Technical Report No. ENV-2022-61

Low Dissolved Oxygen in Releases: Current State-of-Practice

Colorado River Storage Project
Upper Colorado Basin Region

U.S. Department of the Interior October 2022

Mission Statements

The U.S. Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated Island Communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Cover Photo – Night View of Glen Canyon Dam with bypass tunnels open during 2008 high flow experiment (Bureau of Reclamation).

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Acronyms and Abbreviations

DO	dissolved oxygen
FERC	Federal Energy Regulatory Commission
ft^3/s	cubic feet per second
GCMRC	U.S. Geological Survey Grand Canyon Monitoring and Research Center
mg/L	milligram(s) per liter
Reclamation	Bureau of Reclamation
TMDL	total maximum daily load
TVA	Tennessee Valley Authority
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey

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1.0 Introduction

All natural lakes and man-made reservoirs undergo similar processes that result in seasonal inputs of organic matter and nutrients, algal growth periods, stratification, and the potential for decreases in dissolved oxygen (DO) at certain depths due to chemical and biological processes (Figure 1). The degree of DO depletion within a waterbody is impacted by how isolated the hypolimnion is from the upper layers, the temperature, and the amount of oxygen demand at certain depths (Figure 2). Both natural lakes and reservoirs can experience strong stratification, leading to low DO at certain depths, but in regard to downstream water quality, these low DO events are more concerning in man-made reservoirs than in natural lakes.

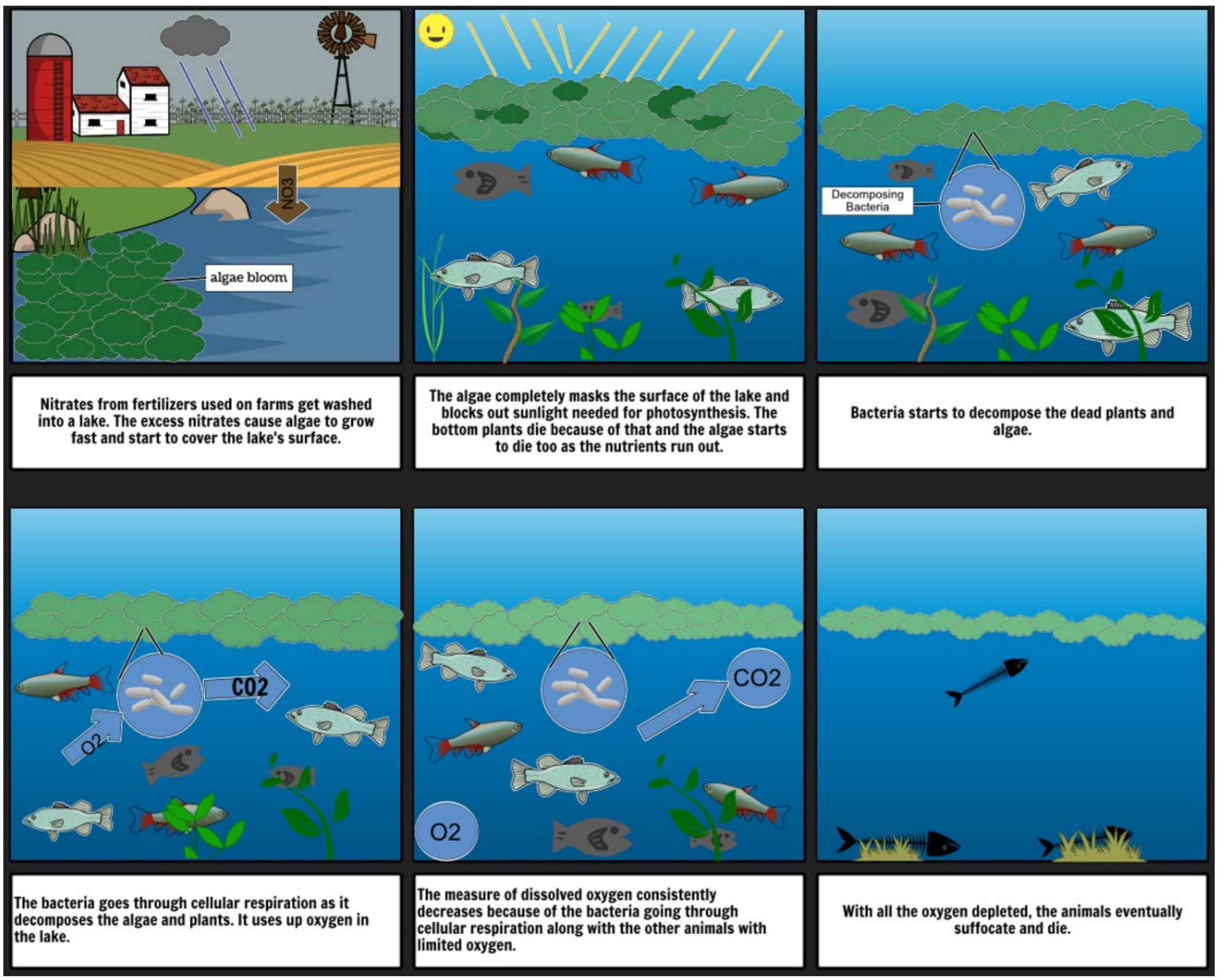

Figure 1.—Cartoon demonstrating (left to right) a simplified version of how eutrophication occurs due to nutrient loading in a waterbody (National Oceanic and Atmospheric Administration 2018).

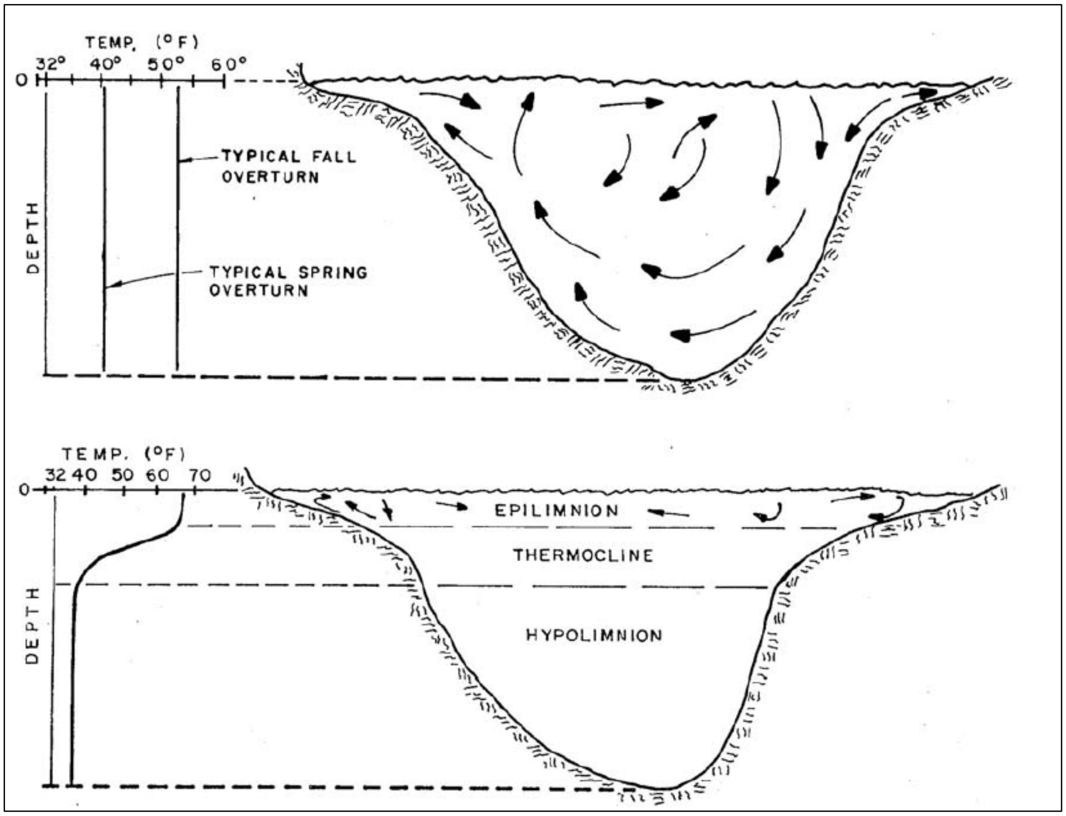

Figure 2.—Typical seasonal thermal mixing and stratification that results in low DO in natural lakes and man-made reservoirs; arrows represent the mixing of water (Bevelhimer 2006).

A key difference in water quality downstream from natural lakes and man-made reservoirs is due to the difference in depth from which water is released. In natural lakes, water typically flows downstream from the relatively well-oxygenated surface waters, whereas many man-made reservoirs release water from a depth that tends to have significantly lower DO (Beutel 1999). Low DO releases have a well-documented potential to cause significant negative impacts to downstream ecosystems (Bevelhimer 2006). However, not all water from reservoirs is released from below the thermocline (the hypolimnion), and not all releases from below the thermocline are bad for downstream habitats. Depending on the reservoir purpose, dam design, and operational requirements, releases can occur at a wide range of depths, and water from many dams is purposefully released from below the thermocline to help route sediment-heavy inflows through a reservoir, draw higher DO water from further upstream to the deeper parts of a reservoir, and to pass colder water downstream to overheated habitats. Although there are some potential benefits to releasing water from below the thermocline, these benefits have largely been outweighed by the intermittent lack of oxygen in the outflow at Glen Canyon Dam, which has caused concern for ecosystem health between Glen Canyon Dam and Lees Ferry in 2003, 2005, 2014, and 2019 (Deemer 2020). Further, as the climate changes, these low DO events are predicted to increase in both frequency and magnitude at Glen Canyon Dam (U.S. Fish and Wildlife Service [USFWS] 2016).

