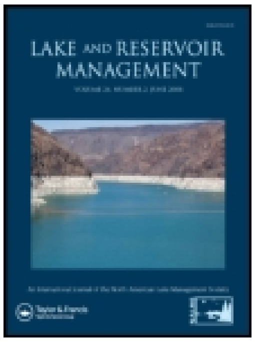

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A Review of the Effects of Hypolimnetic Oxygenation on Lake and Reservoir Water Quality

Marc W. Beutel & Alex J. Horne

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Marc W. Beutel
University of California, Berkeley
Civil and Environmental Engineering Department
Berkeley, California, 94720

Alex J. Horne
University of California, Berkeley
Civil and Environmental Engineering Department
Berkeley, CA 94720

ABSTRACT

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Hypolimnetic aeration is an increasingly common management technique that aerates the hypolimnion while preserving thermal stratification. While most hypolimnetic aeration systems use air as an oxygen source, use of pure oxygen is growing. Potential benefits of hypolimnetic oxygenation include maintenance of an oxygenated source of cool water to meet consumer and environmental needs, decreases in internal nutrient loading, inhibition of sediment release of problematic reduced compounds, and maintenance of summertime habitat for cold-water fish, zooplankton and zoobenthos. A number of short-term experimental oxygenation systems were operated in the 1970s, but large scale systems were not implemented until the 1980s. Deep oxygen injection systems have been operating in Lakes Sempach, Baldegg, and Hallwil, Switzerland, since the early 1980s to ameliorate cultural eutrophication. Deep oxygen injection has also been used to increase DO in hydroelectric releases from a number of large reservoirs in the southern USA. A comprehensive study of physical, chemical and biological impacts of deep oxygen injection was performed at Amisk Lake, Alberta, from 1988-1993. In the early 1990s, downflow oxygen bubble contact chambers (Speece Cones) were installed in Newman Lake, Washington, and Camanche Reservoir, California, mainly to improve the quality of cold-water fishery habitat. Compared to hypolimnetic aeration, oxygenation results in higher hypolimnetic dissolved oxygen levels, lower levels of induced oxygen demand, and maintenance of more stable thermal stratification. Operational experiences over the past two decades confirm that hypolimnetic oxygenation is a successful management strategy with numerous water quality benefits.

Key Words: hypolimnetic oxygenation, stratification, anoxia, orthophosphate, ammonia.

Stratified eutrophic lakes are characterized by summer and fall hypolimnetic anoxia (Wetzel 1984, Horne and Goldman 1994). Anoxia occurs when respiring microorganisms biodegrade algal biomass that has sunk into the hypolimnion. Thermal stratification prevents atmospheric reaeration of the hypolimnion and eutrophic lakes are too turbid to permit photosynthesis below the thermocline. Hypolimnetic aeration is one management strategy used to ameliorate summertime hypolimnetic anoxia while maintaining thermal stratification (Cooke et al. 1993). Traditionally, aeration systems have used air as an oxygen source. However, beginning in the early 1970s a handful of researchers advocated the use of commercially available pure oxygen to aerate hypolimnia (Speece 1971, Fast and Lorenzen 1976). While a number of system designs were proposed, only over the past two decades have a substantial number of hypolimnetic oxygenation systems been implemented. A number of reviews of hypolimnetic aeration have been published (Taggart and McQueen 1981, Pastorok et al. 1981, McQueen and Lean 1986), and some have discussed hypolimnetic oxygenation (Fast and Lorenzen 1976, Speece 1971, Pastorok et al. 1982). However, there is no comprehensive review of current hypolimnetic oxygenation systems.

This paper reviews the benefits of maintaining an oxic hypolimnion, and briefly discusses the advantages of oxygenation over other common aeration techniques. The paper then covers the historical development of hypolimnetic oxygenation, and reviews, in detail, informative and well documented hypolimnetic oxygenation case studies. We have placed particular emphasis on quantifying the effects of hypolimnetic oxygenation by examining water quality before and during system operation.

Benefits of Oxic Hypolimnia

The potential benefits of maintaining an oxic and cool hypolimnion are numerous. In some cases, cool, oxic hypolimnetic water is essential to satisfy the needs of downstream biota (Horne 1995), or to meet the requirements of potable and industrial water users (Bernhardt 1967). Maintenance of oxic conditions generally decreases sediment release of orthophosphate (ortho-P) and ammonia, thereby ameliorating eutrophication. Primary sources of ortho-P release include iron complexes which release phosphate when they dissolve under reduced conditions (Boström et al. 1988), and microorganisms which release ortho-P during metabolism under anoxic conditions (Gächter and Meyer 1993). Oxic conditions can stimulate sediment nitrification and subsequent denitrification, resulting in a net loss of nitrogen from the system (Ahlgren et al. 1994, Rysgaard et al. 1994). Some sediments appear to chemically bind ammonia under oxic conditions (Jones et al. 1982). Oxic conditions can also stimulate bacterial growth resulting in increased rates of nitrogen assimilation (Graetz et al. 1973). Another benefit of maintaining an oxic hypolimnion is the inhibition of the release of problematic reduced compounds such as iron, manganese and sulfide from anoxic sediments. These compounds degrade the aesthetic quality of drinking water and can increase potable drinking water treatment costs (Sartoris and Boehmke 1987). In some cases, reduced compounds can exhibit toxicity to aquatic organisms (Ingols 1975, Horne 1989).

