectives expected of potential oxygenation/aeration systems designed to supplement DO levels in Keno reservoir. The TAC input helped to establish the initially-used criteria and assumptions for desired target DO concentrations at specific locations in Keno reservoir.

2.1.1 Criterion 1: Water Quality Standard Objective

Assuming the overall goal is to comply with the water quality standard for DO applicable to Keno reservoir described in the Oregon Administrative Rules (OAR) 340-041-0016(3), the objective for initial modeling purposes was assumed as follows:

- The waters of Keno reservoir are designated for cool water species (see OAR 340-041 0180, Figure 180A). The applicable DO water quality criterion for the reservoir is 6.5 mg/L year-round (OAR 340-041-0016(3)). The 6.5 mg/L criterion applies as a 30-day mean minimum, with a 7-day minimum mean of 5.0 mg/L and an absolute minimum of 4.0 mg/L.
- The above criterion applies in Keno reservoir throughout the year. However, for this conceptual feasibility study, the analysis focused on the summer-fall period when DO conditions are most consistently less than the above criterion. Specifically, the summer-fall period is assumed as the months from July through October.
- For purposes of this study, it is assumed that the above criterion applies to all areas of Keno reservoir.

Given severe seasonal DO impairment in Keno reservoir, Criterion 1 may be difficult (if not impossible) to attain, particularly during summer, without larger, basin-scale improvements that result in OM load reductions from Upper Klamath Lake. While Criterion 1 is considered an aspirational goal under existing conditions, there may be an opportunity to provide “functional” compliance that facilitates fish passage through interconnected environments. Such a condition could perhaps allow DO to fall below the 6.5

mg/l criterion in localized areas, but with interconnected regions (laterally, vertically, and longitudinally) that meet the 6.5 mg/l criterion (Section 2.1.2).

2.1.2 Criterion 2: Fish Passage Protection Objective

Assuming the overall goal is to provide DO conditions in Keno reservoir that are adequate to support fish passage, the objective for initial modeling purposes is assumed as follows:

- 5.0 mg/L is assumed as adequate to provide DO conditions in Keno reservoir to support fish passage, particularly for redband trout and the potential future presence of anadromous salmonids.
- The above criterion applies in Keno reservoir throughout the times of the year when migration of salmonids through the reservoir would be occurring. However, for this conceptual feasibility study, the analysis focuses on the summer-fall period when DO conditions are otherwise too low to support salmonid fish use. The summer-fall period is assumed as the months July through October.
- For purposes of this analysis, it is assumed that the above criterion would apply to a migratory corridor through Keno reservoir. The migratory corridor is defined to be a continuous and connected area through the length of the reservoir that has width-depth dimensions that are similar to river reaches upstream (i.e., Link River) and downstream (i.e., Klamath River downstream of Keno dam) of Keno reservoir.

This objective would be applied year-round to support redband trout. This objective would be further refined in the future to accommodate anadromous fish passage in the fall (adult), if future reintroduction is achieved.[2] In such a case, oxygenation as contemplated in this study would occur from approximately October 1 to November 30, although with the installation of necessary equipment DO augmentation in any time period could be considered.

2.2 Modeling

Modeling was performed to assess the quantities, rates, and locations of oxygen needed to achieve desired DO enhancement objectives in Keno reservoir. This effort included application of the existing CE-QUAL-W2 model of Keno reservoir developed jointly by USGS and Watercourse (Sullivan et al. 2011; Sullivan et al. 2013; Sullivan et al. 2014). The model was used in an initial analysis mode to determine the effects of oxygenation through the two oxygenation technologies explored (as described in Section 3.1 below).

Initial model applications were completed to test the model's overall sensitivity to oxygenation and identify potential facility locations. Saturation DO (i.e., DO at 100 percent saturation in the water) was calculated based on ambient water temperature in Keno reservoir. Side-stream oxygenation modeling allowed for supersaturation values from 12 to 18 mg/L (125 percent to over 250 percent) near the diffuser because this method does result in supersaturation of DO locally.

For modeling purposes, all oxygen sparged or injected into the reservoir was placed in a single model segment (approximately 1,000 ft in length). Each individual segment where oxygen was input into the reservoir was modeled as mixed laterally and longitudinally.

[2] It should be noted that low DO in Keno reservoir is not the only identified water quality impairment that may present an impediment to successful volitional fish passage through Keno reservoir. Seasonal exceedances of established water temperature criteria for salmonids in Keno reservoir from mid-June to mid-November have been identified by the U.S. Fish and Wildlife Service and the National Marine Fisheries Service as an issue that also must be addressed, with an interim, seasonal trap and haul program around Keno reservoir prescribed to address periods when temperature and DO conditions do not meet established criteria (USFWS and NMFS 2007; USDOI and CDFG 2012). This report, however, addresses only how DO conditions may be improved.

In addition to model simulations of the two oxygenation technologies, a baseline model simulation was performed for existing conditions without oxygenation. Model simulations for the two oxygenation technologies were simulated and then compared to the baseline without-oxygenation results to identify potential implications of oxygenation.

Based on initial model runs, three approximate locations were identified where oxygenation facilities may prove most useful (Figure 2). Subsequently, three alternative simulations were completed for three facility/location combinations, including: (1) facilities at Location A; (2) facilities at Locations A and B; and (3) facilities at Locations A, B, and C. These three alternative simulations were used to assess conceptual feasibility for this study (as discussed further in Section 3.0 below).

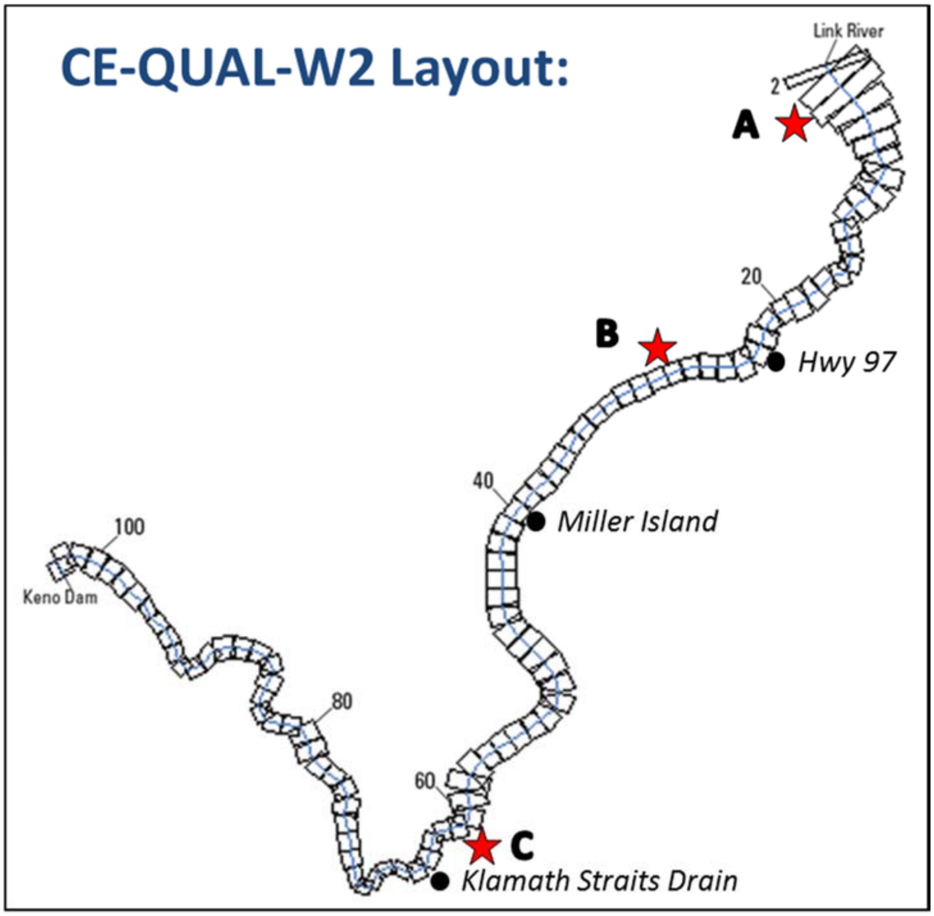

Figure 2. Keno reservoir CE-QUAL-W2 model grid and potential locations (A, B, and C) for oxygenation facilities used in this analysis.

3.0 Oxygenation Systems for Potential Use in Keno Reservoir

3.1 Overview of Techniques

In general practice, DO enhancement techniques include both aeration systems (using air) and oxygenation (using concentrated or pure oxygen) systems. This section provides an overview of these technologies.

Aeration technologies (using air rather than pure oxygen) either use destratification aeration or direct aeration. The difference between destratification aeration and direct aeration is airflow rates. Whereas direct aeration attempts to introduce oxygen directly into the water column through diffusion of oxygen from bubbles into the water column and enhanced mixing, destratification aeration works to destratify the reservoir to address anoxic conditions in the hypolimnion. The aeration rates and power demands for a destratification aeration system are less energy intensive than the direct aeration systems because oxygen transfer is not through bubble diffusion, but through creation of isothermal conditions allowing oxygen-rich surface water to turnover toward the bottom (Cooke et al. 2005; Hanson and Austin 2012). In theory, once isothermal conditions are established, wind mixing can be sufficient to fully mix the reservoir and bring oxygen to the depths of the reservoir.

Oxygenation refers to oxygen transfer to (and dissolution in) the water using pure oxygen. Pure oxygen has been successfully used to remediate DO deficits in reservoirs (Cooke et al. 2005; McGinnis and Little 1998; Speece 2008). Oxygenation technologies used to enhance DO either sparge (i.e., inject) pure oxygen directly into water typically using a diffuser (Figure 3), or into a "side-stream" contact chamber using a downflow contactor (Figure 4).

Solubility of oxygen is water is a function of temperature, pressure, salinity, and the partial pressure of oxygen. In air at sea level, the partial pressure of oxygen is approximately 0.21 atmosphere (atm). In a theoretical pure oxygen atmosphere at sea level, the partial pressure of oxygen would be 1.0 atm. Consequently, in a pure oxygen atmosphere the DO saturation of water would be approximately five times greater than in air. Thus, pure oxygen provides much greater mass transfer of oxygen dissolution in water than air (from aeration). As a consequence, at the scale of fine bubbles, water in the immediate vicinity of a pure oxygen bubble has a higher DO saturation concentration than water next to an air bubble.