Water impairments caused by low DO dam releases are not unique to Glen Canyon Dam. Monitoring and/or mitigating for low DO in dam tailraces is a requirement of an estimated 40 percent of Federal Energy Regulatory Commission (FERC) licenses (Bevelhimer 2006). Because low DO is a historical concern at a wide range of reservoir sites, a number of case studies and other summary documents have been developed for a large suite of projects in the United States and throughout the world. While focused on studies in the United States, this report used sources from other areas of the world as well. Technologies in use are not unique to any particular area but are instead related more to the problem at hand and local conditions. When determining the best method to mitigate low DO dam releases, these case studies can provide valuable lessons and guidance when designing a system intended to overcome the unique challenges inherent to every dam site while operating within a reasonable budget (Higgins 1999).

Increasing DO in dam releases not only has an added expense associated with buildout or equipment installation, it also typically incurs considerable operational costs that must be factored into any successful mitigation plan: Low DO mitigation projects often entail significant operational costs related to losses in hydropower revenue through reduced power generation, ongoing operations and maintenance costs, the cost of monitoring and modeling DO conditions, and the costs of necessary consumables such as liquid oxygen (U.S. Geological Survey [USGS] 2020). To plan for and develop a cost-effective DO mitigation system, a basic understanding of DO mitigation history, methods, and applicability is essential.

In this report, case studies of select Bureau of Reclamation (Reclamation) installations with DO issues and project mitigation success are presented. Monitoring and modeling of DO upstream of and downstream from Lake Powell are discussed, as low DO releases from Lake Powell are threatening the downstream ecosystem. Successful DO mitigation methods at other reservoir locations are also presented to inform managers of mitigation systems that should be considered for use at Glen Canyon Dam.

Note: This is *not* an engineering report or feasibility study. This report presents mitigation alternatives and options to improve DO on a general level.

2.0 Low Dissolved Oxygen Issues at Reclamation Facilities

Many FERC-licensed projects include requirements to mitigate and/or monitor downstream DO, and many have minimum DO requirements (Mobley 1997). Water releases with low DO are a common problem at many existing hydropower facilities because the turbine intakes are often far below the water surface, where DO may be as low as 0 milligrams per liter (mg/L) (United States Department of Energy 2016).

Below, we briefly present a selection of waterways downstream from Reclamation facilities for which there are reports and studies focusing on low DO: Indian Creek Reservoir, the Klamath River, the Malheur River, and the Yakima River Basin. The general overview presents the different DO issues at Reclamation sites as well as possible solutions.

2.1 Indian Creek Reservoir

Indian Creek Reservoir has been on California's 303(d) pollutant list (a State's list of impaired and threatened waters) for low DO since 1998. After studying the DO, sediment load, water temperature, and anthropogenic influences on the water entering the reservoir, oxygen consumption by plants, stimulated by high phosphorous in the water, and sediment oxygen demand were determined to be the two most viable causes of eutrophication (Idaho Department of Environmental Quality 2001). Phosphorous can reduce DO by stimulating nuisance aquatic algae growth. As the biomass of algae increases, its nighttime respiration increases, thereby reducing oxygen in the water. When the biomass dies, its decomposition further reduces DO as shown on Figure 2 (Bolke 1979). In 2008, a hypolimnetic oxygenation system was constructed in Indian Creek Reservoir that uses Speece cones connected to an onsite oxygen generation system. This system was operated from 2009 to 2014, for an average of 3,252 hours each year, and liquid oxygen was injected at an average rate of 517 pounds per day across those six years. Steps were also taken to mitigate phosphorus loads so as to not exceed the maximum total allowable levels for water inflows into the reservoir. Following operation of the hypolimnetic oxygenation system and measures to limit phosphorus inputs upstream, target DO levels within and downstream from Indian Creek Reservoir have consistently been met or exceeded (Bergsohn 2015).

2.2 Klamath River

Reclamation DO concerns are not limited to a single reservoir; there have been concerns about the DO levels throughout much of the Klamath River Basin for many years (McCaughey 2020). Reclamation began monitoring Klamath Basin water quality in the early 1990s and found the Klamath River main stem regularly experienced impairments due to low DO levels (California Water Board [CAWB] CAWB-R1 2010). During a fishkill in 1999, the DO concentrations within monitored portions of the lower Klamath River ranged from 3.1 to 7.6 parts per million (Zedonis 2001), and it was reported that throughout the basin, DO concentrations were regularly too low to meet the Action and Basin Plan objectives (CAWB-R1 2010). In 2009, as a mitigation measure, a blower and turbine venting system were installed at Iron Gate Dam. The system has been used on an ongoing basis beginning in 2013and has demonstrated the ability to consistently increase oxygen levels in the portion of the river near the downstream outlet at Iron Gate Dam to acceptable levels (PacificCorp 2018). To assist with DO issues in other areas of the Klamath Basin, beginning December 2010, the North Coast Regional Board began implementing an Action Plan for the Klamath River. The plan included dam management and control of total maximum daily loads (TMDLs), such as nitrogen and phosphate, to control water quality issues such as low DO (Klamath Basin Restoration Agreement 2010). Unfortunately, this plan only moderately helped to relieve impairments caused by low DO levels in the Klamath River Basin (USGS 2018).

2.3 Malheur River

Similar to the widespread DO concerns in the Klamath River Basin, the Malheur River was listed on Oregon's 303(d) pollutant list for low DO throughout its length (Oregon Department of Environmental Quality 2010). Reclamation has interests in this basin through the Vale Project, which includes Warm Springs Dam, Agency Valley Dam, and Bully Creek Dam, as well as other diversion works and drainage systems. Low DO releases from Warm Springs Dam were the biggest concern of the system (Warm Springs Hydro, LLC 2013). A turbine aeration system was constructed at this location to ensure water discharged during power production met State water quality standards, and a bypass structure was installed to route water with higher DO downstream when not needed for power production. Operation of the turbine aeration system and installation of the bypass structure alleviated low DO concerns downstream from Warm Springs Dam (Dadoly 2010). At the Bully Creek and Agency Valley Dams, low DO remains a concern primarily due to orthophosphate loading. To help mitigate this issue, TMDLs were established and have largely been met; however, impairments due to low DO conditions downstream from these two dams have still been recorded, though they tend to not be as severe as they were before TMDLs were established (Malheur Watershed Council 2019; Rose 2006).

2.4 Yakima River Basin

While reservoirs often exacerbate low DO conditions in a basin, some Reclamation DO issues have little to do with a reservoir; they are caused by conditions in the waterway. The Yakima Basin Project is a complex system with a number of dams, diversions, dikes, and irrigation projects (Reclamation 2022) that has experienced issues in some reaches such as degrading water quality associated with excessive plant growth, which can result in low DO concentrations especially in summer (Wise 2009). Within the basin there were nine 303(d) DO listings: low DO levels observed in some reaches were largely attributed to high agricultural return flows with high levels of nutrients (Hiebert 1999). In addition to high nutrient loading, low water levels in the river reaches were also identified as a contributing factor to the low DO levels. Low water levels in river reaches can accelerate the heating of waterbodies, and it can also increase macrophyte and phytoplankton growth which, in turn, tends to further reduce DO concentrations (Reclamation 2002). The strong link between DO and primary productivity in the Yakima basin produces cyclical DO impairments: during the day, plants and algae typically generate oxygen, but at night and during decomposition, they reduce DO below its acceptable criterion level (Pickett 2016). Fortunately, the Yakima River is one of the more intensely studied rivers in Washington State, and plenty of historical water quality data has been recorded to develop a one-dimensional steady-state model with QUAL2E modeling software that helps predict DO by forecasting water temperatures and considering primary productivity (Carroll 2001). This forecasting tool has helped to create TMDLs for the basin which, in turn, have helped to control DO. However, it has not completely alleviated low DO concerns because water levels in the Yakima River cannot be increased to a sufficient depth to reduce water temperature which, in turn, reduces primary productivity (Urmos-Berry 2019).

3.0 Dissolved Oxygen Monitoring at Reclamation Sites of Concern

Strategies for monitoring water quality vary significantly among Indian Creek Reservoir, the Klamath River, the Malheur River, and the Yakima River Basin so as to allow each system and facility to achieve their monitoring goals without using excessive financial or personnel resources.

To provide more detailed information on the Reclamation sites of concern mentioned above in section 2.0, below we will briefly describe the monitoring strategies used at each site along with a discussion of mitigation steps.

3.1 Indian Creek Reservoir

Monitoring Indian Creek Reservoir 2012 TMDLs required water quality tracking at three monitoring stations. One of the stations (ICR-1) is located near the dam, another (ICR-3) is located near the center of the reservoir, and the third (ICR-5) is located near the upstream end of the reservoir at a relatively shallow depth. Each month, water quality samples are collected along with vertical profiles of water temperature and DO concentration (Figure 3). Water quality samples were collected around pre-dawn to ensure the day's lowest DO measurement was captured (Idaho Department of Environmental Quality 2001). After installation of the hypolimnetic oxygenation system, the reported annual cost of operation was approximately $9,800 from 2010 to 2014 (Bergsohn 2015).

Figure 3.—Location of monitoring stations (ICR-1, ICR-2, and ICR-5), Speece cone, and equipment building where the air blowers are housed at Indian Creek Reservoir (Bergsohn 2015).

3.2 Klamath River

Reclamation has been collecting hourly water quality data, including DO, at most sites throughout the Klamath River Basin since 1990. The USGS Klamath River Basin Water-Quality Mapper (https://or.water.usgs.gov/projs_dir/klamath_wq_mapper) displays current and historical monitoring sites (USGS 2018). As part of this monitoring system, three monitoring stations are associated with Iron Gate Reservoir: One is below Iron Gate Dam, another is at the Camp Creek Campground in the upstream northern branch of the reservoir, and the third is at the Jay Williams Boat Ramp in the upstream eastern branch of the reservoir. The frequency of monitoring varies: once in May, at least twice a month in June through November, and not at all in December through April, as DO is not a big concern during these months (PacificCorp 2018).