The biological effects of hypolimnetic aeration or oxygenation can also be beneficial. During summertime in many eutrophic lakes, cold-water fish have poor habitat, and must survive between a layer of anoxic bottom water and warm surface water (Cooper and Koch 1984). By oxygenating the hypolimnion, aeration provides cold-water fish with an oxygenated, cool water summertime habitat (Fast et al. 1975, Fast 1993, Doke et al. 1995, Aku et al. 1997). Oxic hypolimnia may also provide respiring zooplankton with a dark daytime refuge in which to avoid predation (Fast 1971, Field and Prepas 1997). Benthos diversity and density tends to increase with oxic conditions in the sediment (Jónasson 1978, Pastorok et al. 1981, Sartoris and Boehmke 1987, Doke et al. 1995). A decrease in internal nutrient loading combined with improved zooplankton habitat, both a result of aeration or oxygenation, may cause a decrease in algal biomass or a shift to more beneficial species (Bürgi and Stadelmann 1991, Prepas and Burke 1997, Horne et al. in prep). Finally, oxic conditions may also help to decrease mercury contamination in lake biota by reducing rates of sediment mercury release (Herrin et al. 1998).

Advantages of Hypolimnetic Oxygenation

Techniques employed to solve hypolimnetic anoxia can be broadly grouped into three categories: artificial destratification, hypolimnetic aeration, and hypolimnetic oxygenation. Table 1 qualitatively compares various aspects of these methods. See Pastorok et al. (1981, 1982) for a detailed discussion and comparison of aeration techniques.

The simplest method is artificial destratification where compressed air is injected through perforated pipes or course diffusers located at the bottom of the water column (Pastorok et al. 1981, Cooke et al. 1993). Induced mixing from the rising air bubbles produces vertical mixing, thereby inhibiting the formation of thermal stratification. Destratification increases bottom water dissolved oxygen (DO) by redistributing photosynthetically produced oxygen from surface to bottom waters, as well as increasing contact time between water and the atmosphere. The main drawback of artificial destratification is increased summer bottom water temperatures. Increased temperatures degrade cold-water fishery habitat, and warm discharges from destratified reservoirs may impair downstream biota. In drinking water reservoirs, water may be too warm for potable and industrial water use, and a homogenized water column precludes the optimization of raw water quality via selective depth withdrawal.

Hypolimnetic aeration is another common management strategy used to maintain oxic hypolimnia while preserving thermal stratification (McQueen and Lean 1986, Cooke et al. 1993). The technique uses a confined air-lift system where air bubbles are injected at the bottom of an air-lift tube, and oxygen is transferred to the water as the air-water mixture travels up the tube. Aerated water is then redistributed into

Table 1.–Comparison of various lake aeration techniques.

Operational Feature	Artificial Destratification	Hypolimnetic Aeration	Hypolimnetic Oxygenation
Gas used	air	air	pure oxygen
Popularity	high	moderate	low
Destratification potential	high	moderate	low
Hypolimnetic heating	high	moderate	low
Fall hypolimnetic DO	moderate	low	high
Induced oxygen demand	high	moderate	low
N_2 gas supersaturation	low	moderate	low
Efficiency	low	low	high
Operational Flexibility	low	low-moderate	high
Warm water fishery	yes	yes	yes
Cold water fishery	no	yes	yes
Raw water selective withdrawal	no	yes	yes

the hypolimnion. Lake managers have utilized both full-lift systems that raise the water to the surface (Bernhardt 1967, Ashley 1983, Soltero et al. 1994) and partial-lift systems that raise water partially up the water column (Garrell et al. 1977, Steinberg and Arzet 1984, Heinzmann and Chorus 1994). Lake managers have also used layer hypolimnetic aeration where a number of aerators with inlets and outlets at varying depths aerate and circulate layers of the hypolimnion isolated by functional thermoclines (Kortmann et al. 1988, 1994). Advantages of this method include greater aeration efficiency, maintenance of stronger thermal stratification, and increased operational flexibility.

By maintaining a cool hypolimnion, hypolimnetic aeration avoids many of the problems associated with bottom water warming caused by artificial destratification. However, there are a number of potential problems associated with the method. The oxygen transfer efficiencies of most hypolimnetic aeration techniques, the mass increase in DO of treated water divided by the oxygen mass in the air pumped through the aeration system, are low ranging from 12% (Smith et al. 1975) to 50% (Bernhardt 1967). Thus, aeration units may need to operate at high recirculation rates. This leads to elevated levels of turbulence within the hypolimnion that can increase sediment oxygen demand (Smith et al. 1975, Ashley 1983, Moore et al. 1996). As a result of low transfer efficiencies coupled with induced oxygen demand, a number of aeration systems have been unable to maintain even low levels of DO in the hypolimnion (Smith et al. 1975, Soltero et al. 1994). Large lakes may require the installation of numerous aeration units, and in some case, these large systems produced enough turbulence to cause accidental destratification (Heinzmann and Chorus 1994). In addition, high levels of mixing in the hypolimnion can increase rates of eddy diffusion of nutrients upward through the thermocline (Steinberg and Arzet 1984) and promote the diffusion of ammonia from sediment into overlaying water (Höhener and Gächter 1994). Finally, the introduction of compressed air that predominantly consists of nitrogen may lead to elevated levels of dissolved nitrogen gas in the hypolimnion and the formation of gas bubble disease in fish (Fast et al. 1975).