Most oxygenation applications have been done in deep reservoirs that have strong thermal stratification, but successful shallower water applications (more akin to Keno reservoir) have been reported (e.g., Gerling et al. 2014; Moore et al. 2012). Depth is a key factor controlling the effectiveness of direct sparging systems using linear diffusers. Bubble travel time is a function of the depth at which the diffuser is placed in the reservoir, and determines the amount of contact time for oxygen transfer from the rising bubbles to the water column. In general, longer bubble travel times will transfer more oxygen to the water than short travel times.

Direct sparging is best done where the water column is approximately 10 m or greater in depth to reach oxygen transfer efficiencies near 90 percent (that is, 90 percent of the injected oxygen as fine bubbles dissolves in the water before reaching the water surface). Oxygen transfer efficiencies from direct sparging are progressively less at shallower depths, because the injected oxygen (as fine bubbles) has less time to dissolve in the water before reaching the water surface.

Compared to sparging, side-stream oxygenation has much higher oxygen transfer efficiencies. In the side-stream oxygenation process, water withdrawn from the reservoir flows down through a conical bubble contact chamber (Figure 4). The downflow velocity of water at the top of the cone is greater than the rising velocity of pure oxygen bubble injected into the top of the cone, and downflow velocity at the bottom of the cone is less than bubble rising velocity. Consequently, the pure oxygen bubble swarm dissolves into the water. Pure oxygen bubbles are injected into the chamber and can only leave by dissolution into the water. Because there is a pure oxygen atmosphere inside the side-stream contactor, the DO concentration of the water passing through the contactor becomes supersaturated (i.e., greater than 100 percent).

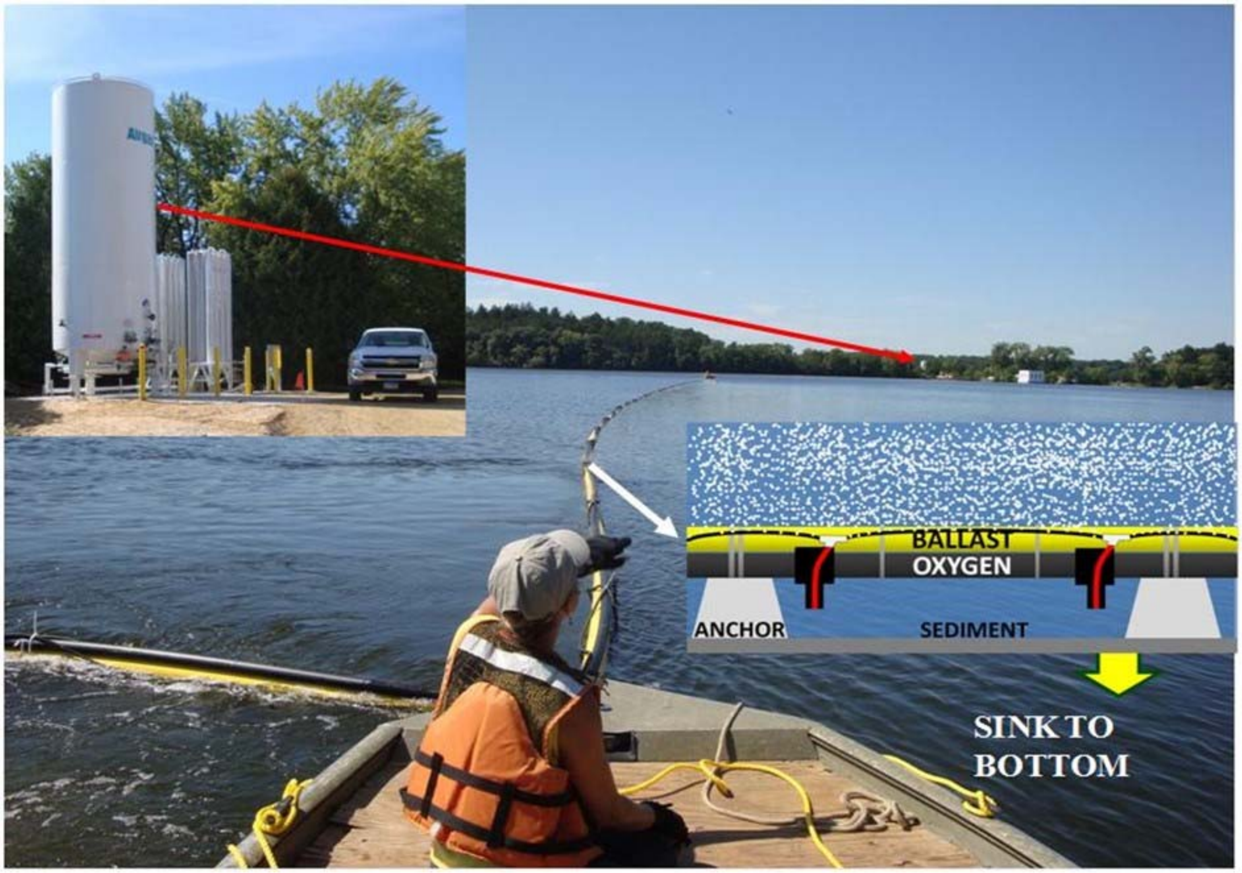

Figure 3. Example placement of linear diffuser for sparging of pure oxygen with diffuser. The diffuser system is manufactured at the water edge from HDPE pipe, floated on the surface close to shore during manufacture, and then sunk into position when completed. Oxygen supply in this instance is liquid oxygen. Source: CH2M unpublished project information with assistance from Mobley Engineering, Inc.

Figure 4. Small scale model of a downflow side-stream oxygenation bubble contactor (Speece cone) with schematic flows and in-cone bubble water velocities. Source: Image Eco2 Technologies.

3.2 Aeration System Ineffectiveness

DO enhancement using aeration technologies is considered ineffective for Keno reservoir because of the reservoir's generally shallow water, lack of stratification, high BOD, and low DO conditions during summer (when DO remediation is of most interest). As described in Section 1.2.1 above, summer and fall anoxia in the reservoir is caused primarily by the substantial BOD from the large organic matter loading from Upper Klamath Lake (Sullivan et al. 2010; Sullivan et al. 2011; Sullivan et al. 2013). Whereas even reservoirs with good water quality and low BOD can experience anoxia in the hypolimnion as a result of thermal stratification, anoxia in Keno reservoir is a consequence primarily of BOD and only secondarily (and intermittently) as a consequence of thermal stratification. The clear pattern of consistent surface water hypoxia and anoxia in unstratified sections of the reservoir is evidence that water column BOD is the primary cause of low DO. These conditions pose particular challenges to DO remediation that would only be adequately addressed using oxygenation systems.

In order to improve DO in Keno reservoir using direct aeration, it is likely that at least the upper half of Keno reservoir would have to be aerated about as intensely as a wastewater treatment lagoon. This would require what is termed a "complete mix" aeration system, such as used for activated sludge aeration. Complete mix aeration would require substantial aeration density and blower power demand to provide about 20 standard cubic ft per minute (SCFM) of air per 1,000 cubic ft of water (Metcalf and Eddy 2003).

In the other areas of the reservoir, DO improvement might be possible with a less-intensive partial mix aeration system, which provides about 10 percent of the aeration intensity of complete mix (USEPA 2002). However, use of partial-mix aeration (around 2.3 SCFM per 1,000 cubic ft of water) in Keno reservoir would still entail substantial aeration density and blower power demand. Partial mix lagoons require approximately 1 to 2 watts (W) per cubic meter (1.2 to 2.4 kilowatts [kW] per 1,000 cubic ft of water) power. For example, even if it is ideally assumed that only 10 percent of the volume of Keno reservoir volume of 18,500 acre-feet (ac-ft) would require partial mix aeration, the power requirements would be 2,220 to 4,440 kW (3,000 to 6,000 horsepower [HP]). Without considering run time to approximate energy consumption, such power requirements are very large and impractical even with the idealistic assumption that aeration of 10 percent of the reservoir volume would suffice.

These aeration system estimates do not consider the additional substantive inefficiencies that would result from the reservoir's shallow depth (poor oxygen transfer efficiency of aeration) and warm water (low DO saturation). Assuming a standard oxygen transfer efficiency of 0.75 percent per ft of depth for coarse bubble aeration, large sections of the upper reservoir will be under 10 percent oxygen transfer efficiency. Fine bubble aeration would have an additional inefficiency issue posed by the likely need to frequently clean diffusers that would be expected to foul in the highly-enriched Keno reservoir environment.

The vertical uniformity of anoxic conditions and the shallow nature of the reservoir also rules out destratification aeration. Destratification aeration would only make sense if Keno reservoir stratified and had oxygen-rich surface water to mix and bring oxygen to the depths of the reservoir. However, even surface waters in Keno reservoir are hypoxic (or even anoxic) during summer. Thus, this method is not feasible because mixing hypoxic surface waters throughout the depth of the reservoir (which is also hypoxic or anoxic) obviously would do nothing to improve DO conditions.

3.3 Potentially Usable Oxygenation Systems

3.3.1 Sparged Pure Oxygen Using Linear Diffusers

Sparged pure oxygen from linear diffusers (such as shown in Figure 3) at low flow rates of 0.02 to 0.03 SCFM per linear ft is the most common method used to remediate reservoir anoxia (Cooke et al. 2005), but have been in reservoirs generally deeper than Keno reservoir. As noted above, a water column of approximately 30 ft is needed to provide sufficient bubble contact time for 90 percent oxygen transfer efficiency under low-oxygen conditions. Therefore, sparged oxygen transfer efficiency would be low in the shallow water depths in Keno reservoir (i.e., average depth is about 7.5 ft) because bubble contact time would be much less.

Because pure oxygen is expensive to generate, a low oxygen transfer efficiency is generally not acceptable. However, sparging diffusers may be technically feasible in parts of Keno reservoir where depths are greater (about 20 ft), particularly in the middle or lower reaches of the reservoir. The mechanical simplicity and possible lower costs of pure oxygen sparging (compared to side-stream oxygenation) are other considerations that may add to the rationale for its potential use in the reservoir (for example, costly fish screens would not be needed with linear diffusers, but may be needed with the more efficient side-stream oxygenation technology option). In addition, the power requirements of sparging systems are much less than for side-stream oxygenation, making sparging systems more advantageous at remote locations. The sparging diffusers run purely on the vaporization pressure of oxygen, so power is only necessary for telemetry, which can be run on photovoltaic panels.