3.3 Malheur River

In the Malheur Basin, the Oregon Department of Environmental Quality maintains four water quality monitoring stations (information is available at: https://orwater.deq.state.or.us/Login.aspx.) In addition, Reclamation monitors approximately 80 locations throughout the basin; data are available through the Environmental Protection Agency's STOrage and RETrieval (STORET) database (https://www.epa.gov/waterdata/water-quality-data). Reclamation monitors two locations in each reservoir created by the Warm Springs: Agency Valley and Bully Creek Dams. In each reservoir, one monitoring site is downstream from the dam, and the other is in a far upstream location. The frequency of monitoring at these sites varies between sites and between years, but regardless of the monitoring regime, low DO conditions are typically found to occur in summer throughout much of the Malheur River (Dadoly 2010).

3.4 Yakima River Basin

In the Yakima River Basin, much of the data gathered on water quality has been from water quality projects or studies, not a long-established monitoring regime. There are three permanent continuous ambient monitoring stations in the Yakima River Watershed: One is located in the Yakima River downstream from Cle Elum, another is located in the Yakima River at Nob Hill, and the third is in the Yakima River at Kiona (Urmos-Berry 2019). The frequency of water quality monitoring varies between sites and between years.

4.0 Management of Dissolved Oxygen at Reclamation Sites of Concern

Management of DO levels at Reclamation sites of concern varies widely depending on, but not limited to, the severity of the issue, impacts on the ecosystem, and funding. At Indian Creek

Reservoir, a hypolimnetic oxygenation system, which uses Speece cones connected to an onsite oxygen generation system, functions to resolve low DO issues in tailwaters through dispersing oxygen at certain depths upstream of the dam (Bergsohn 2015). At Warm Springs and Iron Gate Reservoirs, an oxygenation system oxygenates water as it passes through turbines inside of the dam (Dadoly 2010; PacificCorp 2018). Both systems have been notably successful partly due to implementation of TMDL limits upstream of the dams.

5.0 Assessment of Current Monitoring and Modeling at Lake Powell

5.1 Current Method of Dissolved Oxygen Monitoring at Lake Powell

The Grand Canyon Monitoring and Research Center (GCMRC) has monitored Lake Powell and the releases from Glen Canyon Dam since 1997 to determine not only the status and trends of water quality but also to determine the effects dam management has on water quality (USGS 2020).

Two continuously logging water quality sondes are used to monitor DO from dam releases: One is connected to an active penstock, and one is directly below the dam. Monthly water quality monitoring consists of sampling at three locations: (1) in the forebay area immediately upstream of Glenn Canyon Dam, (2) in the dam draft tubes, and (3) 25 km downstream from Glen Canyon Dam at Lees Ferry (USGS 2020). During this monthly sampling, a vertical profile of various water quality constituents, including DO, is collected from the forebay area. In addition, another ± 27 stations (at full reservoir pool) are monitored quarterly, as these sites (Table 1) mostly represent major areas of the reservoir and are typically located in the thalweg (Vernieu 2015).

Water quality data are entered into a SQL-based data platform the GCMRC developed to house existing data and to provide more streamlined processes for newly generated Lake Powell water quality data. This database provides easier access than the previous Microsoft Access database, but at last report, there were still some portions under testing and development; it is anticipated to be complete in 2022.

In 2021, the sonde directly below Glen Canyon Dam was set up to transmit near real-time data to the GCMRC's Amazon Web Services platform. The data have been linked to an online data visualization platform, which is currently being shared with stakeholders and colleagues at Reclamation (USGS 2020). Data from the sonde from 2015 to the present are currently available at https://www.gcmrc.gov/discharge_qw_sediment/. Data for years before 2015 will be available on the site in the future (Deemer 2020).

Table 1.—List of the 27 primary monitoring stations for the water quality database (Vernieu 2015)

[Channel codes: CR, Colorado River; SJR, San Juan River; ESC, Escalante River. RKM, river-channel kilometers; #, number]

Station group	Station ID	Site name	Latitude	Longitude	Channel	RKM	# of site visits
LPCR-249	LPCR-249	Colorado River at Lees Ferry	36.865241	-111.584485	CR	-24.9	163
LPCR0000	LPCR0000	Glen Canyon Dam draft tubes	variable	variable	CR	0	162
LPCR0024	LPCR0024	Wahweap	36.955278	-111.482778	CR	2.4	203
LPCR0250	LPCR0250	Romano Narrows	37.005474	-111.3606156	CR	25.0	2
LPCR0453	LPCR0453	Crossing of the Fathers	37.039333	-111.256944	CR	45.3	69
LPCR0905	LPCR0905	Oak	37.134444	-110.952222	CR	90.5	70
LPCR1001	LPCR1001	San Juan R. Confluence	37.172744	-110.904269	CR	100.1	45
LPCR1169	LPCR1169	Escalante	37.283056	-110.874444	CR	116.9	67
LPCR1395	LPCR1395	Iceberg	37.332731	-110.762581	CR	139.5	50
LPCR1587	LPCR1587	Lake	37.422500	-110.703056	CR	158.7	49
LPCR1679	LPCR1679	Bullfrog	37.470556	-110.725000	CR	169.2	69
LPCR1799	LPCR1799	Moki	37.484492	-110.645733	CR	177.2	44
LPCR1933	LPCR1933	Knowles	37.579247	-110.598806	CR	193.3	51
LPCR2085	LPCR2085	Lower Good Hope Bay	37.657222	-110.514167	CR	208.5	69
LPCR2255	LPCR2255	Scorup	37.767222	-110.436389	CR	225.5	67
LPCR2387	LPCR2387	Hite Basin	37.805278	-110.436944	CR	238.7	70
LPCR_INF	LPCR_INF	Colorado River Inflow Stations	variable	variable	CR	999	76
LPESC119	LPESC119	Escalante at Davis Gulch	37.324167	-110.917222	ESC	11.9	61
LPESC200	LPESC200	Escalante at Willow Creek	37.346389	-110.938056	ESC	20	46
LPESC273	LPESC273	Escalante Inflow above Garces Island	37.370510	-110.944223	ESC	27.3	28
LPESCINF	LPESCINF	Escalante River Inflow Stations	variable	variable	ESC	999	43
LPSJR193	LPSJR193	San Juan at Cha Canyon	37.170000	-110.813889	SJR	19.3	71
LPSJR329	LPSJR329	San Juan at Lower Piute Bay	37.188889	-110.719167	SJR	32.9	61
LPSJR431	LPSJR431	San Juan at Upper Piute Bay	37.218889	-110.673056	SJR	43.1	67
LPSJR530	LPSJR530	San Juan at Alcove Canyon	37.267758	-110.696148	SJR	53	16
LPSJR625	LPSJR625	San Juan at Lower Zahn Bay	37.229444	-110.623611	SJR	62.5	42
LPSJRINF	LPSJRINF	San Juan River Inflow Stations	variable	variable	SJR	999	55

The GCMRC conducts discharge monitoring and additional water quality monitoring downstream from Lake Powell at 8 mainstem and 16 tributary gage sites for a variety of parameters including DO, turbidity, and suspended sediment concentrations (Figure 4 shows sites for Lees Ferry and those upstream). From the data collected, it has been determined that seasonal variations of DO at the penstocks of Lake Powell can impact the downstream Glen Canyon reach of the Colorado River (USGS 2020).

CE-QUAL-W2 modeling to assist in the prediction of low DO events at Glen Canyon Dam is done through a DO module, which has been shown able to predict low DO events, but it does not consistently predict DO concentrations at penstock intake elevations accurately (Deemer 2020).

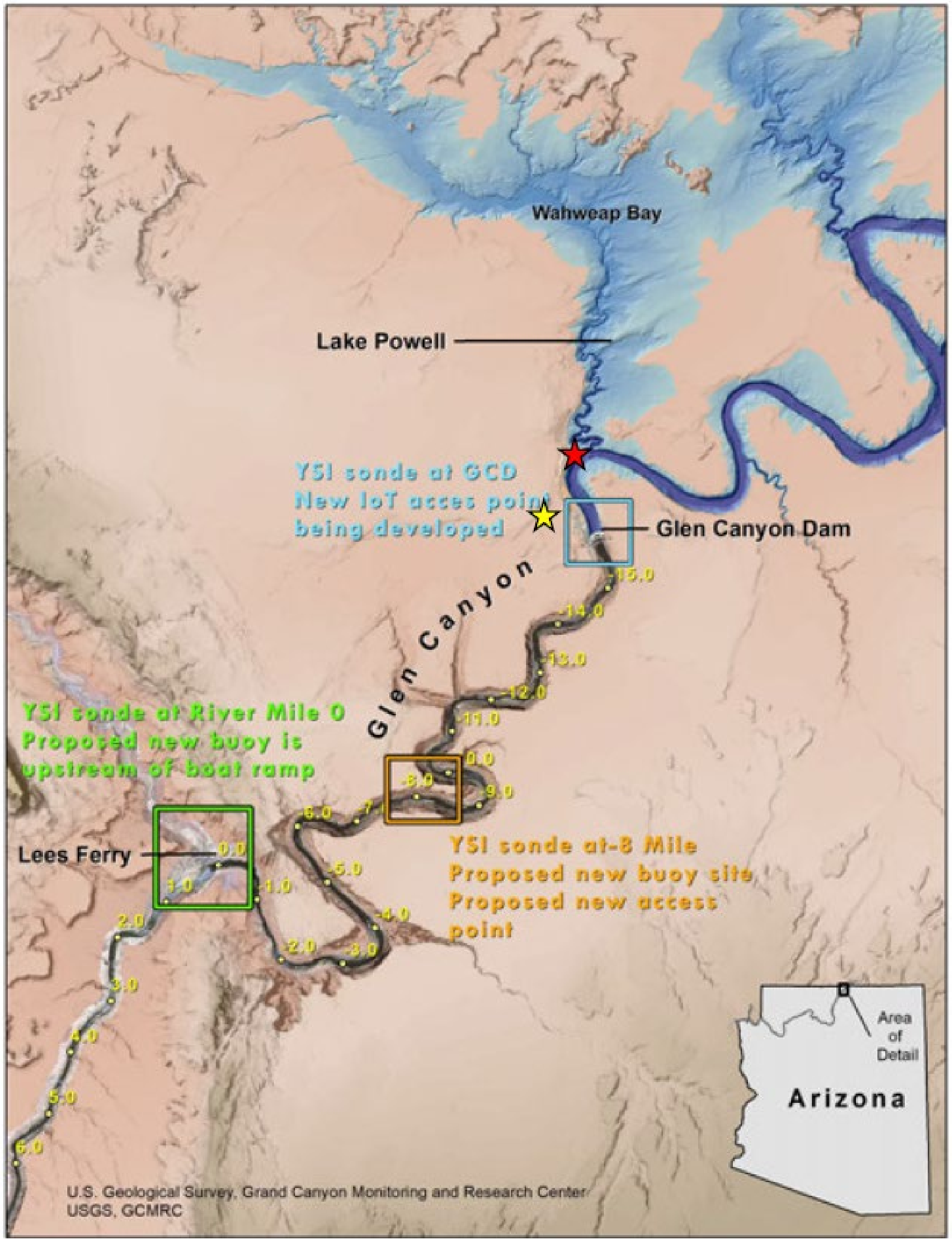

Figure 4.—Yellow dots indicate sondes in the Glen Canyon Reach of the Colorado River and are labeled by river mile from Glen Canyon Dam (the red star indicates a thermistor string in Lake Powell, and the yellow star indicates the Wahweap sampling site (Deemer 2020).