Hypolimnetic oxygenation is the newest and least common aeration techniques used to prevent hypolimnetic anoxia. Like hypolimnetic aeration, it preserves thermal stratification, however pure oxygen rather than air is used. Three types of systems, described in detail in the next section, are currently in use. They include side stream pumping (Boardman 1998), deep water oxygen injection (Imboden 1985, Prepas and Burke 1997, Mobley and Brock 1995), and submerged downflow bubble contact chambers (Speece 1994, Horne 1995). The primary advantage of hypolimnetic oxygenation is that the solubility of pure oxygen in water is roughly five times that achievable via aeration, since air is only about 20% oxygen. For example, injection of pure oxygen at a depth of 30 m into a 10 °C hypolimnion theoretically results in a DO concentration in excess of 150 mg·L^{-1}, but only around 30 mg·L^{-1} using air. A second advantage of hypolimnetic oxygenation systems is their high transfer efficiencies (% uptake of delivered oxygen) which generally range from around 60% (James et al. 1986) to greater than 80% (Speece 1994, Mobley and Brock 1995).

As a result of higher oxygen solubility and higher system transfer efficiencies, the size of the mechanical devices and recirculation rates needed to deliver an equivalent amount of oxygen using pure oxygen rather than air are greatly reduced. This avoids a number of the disadvantages associated with traditional aeration systems. Lower recirculation rates minimize turbulence introduced into the hypolimnion, thereby minimizing induced oxygen demand (Moore et al. 1996). High oxygen delivery rates and low induced oxygen demand allow for the maintenance of high levels of DO in oxygenated hypolimnia throughout the stratified period (Thomas et al. 1994, Horne 1995, Prepas and Burke 1997). Smaller oxygenation systems can also oxygenate large lakes and reservoirs without the potential for accidental destratification (Imboden 1985, Horne 1995). Additional advantages of hypolimnetic oxygenation include avoidance of hypolimnetic dissolved nitrogen supersaturation (Fast et al. 1975) and substantial decreases in system energy use (Speece 1994).

Historical Overview of Hypolimnetic Oxygenation

Side Stream Pumping Systems

One of the first reported applications of hypolimnetic oxygenation was a side stream pumping system (SSPS) used in Ottoville Quarry, Ohio, during the summers of 1973 and 1974 (Fast et al. 1975, Fast et al. 1977). Hypolimnetic water was pumped onto shore, injected with oxygen, then discharged back into the hypolimnion (Fig. 1). A similar side stream pumping system was used in Attica Reservoir, New York, around 1973 (Fast and Lorenzen 1976). However, pumping induced enough turbulence to prematurely destratify the shallow reservoir. Since 1997, a SSPS has operated in a shallow, weakly stratified Australian impoundment on the Canning River with a history of bottom water anoxia and noxious algal blooms (Boardman 1998). In 1997, a total of 7.5 t of oxygen was delivered by the SSPS and a much larger system was used successfully during the summer of 1999. Since oxygenation, water column ammonia, ortho-P, sulfide, iron and manganese have all decreased.

Deep Oxygen Injection Systems

Speece (1971) first proposed the use of a deep oxygen injection system (DOIS) for the oxygenation of lake and reservoir hypolimnia. He suggested injecting pure oxygen through a network of diffusers at the lake bottom. Oxygen would dissolve into surrounding water as a buoyant mixture of oxygen bubbles and water ascends up the water column. The oxygenated plume would rise until it reached neutral buoyancy then stop and spread out horizontally. The oxygenation system would be designed and operated so that the plume would spread out below the thermocline, thereby maintaining thermal stratification.

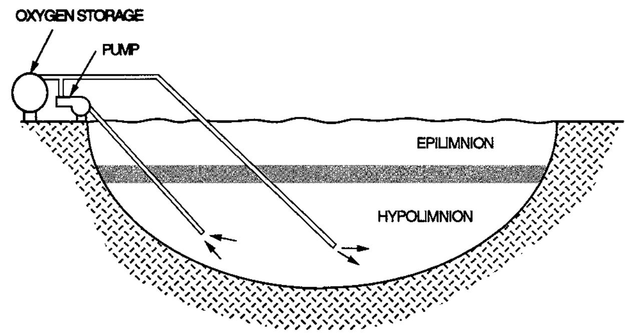
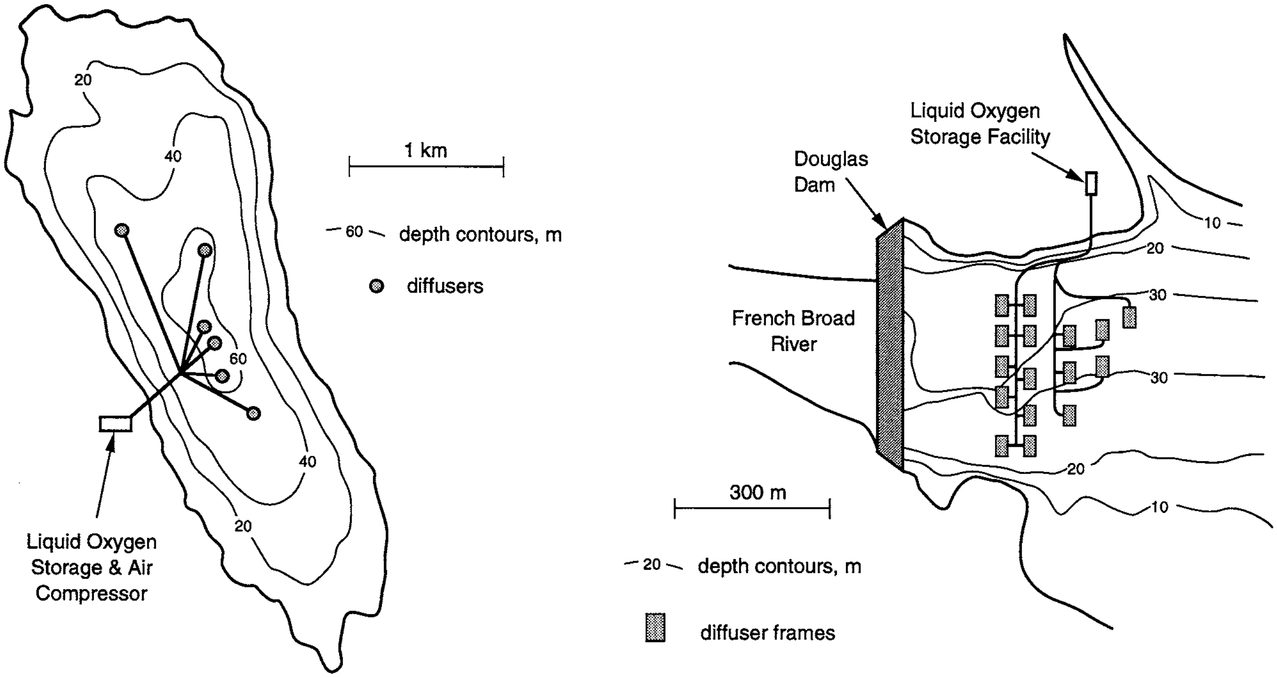