In consideration of its potential use in Keno reservoir, pure oxygen sparging was included in modeling scenarios (as described further in Section 4). Regardless of assumed depth of placement in the reservoir, oxygen transfer efficiency with pure oxygen sparging would still be substantially less than for side-stream oxygenation. For modeling purposes, oxygen transfer efficiency with sparging was conservatively set at 27 percent. It was also assumed that sparged oxygen cannot provide DO greater than saturation (for example, at Keno reservoir, DO saturation is 7.8 mg/L at 20°C and 7.1 mg/L at 25°C) from diffuser locations.

3.3.2 Side-Stream Oxygenation

The side-stream oxygenation method could discharge water from the contact chamber at very high DO concentrations (e.g., 30 mg/L or greater), depending on contactor pressure, water temperature, and instantaneous oxygen demand (Figure 5). Side-stream oxygenation systems may be placed at the reservoir bottom (Figure 6) or above water (Figure 7), but Keno reservoir is generally too shallow (i.e., average depth is about 7.5 ft) for submerged bottom placement of these units. Therefore, we assume that side-stream oxygenation installations at Keno reservoir would be above water along the shore with diffusers discharging DO supersaturated water into the river.

Water discharged from the contactor is supersaturated with DO. At 20 degrees Celsius (°C) and at sea level, DO saturation occurs at 44 mg/L in a pure oxygen atmosphere. Spontaneous effervescence will not occur at this concentration (Speece 2007). Effervescence and loss of DO depends on the gas exchange rate of receiving waters. Bacterial uptake of injected DO and mixing can lower DO levels at short distances away from the injection diffuser.

Turbulence can cause effervescence of supersaturated oxygen into bubbles. There is a direct analogy with off-gassing of carbon dioxide in a shaken can of soda versus one opened gently and placed on a table. In a water column not at supersaturation, oxygen bubbles will tend to partially re-dissolve as they rise, but any oxygen effervescing out of solution will diminish oxygen transfer efficiency. To prevent near-diffuser oxygen effervescence, discharge to water is through a manifold with eductor outlets (Figure 8). Each eductor is a tube discharging supersaturated water by drawing outside water into the discharge stream via the Bernoulli effect.[3] The ratio of outside water mixed into the main discharge is the eductor mixing ratio. With a nominal 2:1 to 3:1 eductor mixing ratio, instantaneous mixing lowers near-diffuser DO concentrations and sharply lowers any tendency towards effervescence to a gaseous phase.

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[3] In fluid dynamics, Bernoulli's principle states that an increase in the velocity of a fluid (in this case, water) occurs simultaneously with a decrease in pressure or a decrease in the fluid's potential energy.

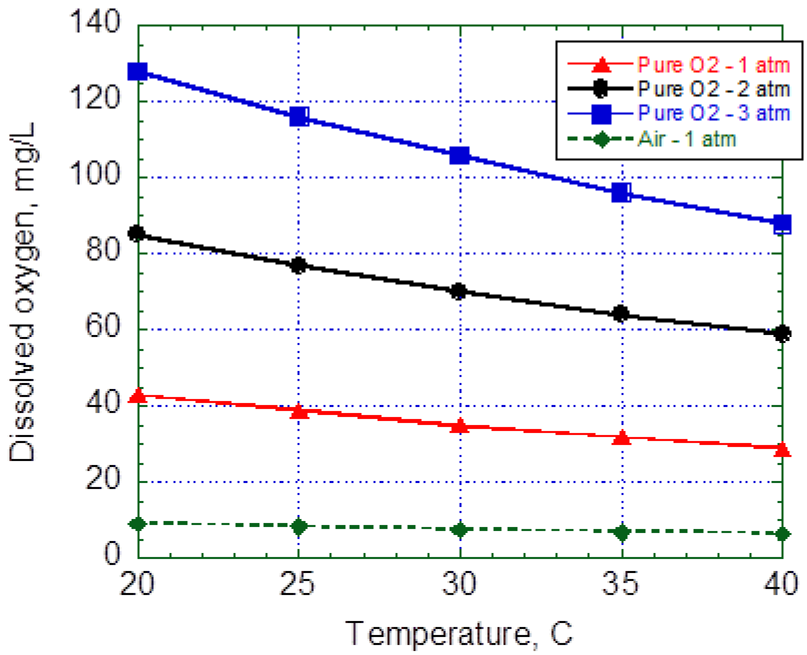

Figure 5. Dissolved oxygen saturation concentrations in air by temperature and pure oxygen by pressure and temperature.

Figure 6. Example of a Speece cone installation readied for reservoir bottom placement. The Keno reservoir placement would be out of the water on the shore. Source: Image Eco2 Technologies.

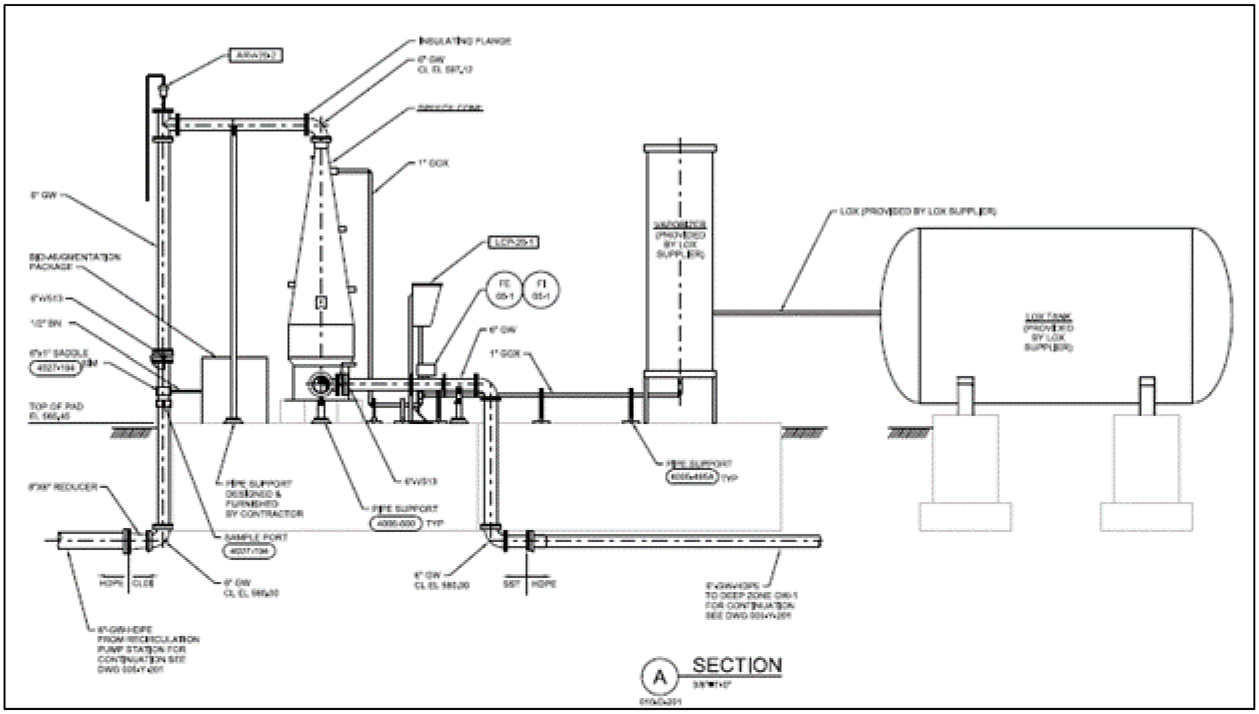

Figure 7. Example construction drawing of a Speece cone for above-water installation. Source: CH2M Unpublished Data.

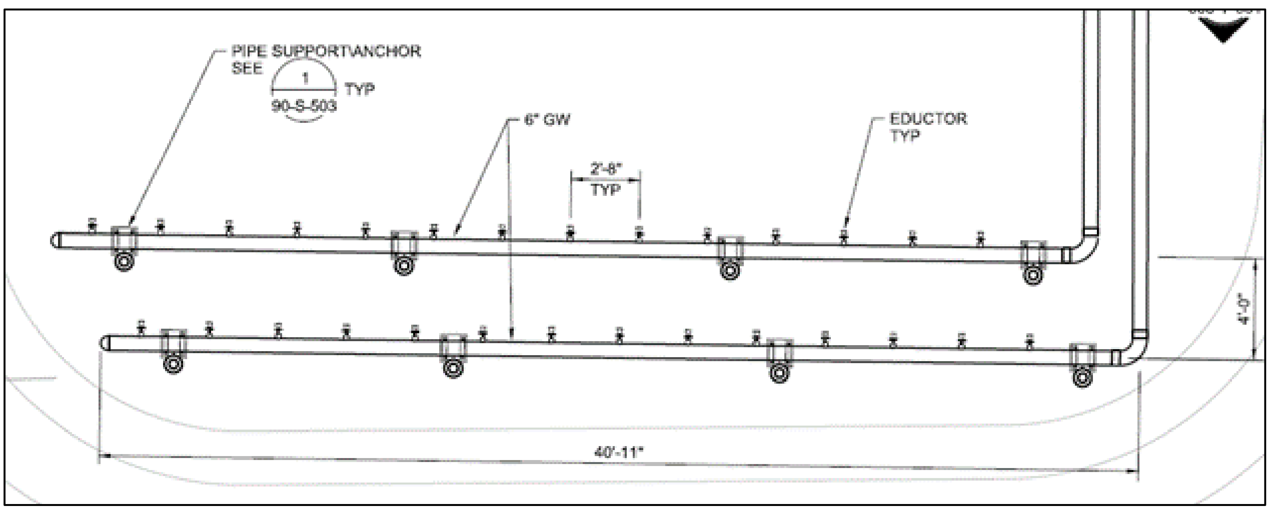

Figure 8. Example construction drawing of an eductor diffuser for injection of DO supersaturated water. Source: CH2M Unpublished Data.

Oxygen transfer efficiency alone favors the potential use of side-stream oxygenation technology in Keno reservoir. As explained above, sparged oxygen transfer would be significantly constrained by the reservoir's relatively shallow depth of water. In addition, sparged oxygen cannot provide DO greater than saturation. In contrast, side-stream oxygenation will supersaturate the discharged water with DO at levels from 12 to 18 mg/L (125 percent to over 250 percent) near the diffuser. Oxygen transfer efficiency with a side-stream oxygenation system to the water column will be in excess of 90 percent (McGinnis and Little 1998; Speece 2008).