5.1.1 Assessment of Current Dissolved Oxygen Monitoring Effectiveness at Lake Powell

CE-QUAL-W2 modeling to assist in the prediction of low DO events at Glen Canyon Dam is done through a DO module that has been shown able to predict low DO events with a mean accuracy of 1.15 mg/L, but it does not consistently predict DO concentrations at penstock intake elevations accurately (frequently in the metalimnion). This model is useful for long-term planning of dam management, but it currently lacks the resolution to accurately predict the length and magnitude of a DO event (Williams 2007). To increase the resolution of the current CE-QUAL-W2 model, a number of factors could be monitored better, including meteorological data (hourly is best):

- Shading influence on the reservoir
- Improved vertical monitoring resolution at the penstocks
- Improved records
- Predictive ability of incoming flows
- Any other modeled inputs for phosphorous or DO (Cole 2015)

6.0 Consideration of Downstream Resources

6.1 Forecasting Ability

The ability to forecast DO levels within a waterbody is directly tied to the ability to monitor and model the net processes that contribute and consume oxygen. The ability to mitigate low DO at the outlet of any reservoir is directly linked to the ability to predict when and to what magnitude low DO will occur. In Lake Powell, like other waterbodies, the primary sources of DO are photosynthesis of algae during the day, wind mixing of surface waters, and the inflow of oxygen-rich waters. The primary processes that consume oxygen are biochemical oxygen demand, sediment oxygen demand, and respiration by algae at night. In turn, primary production, biochemical oxygen demand, and sediment oxygen demand are directly impacted by inflow volume, water temperature, nutrient availability, reservoir stratification, and circulation (Johnson 1981). With a well-developed forecasting tool, the management of dam operations and any mitigation system can be optimized to ensure downstream water quality criteria are met without incurring excessive costs (Cooke 1989).

Generalized seasonal variation of DO is well documented at Lake Powell. The DO levels are highest in spring and early summer chiefly because, at this time of year, inflows are at their highest, bringing well-oxygenated water deep into the reservoir; primary productivity generates oxygen during the day; mass algal die-offs have not begun; temperatures are moderate; and wind-induced mixing tends to be higher. During the late summer into fall, DO concentrations tend to be at their lowest mostly due to increased biological oxygen demand from mass algal die-offs, lower inflows, higher temperatures, and stratification. Throughout the rest of the year into spring, DO concentrations tend to increase as a result of the higher DO capacity of cold water and the natural mixing process created by the cold-water underflow and cooling of surface waters (Vernieu 2009).

Generalized daily variations have also been documented. In the tailwater of Glen Canyon Dam, daily DO oscillations show a notable increase during the day and a decrease at night due to photosynthesis and respiration of the algal community (Vernieu 2009). The amplitude of daily DO changes at Lees Ferry, downstream from the dam, ranges from 0.5 to over 3 mg/L depending on the season, with the lowest fluctuations in winter when the algal community is least active (USGS 2017).

Beyond general seasonal and daily variations at Lake Powell, more specific DO variations occur under different conditions. For example, when reservoir elevations are low in years of high inflow, the inflows cut through delta sediments and resuspend organic matter and nutrients, contributing to increased biochemical oxygen demand, which results in lower DO within the reservoir (Hering 2009). Similarly, in years of low inflows, the incoming water is typically warmer, which may increase primary production, leading to lower DO within the reservoir. These variables, among others, need to be monitored and modeled to accurately forecast low DO events at Lake Powell (USGS 2020). Data and the modeled predictions, with the exception of elevated water temperatures and nutrient concentrations at the penstock inlets, have not been in close agreement, particularly for DO (Williams 2007). Low DO events have also occurred in Lake Powell near the Colorado River inflow through mechanisms that are still not fully understood. These events are suspected to be tied to elevated water temperatures in the river (USGS 2020).

Antecedent conditions may be used to predict low DO events in Glen Canyon Dam tailwaters if a model cannot forecast precise DO concentrations at the outlet works. In fiscal year 2020, monitoring capabilities were limited, reducing our ability to forecast low DO events through the CE-QUAL-W2 model. During this time, data from a subset of monitoring stations were compared to previous low DO events, and the risk of a low DO event was determined to be low. This prediction was correct; the minimum DO recorded at the tailwaters was well above 6 mg/L (USGS 2020). However, this process only worked to predict general risk. Many low DO events have occurred during years when the reservoir water elevation was low and spring inflow high (Vernieu 2010). Low DO in Glen Canyon Dam tailwaters can also occur during years of low inflows or higher reservoir water elevations (Reclamation 2016). Additionally, even if low DO events at Glen Canyon Dam tailwaters only occurred during years of low reservoir elevation and high spring inflows, using only antecedent conditions would not be sufficient to predict the magnitude of a low DO event.

In the future, low DO events are predicted to become more frequent, highlighting the need to continue improving the forecasting ability of the predictive models. Climate-change driven variation in inflow, evapotranspiration, evaporation, and increased temperatures are all anticipated to increase the rate and magnitude of low DO events at Lake Powell (Reclamation 2016). Additionally, reservoir elevations are also anticipated to be regularly below historical norms, which will increase the frequency and magnitude of low DO events (USGS 2020).

6.2 Ecosystem Impacts of Low Dissolved Oxygen Releases from Lake Powell

Managing flows to avoid low DO events at Glen Canyon Dam is limited due to the implementation of the Modified Low Fluctuating Flows established in 1996 for Rainbow Trout recruitment and general ecosystem health downstream from the reservoir (USFWS 2016) and because the bypass tubes may only be used to avoid anticipated spills from Lake Powell (Reclamation 2016). To date, DO levels downstream from the reservoir have usually been below saturation, but the oxygen levels in the water typically do not drop low enough to significantly impact the aquatic ecosystem. There have been negative impacts at Glen Canyon Dam due to low DO events in the past, and climate change is anticipated to increase the frequency and magnitude of these events (USFWS 2016) partially because, as water temperatures increase due to climate change, biological oxygen demand will also increase, further reducing DO in Lake Powell waters (Runge 2011).

6.2.1 Risk of Low Dissolved Oxygen Releases from Lake Powell

Low DO releases from Lake Powell are a risk to the ecosystem downstream from Glen Canyon Dam depending on how low the DO level is and how long the DO remains depressed in the waterway. Ideally, DO levels for fishes should remain from between 7 and 9 mg/L; levels below 5 mg/L can cause chronic stress to fish species, and most fishes cannot survive when the DO level falls below 3 mg/L. The level of DO at the Glen Canyon Dam tailraces typically remains above 5 mg/L, but unintentional fishkills due to short periods of DO levels below 3.5 mg/L have been documented. While these events do not regularly occur downstream from the dam, the intensity, duration, and frequency of low DO in Lake Powell at Glen Canyon Dam have increased in recent years (Figure 5) (USGS 2020).

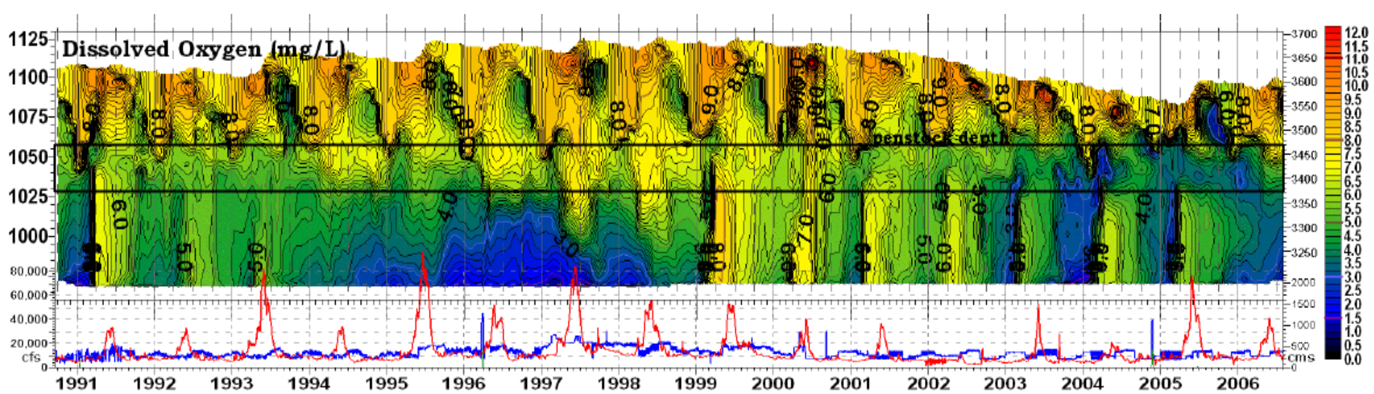

Figure 5.—Historical DO concentration in Lake Powell at Glen Canyon Dam from 1991 to 2006 with elevation in feet on the x-axis and the penstock elevation displayed by the black box overlay. Below the DO concentration plot is a plot of the inflow from the Colorado River to Lake Powell as the red line and outflows through Glen Canyon Dam as the blue lines. As displayed here, low DO passing through the dam has not historically been an issue, but it is becoming more of a concern (Vernieu 2006).