Figure 1.–Schematic of side stream pumping system used in Ottoville Quarry, Ohio, and Canning River, Australia. Not to scale. Modified from Fast et al. (1975)

In the early 1970s, the Tennessee Valley Authority (TVA) began examining the feasibility of using DOIS for reaeration of low DO hydroelectric reservoir discharges at Fort Patrick Henry Dam, Tennessee (Nicholas and Ruane 1975). Ten frames, each roughly 3 m by 2 m and supporting fine bubble diffusers, were installed just upstream of the dam. During operation, stratification was maintained and transfer efficiency ranged from 30-90%. Peak efficiencies were obtained using low oxygen input rates and small-pore diffusers. Since then, the TVA has installed DOIS in over half a dozen reservoirs ranging in volume from 230 to 1,800 million m^3. System oxygen delivery rates range from 15 to 150 t d^{-1}. A DOIS (Fig. 2B) now in operation at Douglas Dam, Tennessee, has successfully oxygenated large turbine discharges since 1993 (Mobley and Brock 1995).

The U.S. Army Corps of Engineers (USACE) also examined the use of DOIS for aeration of low DO hydroelectric reservoir releases. During the fall of 1975, Speece et al. (1976) monitored the performance of an experimental DOIS in Thurmond Lake (formerly Clark Hill Lake), Georgia. Oxygen transfer efficiencies over 90% were achieved by injecting small oxygen bubbles far upstream of the dam. Based in part on these experimental results, a DOIS was designed and installed in nearby Richard B. Russell Lake, Georgia, a large peaking hydroelectric facility located on the Savannah River (James et al. 1986, Mauldin et al. 1988). The system, which has an oxygen delivery



A. Lake Baldegg, Switzerland B. Douglas Dam, Tennessee

Figure 2.–Arrangement of deep oxygen injection diffusers in a) Lake Baldegg, Switzerland and, b) Douglas Dam, Tennessee. Modified from Imboden (1985) and Mobley and Brock (1995).

capacity of over 100 t d^{-1}, has maintained 6 mg $\cdot L^{-1}$ of DO in turbine releases since 1985.

A DOIS has also been used in an attempt to control internal nutrient loading in a number of large, deep lakes. In Switzerland, Lakes Baldegg (Fig. 2A), Hallwil and Sempach have been oxygenated during the summer and fall since the early 1980s (Imboden 1985, Gächter and Wehrli 1998). The fact that both external and internal control measures were implemented coincidentally makes it difficult to determine the effects of oxygenation. The effects of a DOIS in countering eutrophication in Amisk Lake, Canada, have been extensively documented (Prepas et al. 1997). Oxygenation improved water quality, significantly lowering levels of hypolimnetic ortho-P and ammonia.

Submerged Contact Chamber Systems

Whipple et al. (1975) designed and operated the first hypolimnetic oxygenation system that used a submerged contact chamber (Fig. 3A). The system consisted of a rectangular chamber suspended in the hypolimnion from a raft. The chamber had a baffle dividing it into two sides. On one side, oxygen was discharged at the base of the chamber from diffusers fed from an onshore liquid oxygen facility. Water was lifted up one side of the chamber, over the baffle, then discharged into the hypolimnion from an outlet at the bottom of the other side. Three units were tested in an arm of Spruce Run Reservoir, New Jersey, in 1973-1974. The system maintained stratification, but oxygen transfer efficiency was low (30-40%) and little increase in hypolimnetic DO was observed.