In addition to much greater oxygen transfer efficiency, side-stream oxygenation technology will perform better in a high-BOD environment such as Keno reservoir, than other technologies. As seen in the modeling results (as described in Section 4.1), the high BOD in the reservoir would limit the downstream effect of sparged oxygen. As noted above, sparged oxygen cannot provide DO greater than saturation, whereas side-stream oxygenation will supersaturate the water. As such, in the presence of high BOD, the decline (sag) back toward low DO levels would be more precipitous as water flows downstream of the sparge system than the side-stream system. This more precipitous DO sag downstream of the sparge system means that sparge system oxygen diffusers would need to be more closely spaced (thus requiring more total diffusers in the reservoir) than side-stream oxygenation units to ensure that DO levels are maintained. Therefore, these differences indicate that side-stream oxygenation system likely would be the more technically effective approach for oxygenation in Keno reservoir, particularly in the shallower upstream portions of the reservoir.

For application in the upstream portions of Keno reservoir, the Speece cone (down flow contactors) would be the most effective side-stream technology. There are other side-stream technologies that use a different principle of oxygen transfer. These systems spray water into a tank that is pressurized with pure oxygen. In clean water, the oxygen transfer efficiency of this spray technology is very high. In Keno reservoir, however, the water is far from clean. Theses spray systems are vulnerable to clogging from a high particulate influent stream and from iron or manganese fouling. Field trials of these other technologies conducted by CH2M elsewhere in the country have not been successful because of clogging. Speece cone technology can pull water directly from an inflow pipe into the contactor and send it through the eductors without clogging.

For modeling purposes, Speece cones rated to each transfer 1,500 kilograms of oxygen per day (kg O_2/day) were selected as the oxygenation system to be modeled (as described in Section 4). This rating corresponds physically to an 8 ft diameter cone pressurized to 3 atm and using a 140-HP pump. This oxygen supply rate also corresponds to typical output ratings for commercially-available units that could be used to generate the necessary pure oxygen.

4.0 Estimated Effectiveness of Oxygenation Systems in Keno Reservoir

4.1 Simulations of Oxygenation via Sparging

The model simulations of oxygenation via sparging assumed two 500-m linear diffusers in parallel at each of up to three locations in Keno reservoir (Locations A, B, and C as shown in Figure 2). For each location, the modeling assumed a sparging flux rate (total) of 1,850 kg O_2/day, and a transfer rate of 500 kg O_2/day. The sparging systems would be deployed in the reservoir just above the bottom and would require no diversion of water.

Modeling of four scenarios was conducted to illustrate the potential effects of oxygenation via sparging (Figure 9). The scenarios modeled include: (1) existing conditions (i.e., baseline of no oxygenation); (2) sparging at Location A; (3) sparging at Locations A and B; and (4) sparging at Locations A, B, and C. The existing condition simulation (Figure 9; upper left plot) is a baseline simulation for comparison that assumes current conditions in Keno reservoir without oxygenation. The results shown are all example model outputs represented by conditions at midnight of July 19, 2007. Results for midnight are shown to most conservatively assess oxygenation effects because conditions at midnight do not include oxygen that is otherwise contributed by primary production during daylight periods. As such, these results are indicative of lowest DO conditions over the course of the 24-hour day.

The Existing Condition simulation indicates very low mid-summer DO concentrations of about 2 mg/L or less throughout the reservoir (Figure 9; upper left plot), which typify the hypoxic (or anoxic) DO conditions in Keno reservoir during mid-summer (see Section 1.2.1). The exception in the model results occurs in relatively small parts of the reservoir near the inflow (i.e., immediate proximity of Link River) and near the outflow (i.e., near Keno Dam), where DO is estimated at around 6 mg/L. As context, full (100 percent) saturation DO values corresponding to the ambient water temperature and barometric pressure of Keno reservoir during mid-summer (corresponding to this example model simulation date of July 19, 2007) are 7 to 8 mg/L.

The Location A simulation indicates that oxygenation via sparging at Location A produces a relatively modest increase in DO of about 1 to 2 mg/L (over existing conditions) to concentrations of up to about 3 to 4 mg/L in the uppermost reaches of Keno reservoir (Figure 9; lower left plot). However, simulated DO conditions remain below the DO criteria levels (as defined in Section 2.1) throughout the reservoir.

The Location A, B simulation indicates that oxygenation via sparging at Locations A and B produces an increase in DO of about 1 to 3 mg/L (over existing conditions) to concentrations of up to about 3 to 5 mg/L in both upper and middle reaches of Keno reservoir (Figure 9; upper right plot). However, simulated DO conditions remain below the DO criteria levels throughout the reservoir.

The Location A, B, and C simulation indicates that oxygenation via sparging at Locations A, B and C produces an increase in DO of about 1 to 3 mg/L (over existing conditions) to concentrations of up to about 4 to 5 mg/L throughout much of Keno reservoir (Figure 9; lower right plot). Placing the third sparging facility at Location C near the Klamath Straits Drain provides consistently improved DO conditions throughout the lower 7-mi reach of Keno reservoir from Location C to Keno dam.

As with the other simulations at Location A and B, simulated DO conditions with oxygenation via sparging at Locations A, B and C remain below the DO criteria levels throughout the reservoir. However, the improvement in the amount and extent of DO improvement in the reservoir indicated by the Location A, B, and C simulation could yield important benefits on local and downstream water quality and aquatic biota by preventing widespread anoxia. The key limitations of sparging are that the shallow depth of the reservoir limits oxygen transfer efficiency, and sparging cannot create a zone of supersaturation at diffuser locations that would be necessary to produce significantly higher downstream DO that could attain the criteria levels.

4.2 Simulations of Side-Stream Oxygenation

Modeling of four scenarios was conducted to illustrate the results of side-stream oxygenation (Figure 10). The model simulations assumed side-stream oxygenation systems at each of up to three locations (Locations A, B, and C as shown in Figure 2; the same as assumed in the sparging model simulations). For modeling purposes, the systems were assumed to comprise 5 to 10 side-stream oxygenation units at each location in which the units are linked to attain an O_2 flux rate of about 17,000 to 24,000 kg/day and an O_2 transfer rate of at about 14,400 to 20,400 kg/day (to achieve greater than 85 percent oxygen transfer efficiency).

The side-stream intake systems would require a screened diversion pumped to the cone and a corresponding return to the reservoir through the eductor diffuser system. Side-stream oxygenation must pump water from the reservoir and return it supersaturated with oxygen. Side-stream oxygenation likely would produce DO concentrations in the discharges back to the reservoir ranging from 12 to 18 mg/L outside the mixing zone near the diffuser. As with sparging simulations, example model outputs are represented by conditions at midnight of July 19, 2007.

The Location A simulation indicates that side-stream oxygenation at Location A produces a substantial increase in DO (over existing conditions) to concentrations that are well above corresponding full-saturation levels of 7 to 8 mg/L in the upper reaches of Keno reservoir (Figure 10; lower left plot). Increased DO concentrations are above the DO criteria levels (as defined in Section 2.1) in these upper reaches and remain above these levels for about 4 miles down to the vicinity of the Highway 97 bridge (RM 249; “Hwy 97” on Figure 10).

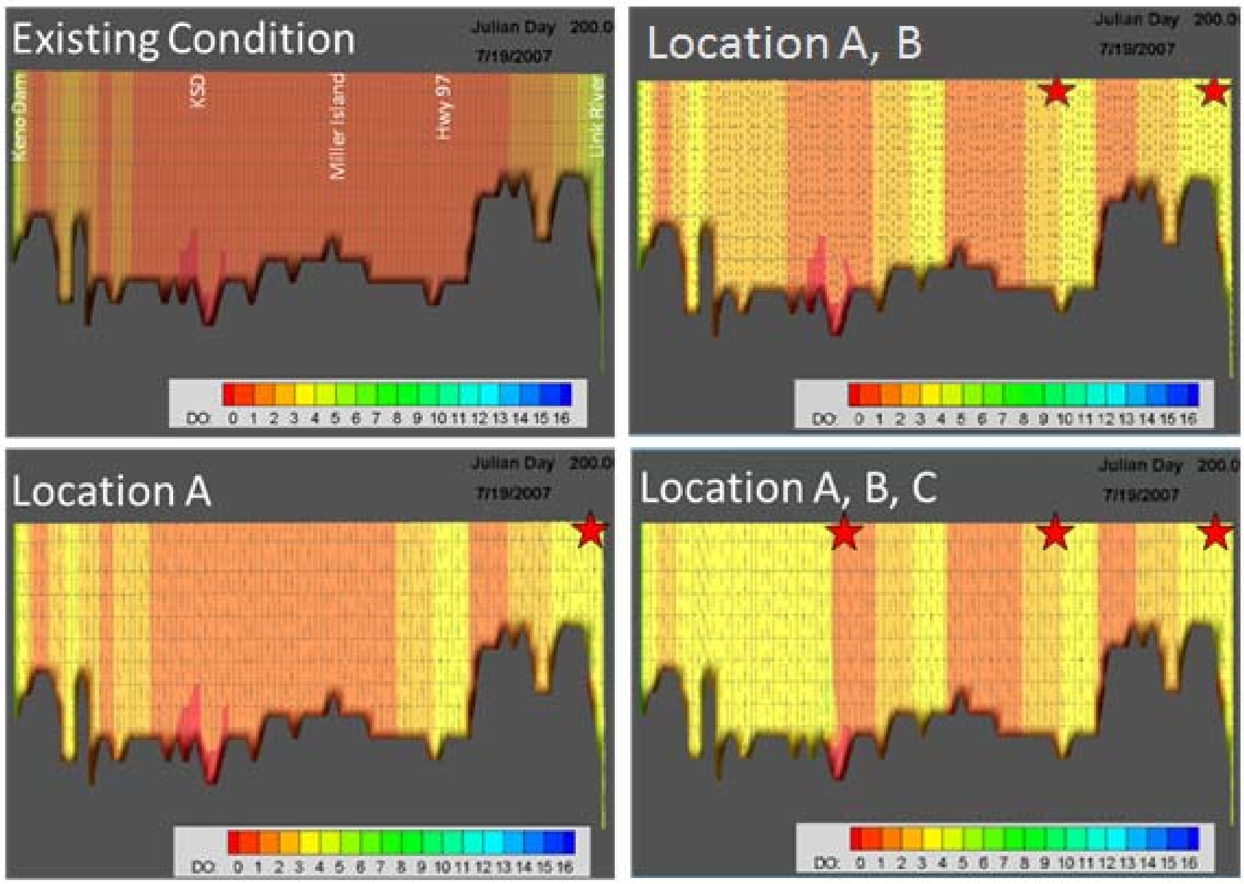

Figure 9. Model simulations of existing conditions and oxygenation via sparging at Locations A, B, and C (showing example model simulation output for July 19, 2007 at midnight).