The impact of low DO levels in waterways can affect the entire food chain. Benthic organisms are a significant food source for the fish community; when the benthic community is reduced by low DO events, fishes can become stressed if they do not find an alternate food source. Organisms that comprise the benthic community typically can tolerate a much lower DO level than fishes, but they have much less mobility to leave a low DO environment; this results in them being more susceptible to die-offs from localized areas of very low DO levels (McCormick 1995).

6.2.2 Brown and Rainbow Trout Dissolved Oxygen Tolerance

Management and water quality released from Glen Canyon Dam can have a direct impact on fish communities downstream. The Rainbow Trout population increased from 1991 to 1997 following the implementation of a steadier flow regime that resulted from the Modified Low Fluctuating Flows guidance established in 1996. However, populations declined from about the year 2000 to 2007 likely due to increased water temperatures, decreased DO, and lower flows. Following habitat improvement efforts at Glen Canyon Dam in 2008, Rainbow Trout populations improved through 2010 (Makinster 2011).

While DO levels at around 6.0 to 7.0 mg/L downstream from Glen Canyon Dam during lower DO months are typically acceptable for fish populations (USFWS 2016), even a small decrease in DO can significantly reduce habitat quality. Declines in Rainbow Trout downstream from Lake Powell in 2001 and 2007 have been attributed to a combination of elevated water temperatures and periodic DO deficiencies (Makinster 2011).

Recent declines in the abundance of fishes below Glen Canyon Dam have largely been attributed to both low DO and increased water temperatures (Makinster 2011). In 2005, a low DO/high temperature event coincided with much lower recruitment and growth in the Glen Canyon Rainbow Trout fishery (Korman 2012). In 2019, a plume of low DO water with elevated temperatures moved through Lake Powell and contributed to historically low concentrations of DO in the Grand Canyon Dam tailwaters. Low DO events tend to coincide with high temperature events, so it is difficult to separate the negative impacts of one from the other; however, improving DO conditions during elevated temperature events would reduce one source of stress on fishes and benthic communities which, if mitigated, would likely increase fish abundance.

7.0 Mitigation Tools for Low Dissolved Oxygen

Mitigation methods for low DO releases from dams can widely be classified as either aeration or management solutions. Aeration is a process that increases the DO concentration in water, typically for the purpose of increasing water quality. This can be accomplished through entraining a large amount of air in the form of bubbles to increase the air-water contact surface area for maximum oxygen transfer. This surface area may then be increased through either hydraulic or mechanical methods.

Hydraulic methods of aeration use the potential energy of the hydraulic head to mix water. Common structures used for aeration include weirs, spillways, water jets, and closed conduit flow arrangements. Through these structures, similar amounts of air transfer that would typically occur over kilometers in a river can occur at a single site.

Mechanical methods of aeration may include the use of pumps, aeration lines, turbines, or other structures that use energy to actively mix oxygen into water (Tennessee Valley Authority [TVA] 2021). Some of these methods include aeration weirs, artificial destratification, hypolimnetic oxygenation, and turbine aeration. Aeration weirs create a waterfall scenario, greatly increasing the uptake of oxygen by the water. Artificial destratification refers to the process of moving compressed air through perforated pipes located at the bottom of a water column to help to mix oxygen into the lower water strata. Hypolimnetic oxygenation increases DO in water with a pure oxygen distribution system that aerates water in the hypolimnion while preserving a lake's thermal stratification. Turbine aeration mixes air with water inside of a hydropower dam at the turbines. Each of these methods have advantages and drawbacks.

Dam management solutions include adjustments such as releasing varying amounts of water downstream at different times or releasing water from various water supply intakes and outlets (an example of adjusting the water supply intake could include releasing water from different strata of the water column, such as through a selective withdrawal intake) (Gelda 2007).

DO mitigation methods are discussed below individually; however, they can also be used in combination, which may increase the overall effectiveness and reduce collective drawbacks.

7.1 Aeration Mitigation

7.1.1 Aeration Weirs

Aeration weirs are hydraulic aeration structures that are placed downstream from a dam to aerate reservoir outlet waters. Similar to a much smaller dam being placed downstream from a larger dam, they increase water oxygenation and can help maintain a minimum tailwater flow (Figure 6). Although there are other methods to hydraulically aerate water, such as using a hydraulic jump, labyrinth weirs, and shuts, the low-head aeration weirs are typically better, and they cost less to operate (Jaiswal 2019). Weir aeration is commonly used at fish hatcheries and water treatment plants to aerate large volumes of water, as the hydraulic head used for aeration is not as costly as using pumps (TVA 2021).

Figure 6.—Picture of an aerating weir in the downstream channel of the regulating dam in the Nam Kathang River (Descloux 2015).

In general, weir aeration occurs as the water drops over it and forms a free jet, similar to a natural waterfall. Most of the oxygen transfer occurs during the breakup of the jet at the water pool's surface and when the jets impact with the bottom of the pool. As such, the shape, size, and general structure of the weir itself, as well as the water pool, heavily factor into design considerations, as the design of a weir can significantly impact oxygen absorption efficiencies. For example, the shape of a weir defines the water jet shape, which strongly influences oxygen transfer efficiency. Efficiency is strongest with a triangular shape and lowest with a rectangular shape. Additionally, the idyllic tailwater depth at which the jet impacts it is dependent on the drop height and water discharge, wherein ideally air bubbles will penetrate to slightly less than the approximate maximum depth (Baylar 1999). Design standards for aeration of water at Reclamation facilities can be found in the guidance for constructing spillways and other outlet works (LaBoon 2014). These design standards consider the aeration needs of water passed downstream and inform development. Modeling of the aeration that occurs in the spillway of a dam may help predict aeration efficiency of a weir (Urban 2008).

To date, there has been more success of reaerating water from a dam due to installing aeration weirs than with nearly any other aeration method (Long 1997). Continued design refinements have increased aeration efficiency. For example, in Laos, a weir made of hexagonal metallic structures with two consecutive falls has been highly efficient (Descloux 2015). Increases in aeration have also been accomplished through other methods, such as modifying the weirs to resemble piano keys (Sangsefidi 2021). In addition to improvements that can be made to the structures themselves, improvements in DO monitoring methods and refinements in hydraulic modeling capabilities should also be pursued.

Although aeration weirs have been successful at reaerating water from a dam, installation and maintenance of an aeration weir at Glen Canyon Dam may be problematic. The steep walls of the canyon hinder access, and the design of the dam itself does not allow for easy installation of the large-scale aeration weirs required to be effective. If these challenges were overcome, aeration weirs could effectively increase downstream DO with minimal operating costs at this dam.

7.1.2 Artificial Destratification

Artificial destratification is typically used in smaller reservoirs with a strong and undesired stratification to help “turn” the manmade lake. While this method can effectively increase DO in the hypolimnion, mixing of the reservoir brings higher nutrient loads and temperatures into the epilimnion. This may have detrimental impacts on large, older reservoirs, such as Lake Powell, which pass water downstream from lower in the water column strata (Brown & Caldwell, Inc. 1995).

7.1.3 Hypolimnetic Oxygenation

Hypolimnetic oxygenation aerates the hypolimnion while preserving thermal stratification by oxygenating the hypolimnion using pure oxygen gas. The reduced thermal mixing reduces not only cyanobacteria growth but also other issues related to mixing a reservoir. Hypolimnetic oxygenation may be accomplished through side stream oxygenation, bubble plume oxygenation, and/or submerged contact chamber systems.

7.1.4 Side Stream Oxygenation

Side stream oxygenation systems (Figure 7) pump hypolimnetic water to the surface, inject the water with oxygen, then discharge the water back into the hypolimnion. This system has high energy costs associated with the continued pumping of water and maintaining a pressurized chamber; as such, it is not often used in deep reservoirs. Side stream oxygenation has more benefits for shallow lakes and streams, and it does not require significant structure installation at the reservoir bottom (Gerling 2014).

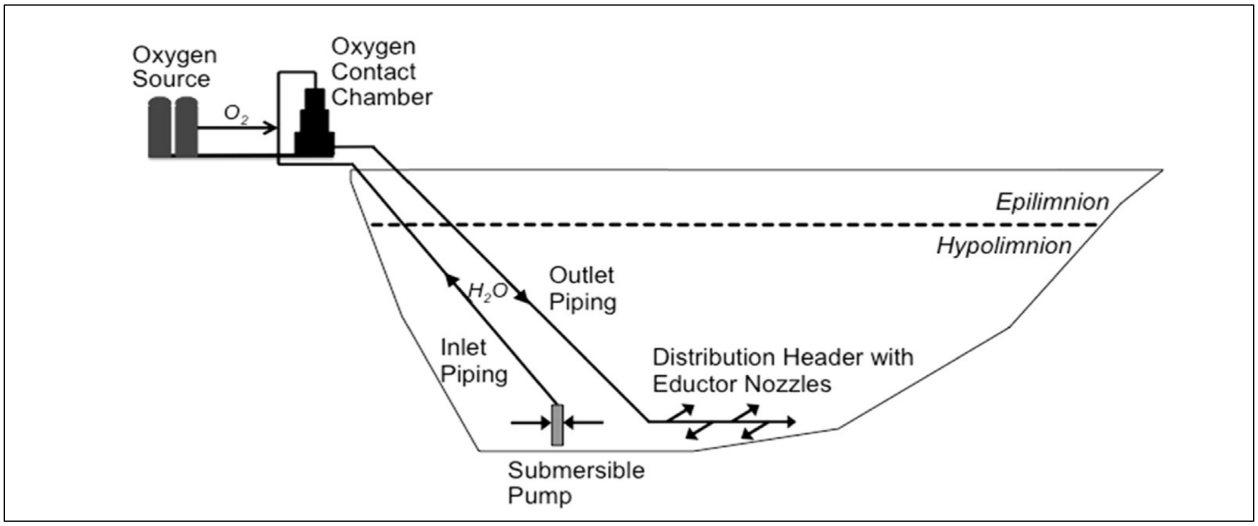

Figure 7.—Schematic of a side stream oxygenation system showing hypolimnetic water drawn to the surface where it is oxygenated then redistributed at the reservoir bottom (Gerling 2014).