In the mid-1970s, lake managers installed a submerged pump oxygenation system in Lake Ghirla, Italy, after increased waste loading caused hypolimnetic anoxia and concurrent increases in hypolimnetic sulfide, ortho-P, and ammonia (Bianucci and Bianucci 1979). The system consisted of a pump and contact chamber submerged on the lake bottom (Fig. 3B). Oxygen from an onshore storage facility was injected upstream of the intake but prior to the contact chamber. Undissolved oxygen bubbles were collected at the top of the contact chamber and recycled back into the intake water. Oxygenated water was discharged through a diffuser system designed to minimize turbulence introduced into the hypolimnion. During operation in the fall of 1976, stratification was maintained and hypolimnetic DO increased to above 5 mg $\cdot L^{-1}$.

Speece (1971) was the first to propose the use of a downflow bubble contact system (DBCS) or Speece Cone for hypolimnetic oxygenation. The proposed system consisted of an inverted cone. Oxygen gas and deoxygenated water were injected into the top of the cone. As the water flowed down the cone it slowed, suspending rising oxygen bubbles within the cone and allowing for nearly complete dissolution of the oxygen.

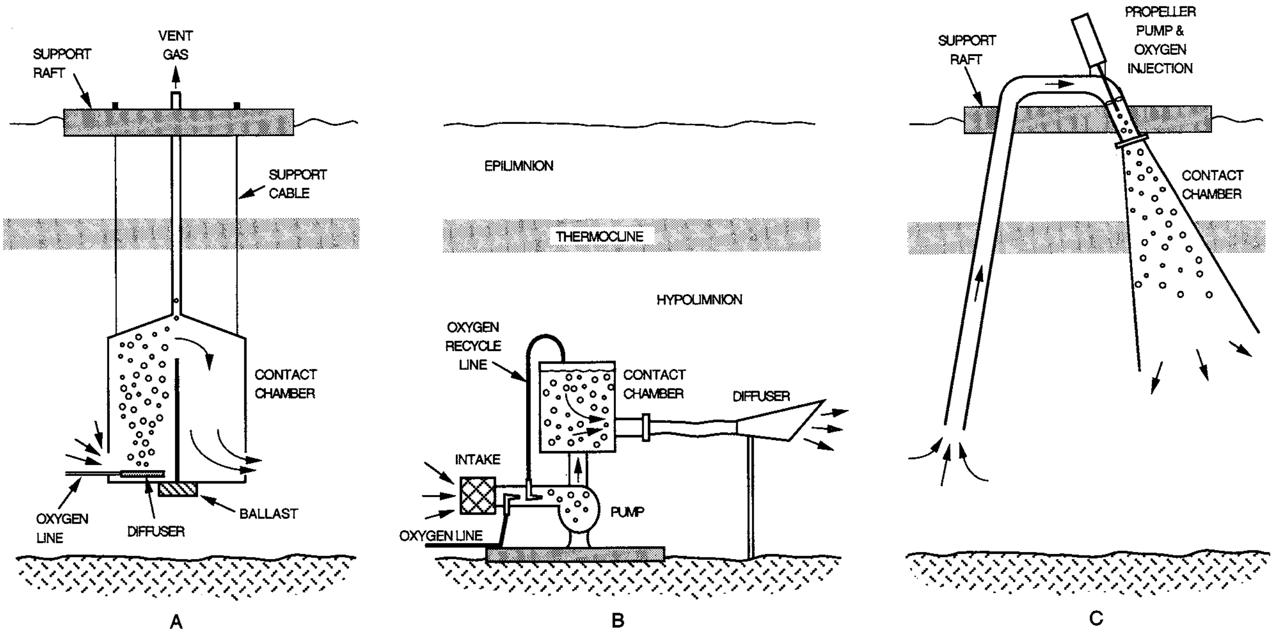


Figure 3.–Schematic of experimental submerged contact chambers used in a) Spruce Run Reservoir, New Jersey, b) Lake Ghirla, Italy, and c) in Finnish Lakes. Not to scale. Modified from Fast and Lorenzen (1976) and Bianucci and Bianucci (1979).

The oxygenated water was then discharged out the bottom of the cone. In an experimental bench-scale DBCS, Speece et al. (1971) observed oxygen transfer efficiency in the range of 80-90%. With the proper horizontal dispersion of reoxygenated water, a DBCS can overcome potential limitations of a DOIS including accidental destratification caused by oxygen bubbles rising through the thermocline (Speece 1994) and localized anoxia as a result of limited oxygen dispersion within the hypolimnion (Fast and Lorenzen 1976).

The first reported use of a DBCS was in Lakes Hemträsk and Kiteenjärni, Finland, in the early 1970s (Fast and Lorenzen 1976). A U-tube sucked water from the hypolimnion into the top of an inverted cone (Fig. 3C). Oxygen was injected near the top of the cone. A propeller pump within the tube forced water down and out the bottom of the cone. Formation of a gas pocket at the top of the U-tube reportedly caused operational problems.

Speece Cones have recently been installed in two lakes, Newman Lake, Washington, and Camanche Reservoir, California (Speece 1994, Horne 1995). Both systems consist of a submerged cone shaped contact chamber mounted on the lake bottom (Fig. 4). A submersible pump draws water from the hypolimnion into the top of the cone. Oxygen supplied from an onshore facility is injected at the top of the cone. The oxygenated water is discharged through a horizontal diffuser pipe. In Newman Lake, oxygenation maintained hypolimnetic DO above 3 mg · L^{-1} throughout the summer and fall 1992 (Thomas et al. 1994). In Camanche Reservoir, the system maintained DO levels above 5 mg · L^{-1} at the dam and sent an oxygenated plume of deep water 3 km up the reservoir (Jung et al. 1998).