The Location A, B simulation indicates that side-stream oxygenation at Locations A and B would extend the substantial increase in DO (over existing conditions) to both the upper and middle reaches of Keno reservoir (Figure 10; upper right plot). Increased DO concentrations are above the DO criteria levels in these upper and middle reaches and remain above these levels for about 8 miles down to the downstream end of Miller Island (RM 245; “Miller Island” on Figure 10).

The Location A, B, C simulation indicates that side-stream oxygenation at Locations A, B and C would further extend the substantial increase in DO (over existing conditions) throughout most of Keno reservoir (Figure 10; lower right plot). Increased DO concentrations are above the Criterion 1 DO level (as defined in Section 2.1.1) along the majority of the 20-mile length of Keno reservoir and above the Criterion 2 DO level (as defined in Section 2.1.2) along the entire length of the reservoir to Keno dam.

The inherent advantage of side-stream oxygenation is that injection of a supersaturated solution into the water column greatly increases the oxygen mass flux rate into the reservoir, resulting in higher and more persistent DO concentrations than would be achievable by sparging. Supersaturation is stable near the side-stream eductor diffuser discharge points. That is, there is no spontaneous effervescence of oxygen out of solution. The rate of oxygen consumption by bacteria exerting BOD is higher than the rate at which the water will off-gas excess oxygen above saturation. At the same time, there is a physical dilution of DO down to saturated values. The combination of dilution and short-term stability of supersaturation would allow for a high oxygen mass transfer rate into the water column.

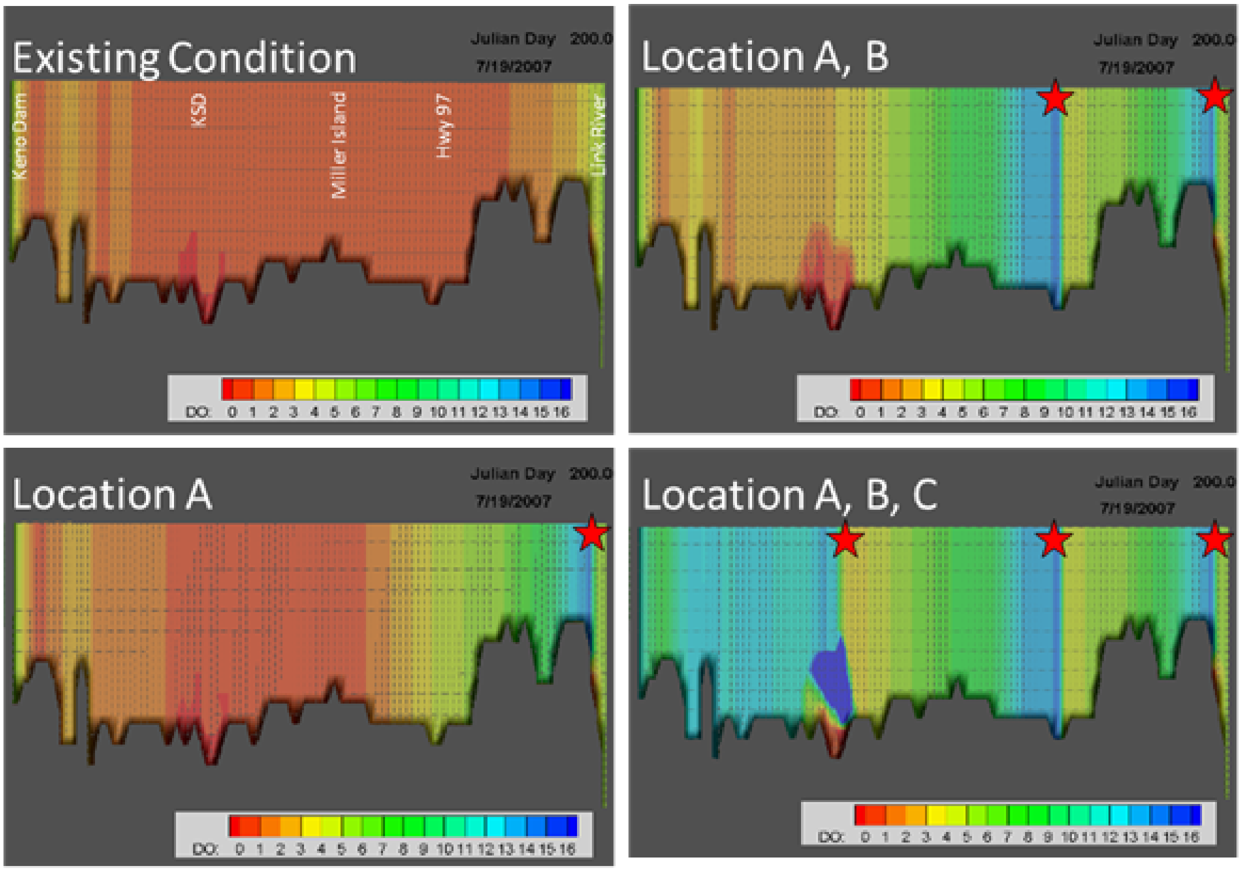

Figure 10. Model simulations of existing conditions and side-stream oxygenation at Locations A, B, and C (showing example model simulation output for July 19, 2007 at midnight). Note that the zone of supersaturation is small at locations A and B because of BOD. At location C, BOD has been sufficiently consumed to allow for a larger plume of supersaturated water.

5.0 Potential Conceptual Layout of Oxygenation Systems in Keno Reservoir

Following the technology-specific and location-specific modeling analysis discussed above, an additional assessment was performed to conceptualize potential layout of an overall oxygenation system that could enhance DO concentrations in Keno reservoir to levels that attain Criterion 1 and/or Criterion 2 (as defined in Section 2.1). The assessment of the potential conceptual layout considered both sparging and side-stream oxygenation systems as building blocks of an overall system that would best fit conditions within the reservoir based on modeling results, as well as professional judgment based on our knowledge of the relative performance requirements of these technologies.

As previously noted, saturation DO (100 percent) values based on the ambient water temperature and barometric pressure of Keno reservoir during mid-summer are 7 to 8 mg/L. These saturation DO values are already close to the DO criteria values. Therefore, attaining the DO criteria values would require a system layout that most efficiently and effectively improves and maintains DO concentrations in reservoir water to levels near or at saturation. As described in Section 4, side-stream oxygenation would be the most effective system for increasing DO to levels that could attain Criterion 1 and/or Criterion 2, particularly in the more-shallow upstream section of the reservoir (i.e., about the upper 4 miles of the reservoir upstream of the Highway 97 bridge) where depths would be insufficient to effectively transfer oxygen using sparging.

However, in the relatively deeper and more-narrow lower section of Keno reservoir (i.e., about the lower 7 miles of the reservoir), the modeling indicates that sparging could be effective at maintaining DO levels. Previous modeling and monitoring data indicate that increases in DO, although modest, often occur in the deeper and more-narrow lower section of reservoir under existing conditions (Sullivan et al. 2011; Sullivan et al. 2013). The model simulations of sparging (as described in Section 4.1) also indicate that DO concentrations would be consistently maintained (i.e., would not degrade) in about the lower 7 miles of the reservoir. Moreover, the relatively greater depth in the lower section of Keno reservoir would double oxygen transfer efficiency of potential sparging diffusers when compared to shallower upstream locations in the reservoir. Consequently, in concert with the cumulative benefits of oxygenation addition at upstream locations, a sparging system could potentially be used in Keno reservoir downstream of Location C (see Figure 2) to provide near-saturation DO levels downstream of this point. Because of potential advantages of lower energy demands and costs, use of a sparging system in the lower section of reservoir was considered in potential conceptual layout alternatives (as described further below).

Three potential conceptual layout alternatives were analyzed relative to ability to meet Criterion 1 and 2 (as described in Section 2.1.1 above). These included: (1) Alternative 1 to provide a DO concentration of 6.5 mg/L (representative of Criterion 1) on a year-round basis; (2) Alternative 2 to provide a DO concentration of 5 mg/L (Criterion 2) on a year-round basis; and (3) Alternative 3 to provide a DO concentration of 5 mg/L (Criterion 2) seasonally from October 1 to November 30 to support fish passage. All proposed layouts are preliminary and simply illustrate the conceptual layouts modeled in this report.

5.1 Alternative 1: DO of 6.5 mg/L Year-round

The layout to attain 6.5 mg/L year-round would require side-stream systems (such as using Speece cone technology) in at least three locations (e.g., Locations A, B, and C) in Keno reservoir. Such a system layout would not be required to run from December through June. During these periods, water temperatures and reduced seasonal oxygen demands currently result in DO concentrations that are typically at or above 6.5 mg/L. Starting in June, water temperatures and seasonal primary production result in sub-saturated DO conditions. In October and November, latent organic loads from summer in both Keno reservoir and Upper Klamath Lake can result in DO conditions well below 5 mg/L in the reservoir.

Therefore, side-stream systems situated at Locations A, B, and C would be required to run from June through November to attain DO concentrations at or above 6.5 mg/L. To attain a DO of 6.5 mg/L throughout the reservoir between locations, the model analysis indicated a target range of DO concentrations of 12 to 16 mg/L would be needed in the initial reservoir segment to which the side-stream oxygenation units would discharge. Specific side-stream unit discharge flow rates were calculated based on assumed modeled in-reservoir concentration of 14 mg/L in the vicinity of the diffuser. Assuming use of Speece cones with 12-cfs flow rate, a table of total flows and necessary contact chamber DO concentrations were calculated for systems ranging in size from 5 to 10 cones (Table 1). Comparison of existing conditions with side-stream oxygenation at the three locations in early October indicates that DO concentrations throughout much of the reservoir are near or above 6.5 mg/L (Figure 11).

Even under Alternative 1 side-stream layout, there would be near-bottom waters in the reservoir that would not attain a 6.5 mg/L concentration, and there may be short duration conditions where the entire water column would fall below 6.5 mg/L for short periods of time (typically days). However, additional side-stream systems could be added (perhaps in the vicinity of Miller Island) to address these conditions. The entire framework of systems could also be designed to operate off DO data from a real-time monitoring system, adding more oxygen when needed and reducing oxygen delivery when not needed.

Table 1. Range of side-stream systems (Speece cones), delivery DO concentration, and approximate in-reservoir DO concentrations for a range of flow rates.