7.1.5 Bubble Plume Oxygenation

While a side stream oxygenation system introduces oxygen to water above the surface, bubble plume oxygenation systems use a group of oxygen diffusers located at a lake's bottom and an oxygen source located above the water's surface. This system is designed so the oxygen plume disperses below the thermocline (Figure 8). Bubble plume oxygenation was developed in the 1980s and has been successfully used in several large reservoirs since its development (Brown & Caldwell, Inc. 1995). Advancements have included using a more spread-out diffuser system and finer oxygen bubbles to ensure the bubbles remain below the thermocline to encourage better dissolution of oxygen into the water.

Of the many options for mechanical aeration, bubble plume oxygenation through air diffusion lines on the bottom of a reservoir has proven to be one of the most popular methods. Like aeration weirs, bubble plume oxygenation systems can be found at fisheries and water treatment plants, as they provide a reliable and cost-effective method of oxygenating large volumes of water (Al-Ahmady 2006).

The modern technology of aerating the hypolimnion of waterbodies is based on what was developed in the early 1980s in Switzerland in an attempt to inhibit phosphorous loading in deep lakes (Gachter 1998). It has been employed at many locations ever since for many different aeration purposes. One drawback of the bubble plume oxygenation system is that it has trouble maintaining a well-oxygenated sediment water interface because, in some waterbodies, most of the oxygen is concentrated in the upper levels of the hypolimnion (Mobley 2006). This may not be a negative at Lake Powell, where the penstock intakes are at an elevation typically near the upper level of the hypolimnion.

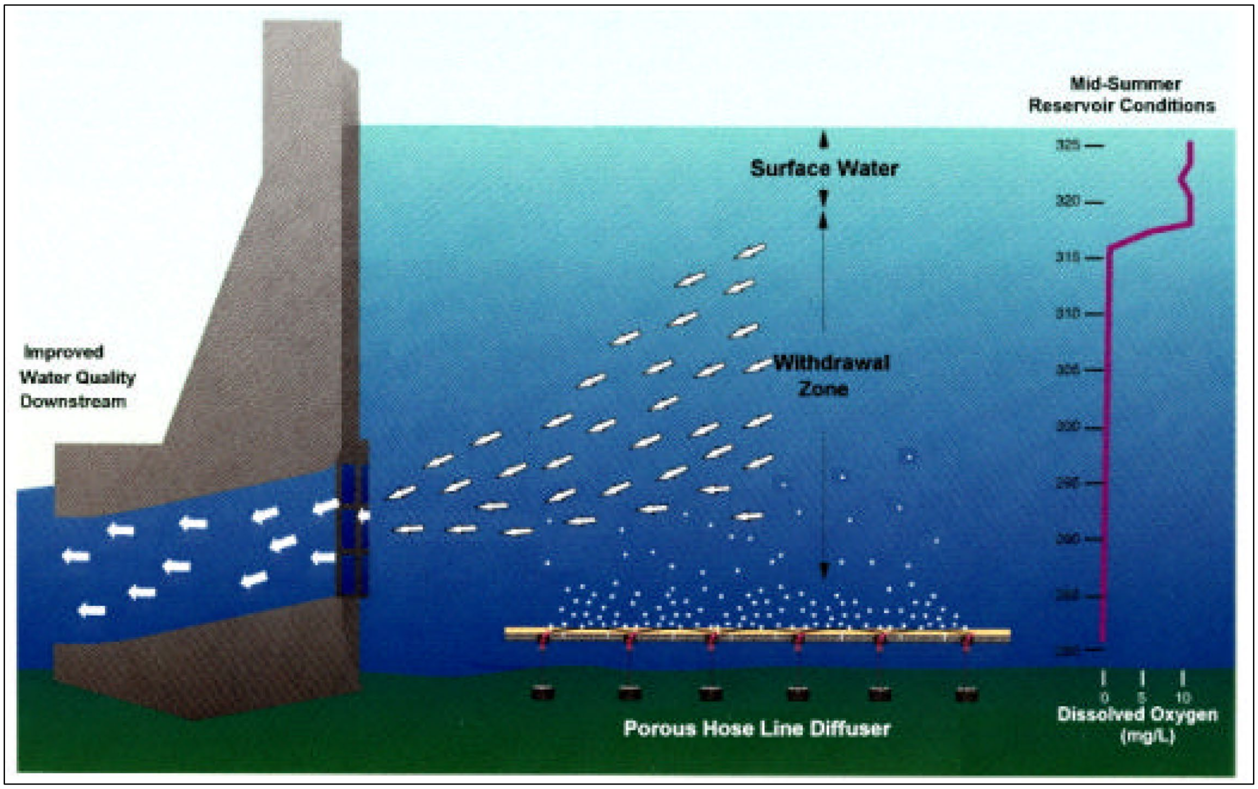

Figure 8.—Schematic view of a bubble plume diffuser and turbine withdrawal (Mobley 2006).

At Douglas Dam in Tennessee, a diffuse deep-water oxygenation system that uses liquid oxygen and an array of 16 diffuser frames to aerate almost 4.5 acres of water directly upstream of the dam is used. The water depth at the dam where the water is being aerated is about 125 feet, and the total impoundment of the dam is approximately 1,408,000 acre-feet of water. This system has effectively improved the downstream DO of water released from Douglas Dam, with minimal upswelling or mixing of the metalimnion. The system's average daily use of pure oxygen exceeds 5 tons/day during the highest use time of year, as it was designed as a "topping off" system to increase DO. A surface water pump is used to provide a baseline for DO improvement (Mobley 1995).

Another bubble plume oxygenation system is operated at Amisk Lake in Canada to increase DO in the hypolimnion and to remediate conditions caused by high internal phosphorous loading. The system is operated year round, with average oxygen injection rates up to 1.4 tons/day during the summer months and up to 0.8 tons/day in winter. These injection rates have improved summer DO concentrations in the hypolimnion from an average of 1.0 to 4.6 mg/L, and they have also reduced phosphorous concentrations in the waterbody near the bubblers (Prepas 1997).

Even though aeration systems are relatively well established as a method to enhance DO in the hypolimnion of waterbodies, they are not always a suitable solution. For example, in 2004, the U.S. Army Corps of Engineers deployed an aeration system at Willow Creek Lake to increase hypolimnetic DO. When the system was installed and tested, it destratified the reservoir, resulting in an increased density and duration of harmful algal blooms. Due to these issues, use of the system was discontinued in 2008 (U.S. Army Corps of Engineers 2019).

There are plentiful case studies on bubble plume aeration, as it is one of the more established methods to aerate a waterbody upstream of a dam. The TVA has been one of the leaders in this field for decades. Initially, they employed bubble plume aeration to supplement other DO enhancement methods, then it was used as a stand-alone enhancement method when less expensive options were not viable. The TVA came to use bubble plume aeration as a stand-alone enhancement exclusively more often, as its advantages became more apparent and justified the higher costs (Moore 2015). The TVA developed an early set of case studies on aeration lines used to increase DO in reservoirs, including an analysis of their performance at six TVA Dams. Although dated, this analysis is a valuable reference; it helps us understand the details of design challenges associated with this aeration method, as it details the basics of system functioning (Mobley 1997).

7.1.6 Speece Cones

The term "Speece cone" is a common name given to a low-pressure downflow bubble contact chamber that functions to saturate water with air (Figure 9). Speece cones can be deployed above water, similar to side stream oxygenation systems, but with low pressure. However, for the purposes of hypolimnetic aeration of large waterbodies, they are typically employed at the bottom of the reservoir as submerged contact chamber oxygenation systems, which reduces pumping expenses (Horne 2019). The conical chamber functions as a downflow bubble contact chamber used for high-efficiency, low-pressure oxygen transfer. The chamber itself has no moving parts; maintenance is limited to pumps, diffusers, and intakes (CH2M Hill 2013).

Through deploying a Speece cone mounted to the bottom of a lake, a submerged pump draws water from the hypolimnion to the top of the cone, where it mixes with oxygen supplied from an onshore facility. A common variation of this type of system is often referred to as a Speece cone oxygenation system. This type of system has been successful in aerating water in large reservoirs, with less chance of turning the thermocline than bubble plume systems, and the oxygenated water has a greater chance of remaining toward the bottom of the hypolimnion (Horne 2019).

Speece cones have been used at a wide range of locations for both wastewater treatment as well as hypolimnetic oxygenation, and a wide range of case studies have been developed on their design. In addition to Indian Creek Reservoir discussed above, one well documented location is the Camanche Reservoir wherein a large, submerged contact chamber oxygenation system was employed successfully long-term as the only oxygenating system in the reservoir. The reservoir impounds up to 417,000 acre-feet and has an approximate depth at dam of up to 60 feet. The system is designed to provide up to 8 tons/day of oxygen and has successfully maintained DO levels above 5 mg/L at the dam (Brown & Caldwell, Inc. 1995).