Hypolimnetic Oxygenation Case Study Review

Ottoville Quarry, Ohio

Ottoville Quarry (z_{mean} = 8.7 m; z_{max} = 18 m; v = 6.3x10^4 m^3, 51 acre-ft) is a small, moderately eutrophic lake which exhibited hypolimnetic anoxia typically by mid summer. Attempts at stocking the quarry were unsuccessful because trout lacked a cool, oxygenated, deep-water habitat during the summer. To improve trout fishing in the recreational lake, a pure oxygen SSPS (Fig. 1) was installed in 1973 (Fast et al. 1975, Fast et al. 1977).

In 1973, the oxygenation system was operated after the initial onset of hypolimnetic anoxia. The average oxygen injection rate was 9 kg d^{-1}, and the water flow rate through the systems was 290 m^3 d^{-1}. The system increased DO in the treated water by roughly 30 mg · L^{-1}. After two months of operation, oxygenation increased hypolimnetic DO from 0 to 8 mg · L^{-1}. In the summer of 1974, the system was operated at an oxygen

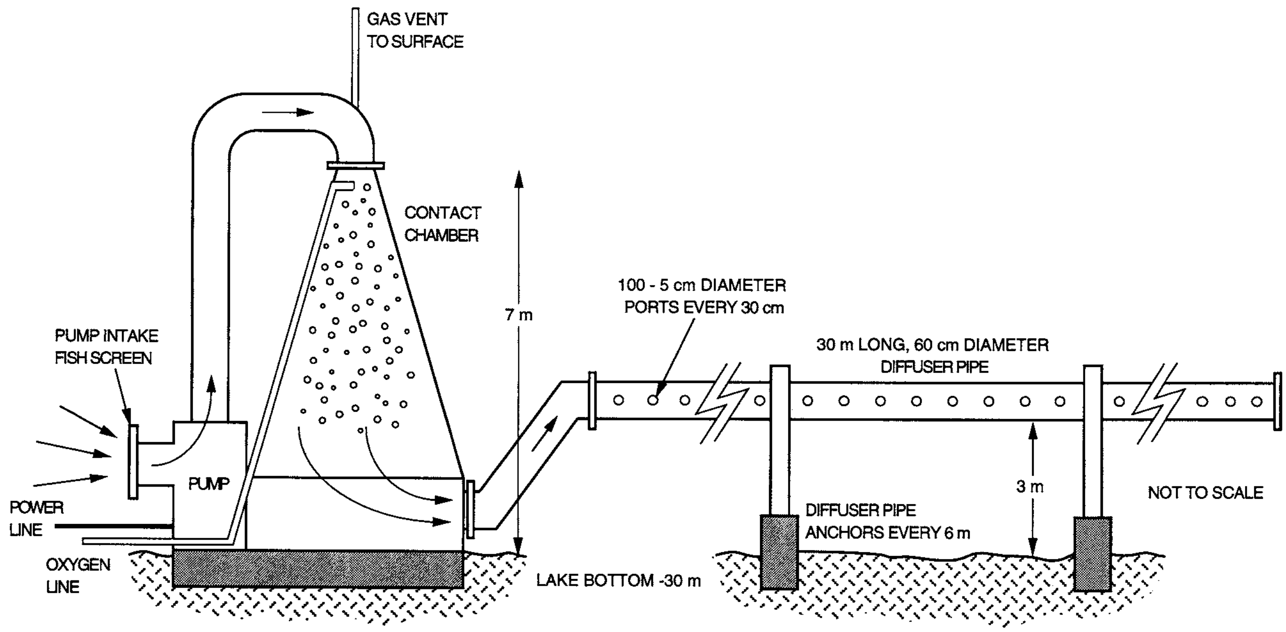


Figure 4.–Schematic of submerged downflow bubble contact chamber system used in Camanche Reservoir, California and Newman Lake, Washington. Modified from Jung et al. (1998).

injection rate of 23 kg d^{-1} to determine the upper limit of the hypolimnion's capacity to retain oxygen. After three months, hypolimnetic DO levels increased to 21 mg · L^{-1} with no apparent negative effects on lake biota.

In both years the system maintained thermal stratification and, unlike previous years, the quarry supported a year-round trout fishery. There was some concern that the hypolimnion might accumulate high concentrations of CO_2, a byproduct of respiration. However, CO_2 accumulation was buffered by the lake's high alkalinity. The peak CO_2 concentration of 13 mg · L^{-1} was well below toxic levels. The authors noted that use of pure oxygen rather than air resulted in no accumulation of toxic levels of dissolved N_2 in the hypolimnion. If air rather than oxygen was used to aerate the lake, it was estimated that the hypolimnion would have reached potentially toxic levels of N_2 after a few months of operation.

Lake Baldegg, Switzerland

Lake Baldegg (z_{mean} = 33 m; z_{max} = 66 m; v = 1.7x10^8 m^3, 137,900 acre-ft) is a large, deep, meromictic lake near Lucerne. The lake has experienced cultural eutrophication since the early 1900's (Imboden 1985). Eutrophication dramatically accelerated after the 1950s with the advent of modern agricultural, dairy and livestock operations. Between 1950 and 1975 lake total phosphorus (TP) content rose from 30 to 90 t. The lake exhibited both winter and summertime anoxia and high rates of internal phosphorus (P) loading. Beginning in the 1950s, large blooms of the nuisance blue-green algae (Cyanobacteria) *Oscillatoria, Microcystis* and *Aphanizomenon* were common (Bürgi and Stadelmann 1991). Through the late 1960s and 1970s, a number of wastewater treatment plants were constructed, and non-point source control measures were implemented. As a result of external pollution control measures, TP content of the lake decreased to 50 t by the early 1980s.