Number of Cones	Total Cone Flow	From Cone DO	Approximate In-reservoir DO*
5	60 cfs	164 mg/L	14 mg/L
6	72 cfs	139 mg/L	14 mg/L
7	84 cfs	121 mg/L	14 mg/L
8	96 cfs	108 mg/L	14 mg/L
9	108 cfs	97 mg/L	14 mg/L
10	120 cfs	89 mg/L	14 mg/L
* based on a representative CE-QUAL-W2 segment volume of approximately 6,000,000 ft^3 (170,000 m^3) and mainstem flow rate of 750 cfs.			

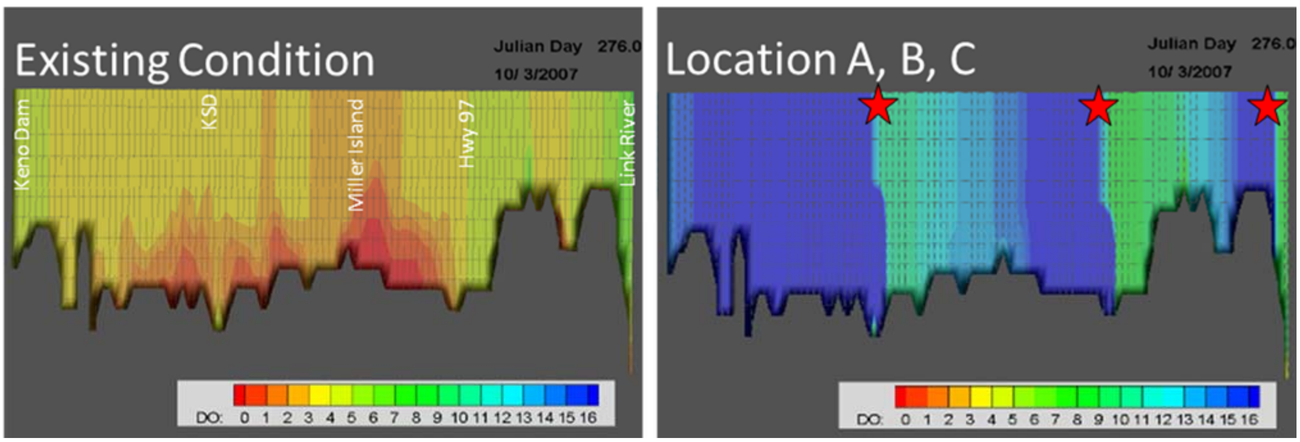

Figure 11. DO concentrations (mg/L) for existing conditions and assumed Alternative 1 side-stream oxygenation at Locations A, B, and C on October 3, 2007.

5.2 Alternative 2: DO of 5.0 mg/L Year-Round

The layout to attain 5.0 mg/L year-round would require side-stream oxygenation systems (e.g., Speece cones) in at least two locations (e.g., Locations A and B), and a sparging system at Location C in Keno reservoir (Table 2). Such a system would not be required from December to June for reasons stated above (Section 5.1).

Side-stream systems situated at Locations A and B would be required to operate from June through November to maintain 5.0 mg/L in the upper and middle parts of Keno reservoir downstream to about the location of Klamath Straits Drain (i.e., near Location C; Figure 2). From there downstream to Keno dam, a sparging system could be used to keep reservoir DO levels above 5.0 mg/L. Similar to Alternative 1, Alternative 2 systems could also be designed to operate off of real-time monitoring data, adding more oxygen when needed and reducing oxygen delivery when not needed.

Table 2. DO concentration of 5.0 mg/L year-round: system summary.

Location	System	Initial DO	Target Instream DO
A	Side-stream	2 mg/L	12-16 mg/L
B	Side-stream	2 mg/L	12-16 mg/L
C	Sparging	2 mg/L	100% Saturation*
* based on local water temperature, but can be assumed to be approximately 8 mg/l.			

5.3 Alternative 3: DO of 5.0 mg/L Seasonally

DO levels of 5.0 mg/L could be attained on a seasonal basis from October through November through sparging systems at Locations A, B, and C in Keno reservoir (Table 3). Because water temperatures are cooler and DO saturation is higher during this time of the year, sparging systems could effectively meet the DO objective. Comparison of existing conditions with sparging at the three locations in early October indicates that DO concentrations throughout the reservoir are near or above 5.0 mg/L (Figure 12). As conditions cool and DO concentrations increase through October and November, oxygen delivery could be reduced and ultimately delivery terminated when it became unnecessary.

Table 3. DO concentration of 5.0 mg/L seasonally: system summary.

Location	System	Initial DO	Target Instream DO
A	Sparging	2 mg/L	100% Saturation*
B	Sparging	2 mg/L	100% Saturation*
C	Sparging	2 mg/L	100% Saturation*
* based on local water temperature, but can be assumed to be approximately 8 mg/l.			

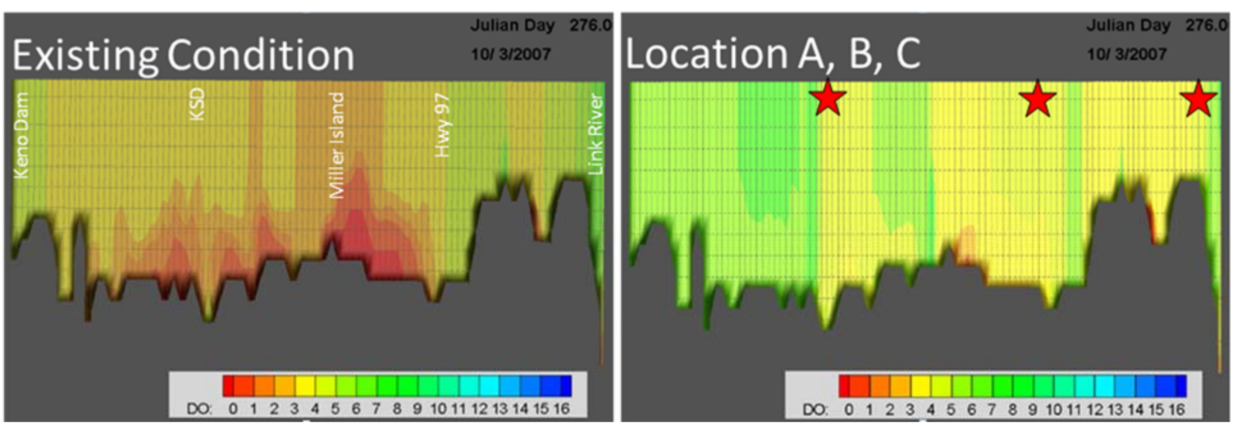

Figure 12. DO concentrations (mg/L) for existing conditions and sparging at Locations A, B, and C on October 3, 2007.

6.0 Potential Costs

Potential costs associated with construction and operation of an effective oxygenation system in Keno reservoir (such as described above) would likely be substantial. A detailed cost estimate is beyond the scope of this study because such an estimate would require more detailed systems design information and analysis. However, it is not unreasonable to expect that overall costs of an effective oxygenation system in Keno reservoir would be in the range of tens-of-millions to $100 million.

For example, as assumed for Alternative 1 above, effective side-stream oxygenation in Keno reservoir could require systems ranging in size from 5 to 10 Speece cones at each oxygenation location to attain an oxygen transfer rate of 17,000 to 24,000 kg/day at each of Locations A, B, and C (Table 4). A reasonable unit-cost for Speece cones is $300,000 to $500,000, indicating that costs could reach $5 million per location just for cones. An on-site oxygen concentrator/generator system sufficient to deliver 17,000 to 24,000 kg/day could cost around $1.5 million to $3 million per location.

Table 4. Conceptual cost estimate[a] for capital costs associated with implementation of Alternative 1 for Keno Reservoir.

Item	Cost per Unit ($1,000s)	Number of Units	Total Cost ($1,000s)
Speece Cones	$300-$500	15-30	$4,500-$15,000
Oxygen Concentrators	$1,500-$3,000	3	$4,500-$9,000
Pump Stations	$12,000-$15,000	3	$36,000-$45,000
Diffuser Pipes	$1,000-$2,000	3	$3,000-$6,000
Other Infrastructure[b]	$2,000-$5,000	3	$6,000-$15,000
		Total Estimate	**$54,000-$90,000**

[a] These are conceptual-level cost estimates (subject to +100/-50 percent accuracy range) in 2016 dollars. These estimates are based on vendor supplied cost estimates, CH2M experience with oxygenation systems, and other CH2M cost estimating information. Specific engineering design and associated cost estimating has not been done. A more finalized and accurate cost estimate would depend on market conditions, site conditions, final project scope and schedule, additional detailed design information, and other variable factors.

[b] Includes roads, electrical, plumbing, buildings, etc.

In addition to the cones and oxygen concentrator/generator, a pump station with an intake that includes the appropriate fish screening would be required at each location. The cost of a pump station capable of the required flows (60 to 120 CFS) could be on the order of $12 million to $15 million, including associated fish screen costs on the order of at least $2 million installed. Once the water has been saturated with oxygen in the cones, the saturated water must be diffused back into the river. Anchoring a large (e.g., 60-inch diameter) pipe into the river bed with an appropriate diffuser would cost in the range $1 million to $2 million per location. In addition to the above costs, other civil and electrical works would be needed to connect and power the facilities which could cost $2 million to $5 million per location. Aside from the above capital costs, there would be on-going operating expenses for the pump stations and the oxygen generation. The oxygen generation alone likely would cost about $400,000 or more per year at each location for power, operations and maintenance expenses.

There is significant precedent and cost data available for oxygenation generation and injection systems used for oxygen remediation in lakes and reservoirs elsewhere. The cost of oxygenation systems is highly variable and depends on site-specific conditions, remediation goals or requirements, and economies of scale (Wagner 2015). For example, Mobley Engineering (2008) estimated capital costs of about $2.8 million to $3.2 million and annual operating costs of $1.2 million to $2.7 million for conceptual sparging oxygenation diffuser systems in Copco and Iron Gate reservoirs, respectively. However, these systems would be considerably smaller than needed for Keno reservoir. As another example, Denver Water invested $2.6 million in 2009 to install a Speece cone in Marston Reservoir (Colorado) sized for a maximum oxygen feed rate of about 900 kg/day to maintain 5 mg/l minimum DO in water at the department's intake pipe from the reservoir (WaterWorld 2012).