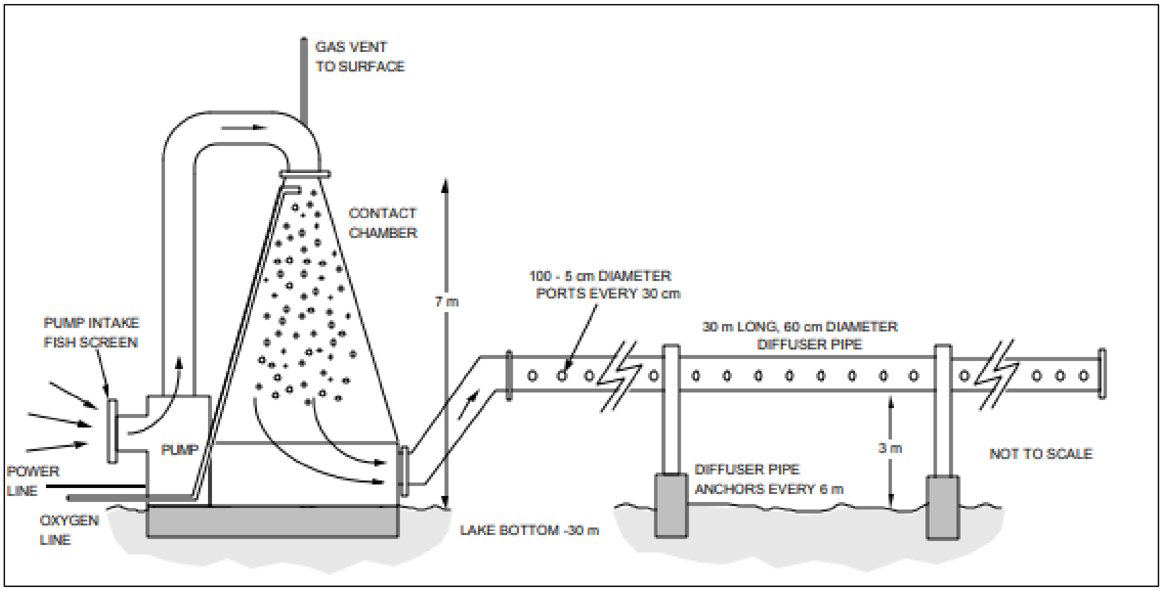

Figure 9.—Schematic of a Speece cone oxygenation system (Brown & Caldwell, Inc. 1995).

7.1.7 Turbine Aeration

Turbines can be modified with air injection systems to mix oxygen with water inside a hydropower dam. These systems can be an appealing option to increase DO in waters downstream from a hydropower dam, as maintenance costs are low, the amount of oxygen used is less (if injecting pure oxygen) than in hypolimnetic oxygenation systems, and the aeration effects can be more controllable than with other methods (Key 2009).

Turbine aeration systems can be designed in a variety of ways. For example, large-scale design considerations include where aeration occurs within turbines (central, peripheral, and distributed) (Figure 10). Each of these locations of air injection impact the efficiency of the aeration system at different portions of the turbine's operational range (Rohland 2010). In addition to air injection location within the turbine itself, there are a significant number of other design considerations that can impact the efficiency of turbine aeration. Fortunately, there are plentiful case studies: in 2017, 178 aerating turbines at 58 hydropower plants existed in the United States, with 137 of these being vertical francis turbines with a capacity over 5 megawatts, similar to those at Glen Canyon Dam (March 2017).

An alternative method to air injection in turbines involves using a draft tube to encourage air mixing in the turbines through a passive air intake. This method uses the pressure change as water flows over the turbine blades to draw air through the draft tube to mix with the water. This has been attempted at Canyon Ferry Reservoir, with multiple modifications, initially without success. With initial modifications, sufficient air was not drawn into the draft tube passively. However, after installing a blower to force air through the draft tube, acceptable DO levels were reached, but only when the turbines were running at a reduced load (Reclamation 2007).

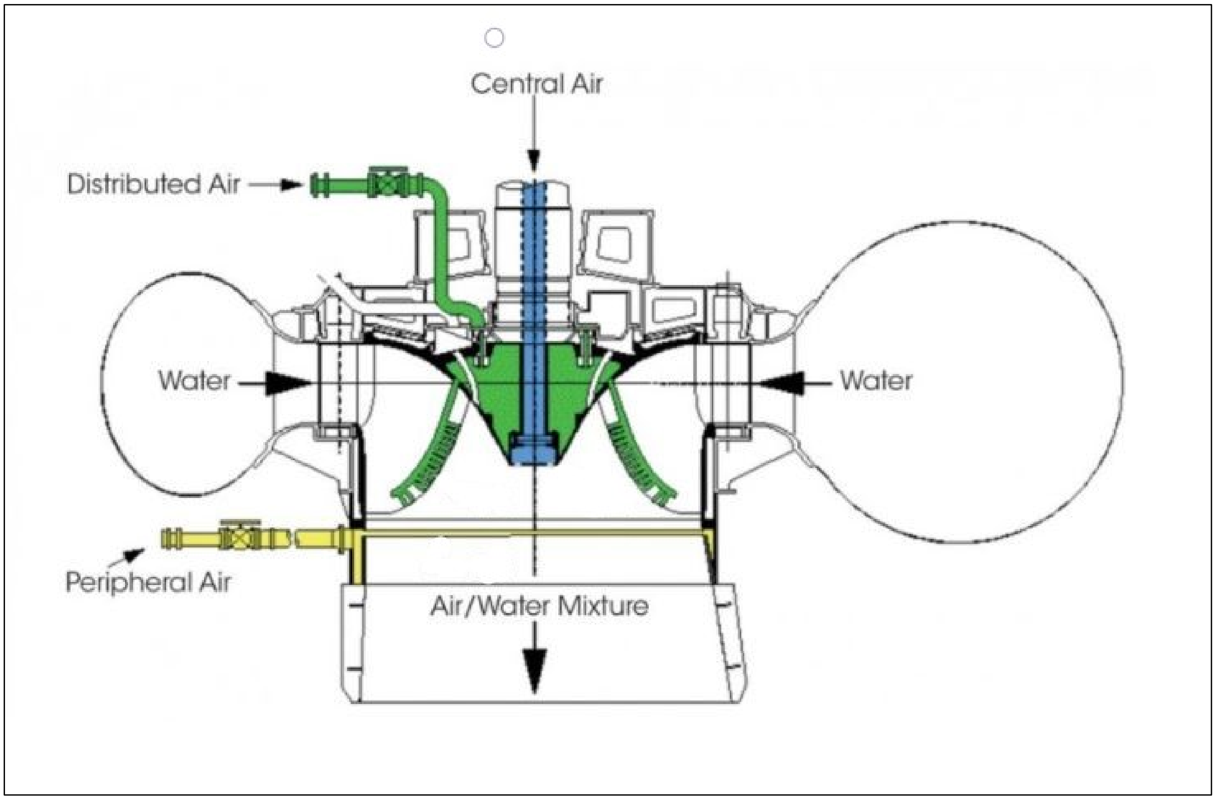

Figure 10.—Schematic representing three methods for an auto-venting turbine, including central (blue), distributed (green), and peripheral (yellow) (Rholand 2009).

Other experiments have been successful in increasing the DO of water passed through a turbine without requiring forced air. For example, at Deer Creek Reservoir in 1992 through 1994, passive aeration was able to improve DO levels from about 1.7 to 2.7 mg/L. The primary cost was the loss of power generated due to running the turbines less efficiently and an increased tailwater level (Wahl 1995).

In addition to the above methods of passive turbine aeration, “rough zone” operation may be conducted wherein a turbine is operated to produce an increased vacuum in order to draw more air through draft tubes, vacuum breaker systems, or snorkel tubes. Operating a turbine in the rough zone induces cavitation which, in turn, increases the vacuum inside a turbine. During cavitation, air is mixed with water, which increases DO levels, but it may damage turbines, decreasing power grid reliability and increasing maintenance costs. In theory, rough zone operation is possible without damaging turbines, but it does require operation at reduced efficiency, which decreases the power generated, and it may not be consistent within a dam managers statutory authority.

7.1.8 Penstock Intake Aeration

A penstock aeration system injects either pure oxygen or natural air at point sources near the penstock inlet (Figure 11) so bubbles are swept along through the penstock, which oxygenates water released from the dam. These systems are best applied to dams with long, deep penstocks that can provide sufficient time to increase oxygen transfer and have a minimum number of penstock inlet locations that need to be outfitted with aeration equipment (Reservoir Environmental Management, Inc., and HDR, Inc. 2010). The penstocks at Glen Canyon Dam are 500-foot long, 15-foot-diameter steel tubes that carry water from the reservoir to the turbines. They should provide sufficient surface area and length for aeration (Vernieu 2009).

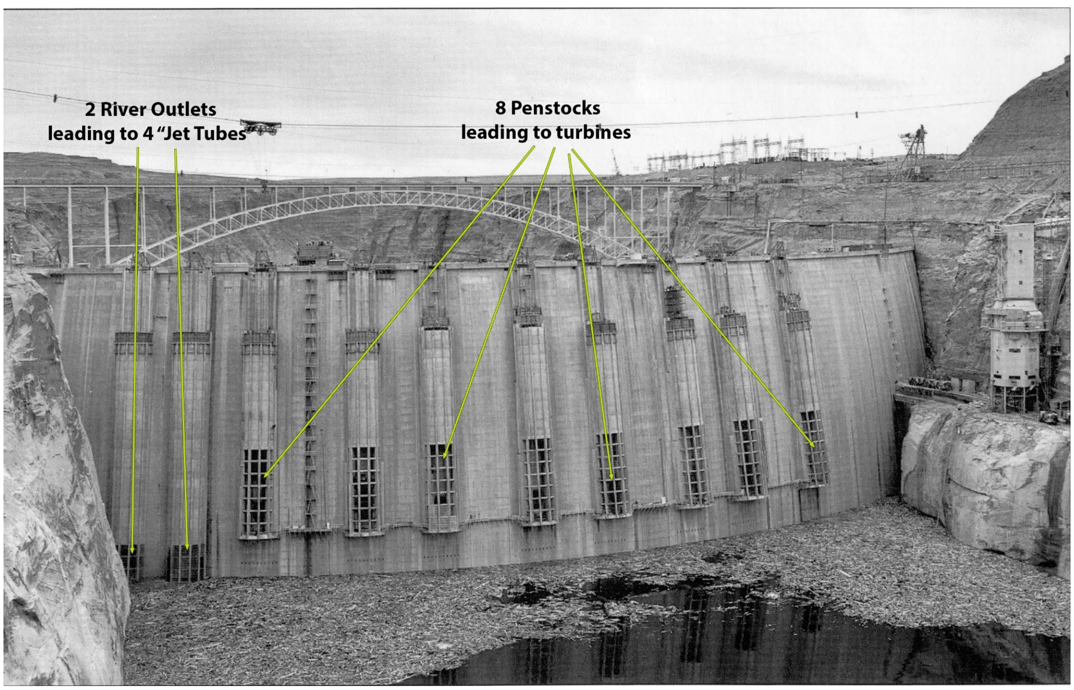

Figure 11.—Upstream face of Glen Canyon Dam circa 1964 showing the penstocks. Here the water level is below the penstocks but above the dam outlets (Bureau of Reclamation/A.E. Turner).