In order to accelerate the pace of lake restoration, lake managers installed a destratification/DOIS in 1982 (Imboden 1985). The system consists of an oxygen tank and an air compressor onshore connected to 6 fine pore diffusers located near the bottom of the lake (Fig. 2A). Artificial mixing via compressed air is maintained from November through May by injecting 6 t d^{-1} of air through 3-4 deep diffusers. Hypolimnetic oxygenation is operated from May through November with 3-4 t d^{-1} of oxygen injected through 4-6 diffusers.

Since 1983, DO levels in the hypolimnion have for the most part remained above 3 mg · L^{-1} and TP content of the lake has dropped from 40 to 18 t (Gächter and Wehrli 1998). Since both external and internal P control measures were implemented concurrently, it is difficult to estimate the effects of oxygenation alone. Based on the brief data set presented by Imboden (1985), oxygenation appears to have decreased internal P loading. In 1982, the year prior to system operation, 7.0 t of TP was released from anoxic hypolimnion sediments. In the following two treatment years, internal TP release was 2.0-2.8 t. However, Gächter and Wehrli (1998) contend that observed TP decreases are solely the result of external controls.

While the effects of oxygenation on internal P loading are unclear, oxygenation did appear to reduce levels of hypolimnetic ammonia and manganese (Gächter and Wehrli 1998). In the two years prior to treatment, deep-water ammonia was around 1,500 ug-N L^{-1}. Post aeration deep-water ammonia levels dropped to 50 ug-N L^{-1}. This drop occurred even though nitrogen loading was largely unaffected by external controls (Bürgi and Stadelmann 1991). Deep-water manganese levels dropped from 800 to 230 ug $\cdot L^{-1}$. It is possible that mixing by the oxygenation system merely redistributed high levels of bottom water ammonia and manganese throughout the hypolimnetic water column rather then actually decreasing sediment release rates of the compounds. However, more detailed monitoring of hypolimnetic ammonia in nearby Lake Sempach showed that hypolimnetic accumulation of inorganic nitrogen mass decreased from 28 t yr^{-1} to 3 t yr^{-1} a few years after the operation of a DOIS (Höhener and Gächter 1994).

Richard B. Russell Lake, Georgia

Richard B. Russell Lake (z_{mean} = 12 m; z_{max} = 47 m; $v = 1.3 \times 10^9$ m^3, 1.07 million acre-ft) is a large, peaking hydroelectric reservoir located on the Savannah River operated by the USACE. The reservoir was filled in 1983-1984, and as anticipated by lake managers, it exhibited hypolimnetic anoxia during the summer and fall of 1985 (James et al. 1985). Anoxia led to hypolimnetic accumulation of ammonia (100-800 ug-N L^{-1}), SRP (soluble reactive phosphorus) (50-150 ug-P L^{-1}), dissolved iron (2-10 mg $\cdot L^{-1}$), and manganese (1-3 mg $\cdot L^{-1}$). While the reservoir's main basin overturned in mid December, water column DO did not reach saturation until late February due to the high DO demand of reduced compounds remaining in the water column. During 1984, because of its degraded quality, no hypolimnetic water was released from the reservoir.

Based on experimental work performed by the USACE in Thurmond Lake and extensive field monitoring during 1984, a DOIS was installed in the reservoir in 1985 (James et al. 1986, Mauldin et al. 1988). The system was sized to maintain 6 mg $\cdot L^{-1}$ of DO in turbine releases of up to 1,700 m^3 s^{-1} (60,000 cfs). The system consists of an onshore oxygen storage facility that feeds two diffuser lines located 1.6 km upstream of the dam. The diffuser lines are 30 m apart and are aligned parallel to the dam. Each line is 0.2 m in diameter, around 400 m long, and supports hundreds of 18 cm diameter ceramic and rubber diffusers. In addition, a second fine bubble diffuser system at the dam is operated under high flow and low DO conditions. The system has a huge peak oxygen delivery capacity of over 100 t d^{-1}.

Oxygenation, combined with higher rates of flushing as a result of power generation and the lower oxygen demand of aging inundated organic material, led to improvements in hypolimnetic water quality (James et al 1986). In 1985, DO was maintained above 5 mg $\cdot L^{-1}$ in most of the water column downstream of the oxygenation system, and thermal stratification was unaffected. Hypolimnetic mass of ammonia, SRP, iron and manganese in the reservoir's main basin all dropped 50-80%. Oxygen system transfer efficiencies ranged from 45-70% in 1985 (James et al 1986), while an intensive 1995 study estimated average system efficiency at 55% (Lemons et al. 1998). During the first few years of operation, oxygen demand steadily decreased with annual oxygen delivery dropping from 14,000 to 8,000 t from 1985 to 1987 (Mauldin et al. 1988).