Because of the more riverine-like conditions in Keno reservoir and the large advected load of organic matter from Upper Klamath Lake (resulting in large oxygen demand), the system requirements for oxygenation in Keno reservoir would be relatively substantial compared to systems that have been installed elsewhere. Perhaps the closest analogy of a similarly-sized project is provided by the Savannah Harbor oxygenation project. As part of the Savannah Harbor Expansion Project[4], the U.S. Army Corps of Engineers awarded a $99.6 million contract in 2015 to install an oxygen concentration and injection system including a total of a dozen Speece cones split between two sites to inject 18,000 kg/day of oxygenated water into the Savannah River (Buddemeier 2016). While the scope is not identical to the Keno reservoir alternatives assessed above, it does provide an order-of-magnitude confirmation of potential conceptual-level cost estimates.

7.0 Conclusions

Commercially-available oxygenation systems could deliver oxygen to Keno reservoir to substantially enhance DO conditions and attain water quality objectives (such as assumed under Criteria 1 and 2 in this study) from strategically-located oxygenation input locations along the 20-mile Keno reservoir. For example:

- The Alternative 1 system layout (described in Section 5.1) could enhance DO levels to 6.5 mg/L year-round through most of the reservoir's length and depth. This could be achieved by using side-stream oxygenation systems delivering 60 to 120 cfs of water at supersaturated DO levels of 89 to 164 mg/L at three locations (e.g., Locations A, B, and C).
- The Alternative 2 system layout (described in Section 5.2) could enhance DO levels to 5.0 mg/L year-round through most of the reservoir's length and depth. This could be achieved by using side-stream oxygenation systems delivering 60 to 120 cfs of water at supersaturated DO levels of 89 to 164 at two locations (e.g., Locations A and B), plus a sparging system at one location (e.g., Location C).
- The Alternative 3 system layout (described in Section 5.3 above) could enhance DO levels to 5.0 mg/L on a seasonal basis (October-November) through most of the reservoir's length and depth (such as in support of seasonal fish migration). This could be achieved by using sparging systems water at three locations (e.g., Locations A, B, and C).

If such systems are identified as a desired strategy for further consideration, additional modeling analysis is recommended to refine locations, oxygen delivery rates, and compliance reliability (e.g., percentage of reservoir at or above criteria, or frequency and magnitude of any deviations below criteria). The additional modeling analysis would also provide key information upon which initial system design features, equipment requirements, and costs can be more accurately determined.

The results of this study indicate that substantial improvement in DO levels in Keno reservoir are technologically achievable, but costs would likely be substantial. However, if further pursued, the results suggest several important design-related considerations. Foremost among these is that side-stream

[4] The Savannah Harbor Expansion Project involves deepening of the harbor to 47 feet to enable larger container ships access to the Port of Savannah, Georgia. The Savannah Harbor oxygenation project will provide remediation for reduced dissolved oxygen levels associated with the deepening of the harbor.

oxygenation will be necessary to attain DO criteria in the shallower portion of Keno reservoir upstream of Klamath Straits Drain. Side-stream technology requires six basic elements:

1. In-reservoir diffusers
2. Contact chambers (Speece cones)
3. Oxygen gas supply (liquid oxygen or site generation)
4. Contract chamber pump
5. Pump power
6. Reservoir intake and fish screen

The machinery is technically straightforward for such systems. However, the complete systems will comprise considerable civil works at substantial costs, including intensive operational attention to screens, pumps, and oxygen supply. A local entity would need to take responsibility for systems operations and maintenance, which would need to be done in a disciplined on-going manner analogous to the effort necessary to operate a water or wastewater treatment plant. Design, operations, and maintenance would need to address redundancy and avoidance of system failure that could lead to rapidly-occurring oxygen sags.

The simplicity and relatively lower costs of sparging merits its possible prioritization for use in the deeper and narrower portion of Keno reservoir downstream of Klamath Straits Drain. Sparging units would require less-intensive operations and maintenance, thereby potentially freeing up resources for higher-intensity Speece cone installations to be grouped in one or two locations in the upper reservoir. The modularity of Speece cone installations when grouped close together also can help to simplify operations and maintenance requirements.

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Appendix A: IMIC Comments and Responses on Draft Report

PacifiCorp Responses to IMIC Comments on the Draft Technical Report for Activity 4 – Conceptual Feasibility Study of Oxygenation Systems at Keno Reservoir			
Commenter	**Section/Page**	**Comment**	**PacifiCorp Response**
SWRCB/ Thaler - 1		State Water Board staff would like additional information and/or analysis regarding any potential negative impacts to listed aquatic species associated with adding supersaturated dissolved oxygen into Keno Reservoir.	As described in the report, potential negative impacts of such a project to listed species could be entrainment in the water supply intakes for feed water to Speece cones. Fish screens meeting agency design criteria would be required to address those potential impacts. Fish are subject to gas bubble disease (GBD) caused by exposure to supersaturated levels of gases that have been dissolved in water. Weitkamp (2008) reports that total dissolved gas concentrations over 120 percent cause GBD at some level. Colt et al. (1991) report that safe levels of dissolved oxygen for hatchery environments at 12°C and 25°C were 21 mg/L and 16 mg/L respectively. These levels are considered appropriate for chronic exposure while rearing fish and should probably not be considered the same as incidental exposure from a localized source like an oxygenation system. Field observations of naturally-occurring fish populations where dissolved oxygen levels were 150 and 200 percent of saturation resulted in no ill-effects for fish; a function the authors attributed to behavior and species-specific tolerances (Serafy and Harrell 1993). Woodbury (1942) reported on fish mortalities at dissolved oxygen levels of 30-32 mg/L that were naturally occurring in a Wisconsin lake. A saturation value of 300 percent is often presented as the lethal threshold for fish (e.g., Serafy and Harrell 1993). Speece cones can generate dissolved oxygen levels ranging from 90 to 160 mg/L depending on the flow of water through the cone and the number of cones (see Table 1 in main report). The water released from a dispersal systems would have a very high level of dissolved oxygen; however, this

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			supersaturated water would rapidly mix and dissolved oxygen levels would drop to 12 to 18 mg/L outside the mixing zone near the diffuser. Except for a very small area immediately around the diffuser port, released water would generally be below the thresholds reported in the literature as harmful to fish. Should further evaluation of Keno oxygenation systems occur, more detailed research relating to the oxygen tolerance of species present in Keno reservoir could occur, the modeling could include parameters limiting the oxygen concentration in the released water, and diffusers could be designed to maximize mixing in the smallest area possible. Collectively these measures would ensure that adverse effects to fish were avoided.
SWRCB/ Thaler - 2		State Water Board staff would like additional information and/or analysis regarding any turbidity or negative water quality impacts associated with large scale use of either a sparging or side-stream oxygenation system in Keno Reservoir.	PacifiCorp is not aware of turbidity or other negative water quality effects associated with sparging or side-stream oxygenation systems.
SWRCB/ Thaler - 3	p. 21	TM4, Page 21, describes fish screens associated with an oxygenation system as a "costly item". If the study moves forward, in an effort to reduce implementation costs, State Water Board staff suggests the IMIC consider other fish screen alternatives such as infiltration galleries.	Comment noted. Different screening methods/technologies could be evaluated as part of future scoping/design efforts should this project advance.
SWRCB/ Thaler - 4	Section 5, Figure 2 and text	TM4, Section 5: *Potential Conceptual Layout of Oxygenation Systems in Keno Reservoir* states, "Consequently, a sparging system could potentially be used in Keno reservoir downstream of Location C (see Figure 2) to provide near-saturation DO [dissolved oxygen] levels downstream of this point." Results in Figure 2 included a sparging system at Locations A and B in addition to Location C indicating a cumulative dissolved oxygen benefit below Location C. To assess Location C's benefits to dissolved oxygen in lower Keno Reservoir, Location C should be modeled without Locations A and B.	The report text was clarified to indicate that the benefits of oxygenation downstream of Location C would result from the cumulative benefit of oxygenation addition at upstream locations.
USFWS/ Hamilton - 1	Section 1.1	Section 1.1 -We agree that oxygenation of Keno reservoir has the potential to improve water quality and look forward to the completed feasibility report for Activity 4.	Comment noted.

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Commenter	Section/Page	Comment	PacifiCorp Response
USFWS/ Hamilton - 2	Section 2.1.2	Section 2.1.2 -Please revise this section to clarify that Keno reservoir currently: a) provides benefits for endangered suckers, and b) has water quality conducive to anadromous fish passage during most months of the year (mid-November through mid-June). Because the diverse life histories of anadromous fish will likely mean migration during all seasons of the year, not all reintroduced anadromous salmonids would be limited by poor water quality during the summer/fall period. Additionally, during good water years, the poor water quality period in Keno Reservoir is abbreviated. Nevertheless, water quality improvements in Keno reservoir during mid-June through mid-November would benefit both suckers and anadromous salmonids.	While Keno reservoir is designated as critical habitat for listed suckers, supports some number of these species, and has periods in which water quality may not adversely affect anadromous fish passage, PacifiCorp disagrees that water quality conditions in Keno reservoir are conducive to anadromous fish passage given elevated temperature and low dissolved oxygen conditions during some periods of the year that are important for anadromous fish passage.
USFWS/ Hamilton - 3	Section 3.3	Section 3.3- The Service requests analysis regarding extent of potential dissolved oxygen (DO) supersaturation and impacts to federally listed suckers or other aquatic species associated with side-stream oxygenation in Keno Reservoir. This section states that "Bacterial uptake of injected DO and mixing can lower DO levels at short distances away from the injector diffuser." By this, we assume that you mean DO levels are no longer supersaturated at these distances. Please define 'short distances' in the final report.	The extent of supersaturated dissolved oxygen can be seen in the report in Figures 10 and 12. As shown in the figures, supersaturated dissolved oxygen (which, for example purposes, can be represented by dissolved oxygen > 10 mg/L) can extend from a few hundred feet to several miles downstream of the oxygenation locations (Figures 10 and 12). A discussion of supersaturation as it relates to fish health is provided in response to SWRCB/ Thaler-1.
USFWS/ Hamilton - 4		The Service requests any additional analysis regarding potential screening impacts to federally listed suckers, or other aquatic species, associated with the side-stream oxygenation in Keno reservoir.	Should this project proceed, additional analysis on screening effects would be conducted and shared with USFWS as part of consultation regarding the potential effects of the project on listed species.
USFWS/ Hamilton - 5	Section 5	Section 5. The Service requests that PacifiCorp add to the report the estimated costs of the Oxygenation Systems at Keno Reservoir and the costs of fish screening for the side- stream oxygenation. Please break down estimated costs of the Oxygenation Systems to clearly show electrical or other power related costs.	Additional conceptual-level cost information has been added to the report (see Section 6).
USFWS/ Hamilton - 6		Please analyze an Alternative 4 to provide DO concentration of 6.5 mg/L seasonally from October 1 to November 30.	The analysis of additional dissolved oxygen objectives is beyond the scope of the current study. The evaluation of additional alternatives could be part of additional study efforts if further study work on Keno oxygenation is pursued.