Similar to turbine aeration systems, one disadvantage is that penstock aeration systems can only increase oxygen during hydropower operation. An additional disadvantage is that, compared to hypolimnetic aeration and turbine aeration, controlling the system can be more difficult because, at lower penstock flows or at higher volumes of air injection, much of the air may not be captured by the penstock intake. This limits how many low DO events can be mitigated (Reservoir Environmental Management, Inc., and HDR, Inc. 2010).

7.2 Management Mitigation

7.2.1 Selective Withdrawal Structures

Selective withdrawal structures allow project operators to release water from several levels (Figure 12) within a reservoir. They may release warmer water, which carries more oxygen, or colder, less oxygen-rich waters (Sherman 2001). Reclamation has multiple case studies for reference to assist in understanding the benefits and limitations of a selective withdrawal system. These structures were developed primarily to control temperature releases, but they also have a documented ability to help control DO concentrations of released waters (Svodoba 2019).

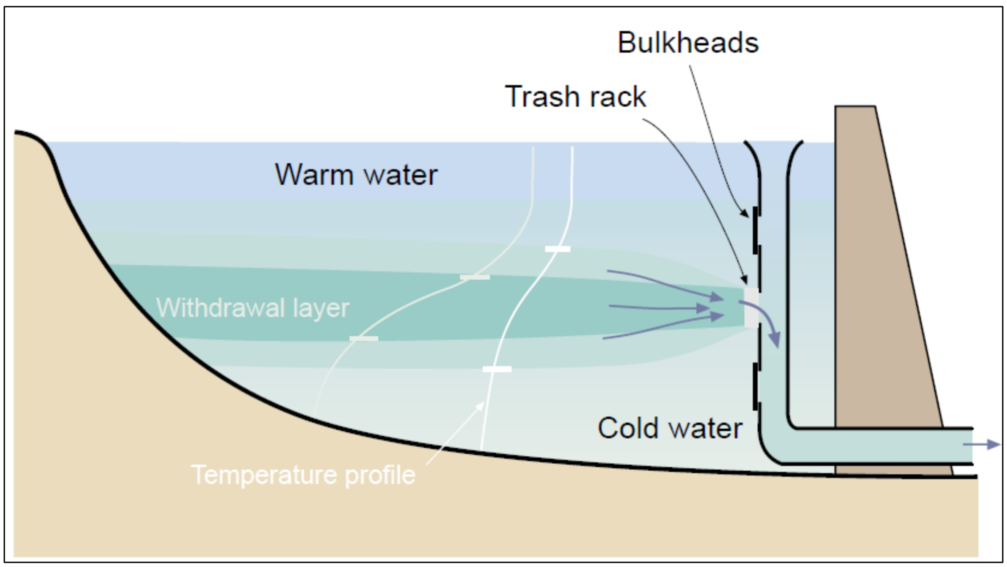

Figure 12.—Schematic of a selective withdrawal structure demonstrating the ability to remove water from a targeted strata within the water column (Sherman 2001).

The powerplant penstock intakes at Glen Canyon Dam provide little option for controlling the water level that is passed through the penstocks. The penstocks have an average 100-foot-thick withdrawal zone and a near-field acceleration zone of about 100 feet from the dam face depending on stratification, the wind, the withdrawal rate, and other factors (Vermeyen 2011). Reclamation has modeled a multilevel intake that withdraws water through an opening cut into the top of an existing trash-rack structure to allow warmer, higher oxygen water to flow into the turbines and downstream, which could help improve downstream water quality. However, due to cost restrictions and few anticipated benefits, the project has not moved forward (Vermeyen 1999).

7.2.2 High Flow Events

Water management solutions at Glen Canyon Dam for increasing downstream DO at Lake Powell are currently limited to high flow events through the outlet works, which bypass the power turbines. While high flow events do effectively increase oxygen levels below the dam, the benefits quickly diminish at the return to normal flows (Reclamation 2016). Another limit to this management option is that the bypass tubes may only be used to avoid anticipated spills from Lake Powell, and the costs associated with any release that bypasses the powerplant for reasons other than to avoid a spill must be paid for by the Glen Canyon Dam Adaptive Management Program (Reclamation 2016) partially because, at Glen Canyon Dam, the electricity sales are the only direct form of revenue; the reservoir's waters are not sold (Thompson 2022).

An additional limitation of management solutions to low DO events at Glen Canyon Dam is that the outlets and spillways were never designed to be used long term. The intent was for all of the water routinely flowing from Glen Canyon Dam to go through the eight penstocks to generate electricity. If the dam's outlet works were to be used regularly to bypass water around the penstocks, significant redesign of the bypass outlet works would likely be necessary to ensure they could safely handle the increased use. For now, the water quality of Lake Powell at its penstocks typically defines the water quality of Glen Canyon Dam releases (USGS 2020).

7.3 Feasibility of Using Dissolved Oxygen Mitigation Tools at Glen Canyon Dam

Regardless of the method used to mitigate low DO events downstream from Glen Canyon Dam, it will take significant engineering analyses to determine what process is the most feasible and economical. While it is beyond the scope of this report to recommend a specific technology for increasing DO, it is our aim to provide a brief overview of the state of technology and how it may be applied at the dam. Below we provide a summary of the overall feasibility of using various DO mitigation tools at Glen Canyon Dam.

Upstream changes that might reduce organic loads have had relatively little success because, unless contaminant sources are point sources, such as effluent streams, manufacturing plants, or something similar, it is difficult to reduce the amount of organic matter entering a reservoir. Much of the organic matter that flows downstream into Lake Powell comes from sources that are spread over a very wide area; it may be from anywhere in the very large upstream watershed. With an increasing watershed size, the problem of limiting inputs grows exponentially.

Of the methods discussed above to increase DO below Glen Canyon Dam, two methods have a high potential to effectively mitigate low DO events with minimum drawbacks: turbine aeration and hypolimnetic aeration. Both have a reasonably well-developed design and are efficient at controlling the DO in waters passed through large dams.

Turbine aeration is an appealing option to increase DO levels. It allows for significant control over the oxygenation of released waters, as oxygen input to water passing through the dam can be immediately controlled. Turbine aeration also uses less oxygen, if pure oxygen injection is used, than in hypolimnetic oxygenation, as only the water passing through the dam is oxygenated. Additionally, the components of this system are easy to access and maintain because they are not at the bottom of the reservoir. However, this method can require significant alteration to the turbines at a high expense, and some variations of turbine aeration systems decrease turbine efficiency. Alternatively, some variation of rough zone operation can be easily implemented, though at a cost to hydropower generation. Running in the rough zone may or may not produce much benefit, as the amount of air used will depend on how well balanced the turbines can remain under this scenario.

Hypolimnetic aeration consists of a broad class of methods, as discussed above, but the most applicable to increasing downstream water quality at Glen Canyon Dam are bubble plume aeration and Speece cones. The primary difference between the two is where water oxygenation occurs. In Speece cones, oxygenation occurs in a chamber, and in bubble plume aeration, oxygenation occurs in an open waterbody. Both systems have proven to be effective at aerating a reservoir's hypolimnion upstream of a dam and, in turn, have increased the DO of water passed through the dam. One advantage of hypolimnetic aeration is that it does not require any direct modification to the dam or any of its facilities, although it does use more oxygen than turbine aeration. It also increases DO within the reservoir near the dam, which may benefit the aquatic ecosystem.

The cost of using pure oxygen can be high in either turbine or hypolimnetic aeration systems, but neither should not be discounted. In order to use pure oxygen for aeration, either an oxygen generator must be installed onsite, or oxygen must be delivered, both of which are associated with a significant cost. Many hypolimnetic aeration systems in use today have moved toward onsite oxygen generators for both reliability and ensuring availability of oxygen when needed. The advantages of using pure oxygen instead of atmospheric air include higher solubility, higher system transfer efficiencies, reduced size of mechanical devices due to lower volumes needed, and lower recirculation rates, all of which allow for maintenance of higher DO levels in oxygenated waters and help to not disturb the metalimnion during hypolimnetic aeration.

In regard to oxygen transfer efficiency alone, pure oxygen has significant advantages: transfer efficiencies of 10 percent for air and 20–30 percent for oxygen inline diffusers. Turbine aeration has transfer efficiencies of 20–40 percent for air and 60–90 percent for oxygen (Herrmann-Heber 2021). These differences in efficiencies arise because air itself is only 21 percent oxygen; therefore, a much higher volume is needed to achieve the same results. The transfer efficiency of oxygen is partially driven from the saturation deficit, meaning the higher the target DO concentration, the more oxygen will be required. As the saturation limit is approached, there are diminishing returns of adding more oxygen the closer we get to saturation. The DO saturation limit of water is also regulated by water temperature, salt content, and depth. Colder, deeper fresh water has a higher saturation limit than warmer, saltier, shallow water (Al-Ahmady 2006).

Assuming that a 100-percent transfer efficiency is attainable, and given that Glen Canyon typically releases at a rate of 8–10,000 cubic feet per second (ft^3/s) on average during months low DO is likely to occur within the reservoir, there would be approximately 22 tons of pure oxygen/day required to achieve a 2 mg/L increase of DO at a discharge of 8,000 ft^3/s. As 100-percent oxygen transfer is not possible, the real amount of oxygen used would be higher, and that amount of oxygen should serve as a starting point for any feasibility study at a facility the size of Glen Canyon Dam under normal flow conditions.

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