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ODEQ/ Stine-1		After the review it is unclear what the cost would be associated with the oxygenation systems, listed in Activity 4 - Conceptual Feasibility Study of Oxygenation Systems at Keno Reservoir (TM4), within the Keno Impoundment. The Department would request that further information be developed to provide additional details on the cost of installation, maintenance, and monitoring of these units. The Department would also suggest providing information from the U.S. Fish and Wildlife Service (USFWS) in terms of the analysis of potential impacts to aquatic life and the endangered species who have adapted to the current conditions within this reach.	Additional conceptual-level cost information has been added to the report (see Section 6). Detailed review of oxygenation effects on aquatic species in Keno Reservoir is beyond the scope of this study. If work on Keno oxygenation is pursued and more detailed alternatives are developed, such analysis may be reasonable to conduct.
Karuk/Yurok - 1		**Lack of cost information provided in the report** This study does not provide any cost estimates, contrary to what many IMIC members requested at the outset of the project, and what was written in PacifiCorp's 2015 study plan (PacifiCorp 2015): "Based on above initial design criteria, develop matrix of applicable commercially-available systems and/or system-components, including information on system performance specifications, power needs, installation requirements, *and costs*." (*emphasis added*) The lack of any cost information is extremely disappointing. Without any information on costs, we are unable to determine if it is worth the additional investment that would be required to further evaluate this technology. Since the study did not include any cost estimates, we decided to do some of our own calculations, combining information from the study with PacifiCorp's previous evaluations of aeriation/oxygenation of other Klamath River reservoirs which did provide some cost information (MEI 2008, Horne et al. 2009, and CH2MHill 2013). We provide these calculations in our comments here as an example to indicate the type of cost information that would be would like to have for Keno Reservoir, and to provide other IMIC members with this information because it is currently the only information we have to infer anything about costs for an oxygenation system for Keno Reservoir. We would appreciate it if PacifiCorp and its consultants can review these calculations and see if they appear to be in the right "ballpark." In the calculations below, we very roughly estimate that the side-stream oxygenation system for Keno Reservoir would have annual O&M costs of approximately $400,000 per year and one-time capital costs perhaps on the order of $1-3 million dollars plus whatever fish screens were necessary which could be an additional millions of dollars.	Additional conceptual-level cost information has been added to the report (see Section 6). PacifiCorp appreciates the effort to estimate potential project costs, but notes that the costs associated with prior estimates of aeration/oxygenation costs for J.C. Boyle, Copco and Iron Gate reservoirs are not directly comparable due to the much greater biological oxygen demands in Keno reservoir (compared to the other reservoirs) and the differences in DO enhancement objectives assumed in the studies.

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Commenter	Section/Page	Comment	PacifiCorp Response
Karuk/Yurok - 2		**Information and method used to generate of our rough approximate cost estimates** The oxygenation systems proposed by MEI (2008) were for 18.6 tons/day of oxygen for Copco ($1.6-2.4M annual O&M) and 16.3 tons/day at Iron Gate ($0.8-1.4M annual O&M), which are both approximately three times larger than the 5,250 kg/day (5.8 tons) system modelled for Keno Reservoir in the April 2016 Activity 4 draft report. Comparing the tons/day and the estimated O&M estimated by MEI (2008) for Iron Gate and Copco reservoir, our rough estimate cost estimate of $400,000 per year O&M costs for Keno Reservoir seems to be in the right ballpark. We do not have much information upon which to base an estimate of potential capital costs for a Keno Reservoir oxygenation system, but is perhaps on the order of $1-3 million dollars (the range of costs for the oxygenation systems listed on page 6-4 of the CH2MHill 2013 report), plus whatever fish screens were necessary which could be additional millions of dollars.	As stated above, PacifiCorp appreciates the effort to estimate potential project costs, but notes that the costs associated with prior estimates of aeration/oxygenation costs for J.C. Boyle, Copco and Iron Gate reservoirs are not directly comparable due to the much greater biological oxygen demands in Keno reservoir (compared to the other reservoirs) and the differences in DO enhancement objectives assumed in the studies.
Karuk/Yurok - 3	p. 3	p. 3: "However, at times of severe anoxia the reservoir has limited primary production, apparently as a result of the lack of available oxygen to meet algal respiratory demands (Deas 2008)." - We recommend discussing this issue with Annette Sullivan to get her most current thoughts on this matter, because what is stated here may not be correct? The Deas 2008 report is about the river reach downstream of the dam, and in our brief review of the Deas et al. 2008 report, we did not see anything that supports this claim. Should this citation be changed to refer to another report? Here is a relevant excerpt from Sullivan et al. 2011: "The model simulates the characteristic decrease in blue-green algae concentration that occurs with increasing distance downstream of Link River (Sullivan and others 2008, 2009). Populations of diatoms and other algae do not decrease in the downstream direction, and at certain times, increase in the downstream direction. It is unknown why the blue-green algae populations from Upper Klamath Lake are not able to sustain themselves to the same levels in this reach. Several explanations have been proposed, including physical cell damage as a result of transport past Link Dam, differences in the characteristics and vertical thermal structure of the hydrodynamic system of the lake versus the river, or algal mortality due to low dissolved-oxygen concentrations. The latter mechanism was hypothesized and invoked by a previous model of this reach; that model separated algae into a "healthy" or, upon exposure to low dissolved oxygen, an "unhealthy" algae group. The two groups were assigned	This sentence has been deleted from the report. The sentence was intended as informational only, and is not essential to the analysis or conclusions in the report.

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		different growth, respiration, excretion, and mortality rates (Tetra Tech, 2009; Rounds and Sullivan, 2009, 2010). However, at present, insufficient evidence is available to support a specific mechanism for the decline in algal populations through the Link–Keno reach. The model described herein does not simulate the details of this unknown process, but it does simulate the end result, which is an increase in settling and mortality losses for blue-green algae in this reach. If future research reveals the causal mechanism for blue-green algae losses in this reach, that process could be encoded into the model."	
Karuk/Yurok - 4	p. 4	p. 4: "For example, extensive modeling work by the U.S. Geological Survey (USGS) has shown that Keno reservoir experiences seasonal anoxia due to the processing of OM loads from Upper Klamath Lake, and that conditions may be improved through load reductions (Sullivan et al. 2011; Sullivan et al. 2012; Sullivan et al. 2013)" - Please add citation to Sullivan et al. (2014).	Citation to Sullivan et al. (2014) has been added.
Karuk/Yurok - 5	p. 10	p. 10: "It was also assumed that sparged oxygen cannot provide DO greater than saturation (for example, at Keno reservoir, DO saturation is 8.6 mg/L at 20°C and 7.8 mg/L at 25°C) from diffuser locations." - These values appear to be incorrect, please check the calculations. Also please verify that this apparent error did not affect other parts of the report including the model outputs. DO saturation is affected not just by temperature but also by atmospheric pressure (and salinity, but in freshwater, salinity is negligible). Atmospheric pressure is affected by elevation. The elevation of Keno Reservoir is approximately 4,085 ft above sea level. According to the calculator at http://www.waterontheweb.org/under/waterquality/DOSatCalc.html (for more information, see http://www.waterontheweb.org/under/waterquality/oxygen.html), at 4085 ft elevation (1245 m) the pressure is 0.861 atmosphere (or 872 millibars), which results in a DO saturation of 7.8 mg/L at 20°C and 7.1 mg/L at 25°C. The 8.6 mg/L at 20°C and 7.8 mg/L at 25°C DO saturation values presented in the report are what should be expected for 1500 ft elevation, not 4085 ft elevation.	The DO saturation values in this sentence have been corrected, and do not affect other parts of the report including the model outputs.
Karuk/Yurok - 5	p. 14	p. 14: "The side-stream intake systems would require a screened diversion pumped to the cone and a corresponding return to the reservoir through the eductor diffuser system." and p. 21: "Fish screening would likely be a costly item and because of this, it	The possibility of using the Klamath Straits Drain or the A-Canal (behind the A-Canal fish screen) as oxygenation sites may have been discussed on TAC

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		may be most cost-effective to group Speece cones that draw from a common fish screen." - Please add a sentence mentioning the possibility of using the Klamath Straits Drain as one of the oxygenation sites (i.e., minor relation of Location C), as was discussed several times during the Technical Advisory Committee calls. The drain is extremely poor quality fish habitat and therefore may not require a fish screen, which might save a significant amount of money. - In addition, it is also worth considering moving the site of Location A from Lake Ewauna upstream to behind the A-Canal fish screen. This would save money by not having to construct a fish screen; however, it would require some means of returning the oxygenated water to Upper Klamath Lake or Link River. One possibility to explore for returning the oxygenated water would be to use the pumped fish bypass (which is not currently typically in use, fish are bypassed by gravity down below Link Dam).	calls, but is beyond the scope of the current study. The consideration of additional or different oxygenation sites could be part of additional study efforts if further study work on Keno oxygenation is pursued.
Klamath Tribes/ Skinner - 1		Cost estimates provided by The Karuk Tribe indicate annual operation and maintenance costs associated with either type of oxygenation unit are almost entirely due to the cost of oxygen. I would therefore recommend the authors look further into the feasibility of on-site oxygen generation. For a line-diffuser oxygenation project in northeast WA, producing oxygen onsite was estimated to reduce annual O&M costs by 26-41%, relative to O&M costs with oxygen delivery. See "Twin Lakes O2 cost comparison" (attached) for more details. Major costs associated with onsite generation include capital and the cost of electricity, so further research into savings and feasibility for the Keno Reservoir project is necessary.	Additional conceptual-level cost information has been added to the report (see Section 6). This information refers to oxygen concentration generators (that would be located on-site).
Klamath Tribes/ Skinner - 2	P. 4	On pg, 4, the authors support the statement "successful shallower water applications…have been reported" with a single citation. I believe Moore et al. 2012 (attached) should be added. This study may also provide useful information to help guide system design and operation.	Citation to Moore et al. (2012) has been added.

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