Amisk Lake, Alberta

Amisk Lake (z_{mean} = 14.5 m; z_{max} = 60 m; $v = 8.0 \times 10^7$ m^3, 65,000 acre ft), is a meromictic/dimictic lake located in central Alberta, Canada. The lake is long, narrow and has two main basins, a smaller north basin (z_{max} = 34 m, $v = 2.5 \times 10^7$ m^3) and a deeper south basin (z_{max} = 60 m, $v = 5.5 \times 10^7$ m^3). In the 1980s the lake exhibited common symptoms of eutrophication including high rates on internal nutrient loading, a declining cold-water fishery and noxious blooms of blue-green algae. In response to deteriorating water quality, an experimental hypolimnetic oxygenation project was initiated (Prepas et al. 1997, Prepas and Burke 1997). The primary goal of the project was to determine if oxygenation would decrease internal P loading, thereby decreasing phytoplankton biomass.

Full-scale, year-round hypolimnetic oxygenation began in the north basin in summer of 1990. The DOIS consisted of an onshore liquid oxygen tank and evaporator, connected to a fine bubble diffuser system suspended 1 m above the sediment near the deepest point of the basin. From 1990 through 1993, summer oxygen input ranged from 0.5-1.1 t d^{-1}. The project was terminated at the end of 1993.

Hypolimnetic oxygenation had significant effects on water quality in the Amisk Lake's north basin. The clearest picture can be obtained by comparing pretreatment (1980-1987) and full treatment (1990-1993) mean summer water quality data. In the hypolimnion, sediment P release dropped from 7.7 to 3.0 mg m^{2} day^{1} and volume-weighted mean hypolimnetic TP decreased from 123 to 56 ug-P L^{-1}. Volume-weighted mean hypolimnetic ammonia decreased from 120 to 50 ug-N L^{-1} with no concurrent increase in hypolimnetic nitrate content. In the epilimnion, volume-weighted mean summer TP decreased from 33 to 28 ug-P L^{-1}, ammonia decreased from 28 to 13 ug-N L^{-1}, and chlorophyll *a* decreased from 17 to 8 ug $\cdot L^{-1}$.

Hypolimnetic oxygen also affected lake mixing and stratification in the north basin. While stratification was maintained, full-scale oxygenation degraded the bottom of the metalimnion, causing it to decrease in thickness by an average of 1 m when compared to pre-treatment years. As a result, hypolimnetic temperature increased from 7.0 °C in pretreatment years to 9.9 °C during full-scale oxygenation. Oxygenation also caused hypolimnetic oxygen demand to increase two-fold between pretreatment and full-scale oxygenation years.

A number of additional improvements relating to lake biota were observed. Summer phytoplankton biomass decreased and blooms were less dominated by blue-green algae (Webb et al. 1997). In addition, turbulence from the oxygenation system extended the period of spring mixing, thereby favoring a longer spring diatom bloom and delaying and diminishing the magnitude of subsequent blue-green algal growth. Researchers observed an increase in the abundance of deep-water *Daphnia* (Field and Prepas 1997). Finally, whole-lake fish biomass increased, as did the horizontal depth distribution of cold-water fish when compared to pre-treatment years (Aku and Tonn 1997, Aku et al. 1997).

Newman Lake, Washington

A restoration program for Newman Lake (z_{mean} = 6 m; z_{max} = 10 m; v = 2.8x10^{7} m^{3}, 23,000 acre-ft) was developed in the late 1980s to ameliorate eutrophic conditions including noxious blooms of blue-green algae, intense summertime hypolimnetic anoxia, a degraded cold-water trout fishery, and high rates of internal nutrient loading. Watershed best management practices were implemented, and in 1989 lake managers performed an alum treatment to promote the retention of P in lake sediment. To further improve water quality, hypolimnetic oxygenation was implemented using a DBCS or Speece Cone in 1992 (Thomas et al. 1994).

The system consists of a submerged pump and inverted cone mounted on the bottom of the lake (Fig. 4). Oxygen is piped to the chamber from two onshore molecular sieve O_2 generators. Highly oxygenated water is discharged horizontally into the hypolimnion through a 46 m long diffuser pipe. The discharge helps to promote dilution of the highly oxygenated water while transporting oxygenated water horizontally into the hypolimnion. The oxygenation system is designed to add up to 2 t d^{-1} of oxygen to the lake. Flow rate through the chamber is 0.6 m^{3} s^{-1}.

Oxygenation maintained a hypolimnetic DO of 5.5 mg $\cdot L^{-1}$ throughout the summer and fall 1992. In the previous year the hypolimnion was anoxic late May through early August. Oxygenation resulted in induced oxygen demand (Moore et al. 1996). Pretreatment hypolimnetic oxygen demand was 915 kg d^{-1} while post oxygenation demand was 1,530 kg d^{-1}. To date published data on the project emphasize the biological effects of oxygenation (Doke et al. 1995, Schumaker et al. 1993). Oxygenation expanded suitable trout habitat and increased benthos diversity. Thomas (1994) reported that during the first summer of oxygenation hypolimnetic levels of ammonia decreased, nitrate was unchanged, and P increased slightly.

Douglas Dam, Tennessee

Douglas Reservoir (z_{max} = 38 m; v = 1.7x10^{9} m^{3}, 1.4 million acre-ft) is an extremely large power generation reservoir located on the French Broad River operated by the TVA. During the late summer, turbine releases from Douglas Dam historically contained low DO and noxious levels of hydrogen sulfide. To protect downstream biota and recreational facilities from degradation, reservoir managers installed a DOIS in 1993 (Mobley and Brock 1995). The system includes 16 diffuser frames that are placed 200-300 m upstream of the dam (Fig. 2B). Each frame measures 30 m by 36 m and supports 1,200 m of porous hose. The hose is fed pure oxygen from an onshore facility that includes a 75 m^{3} liquid oxygen storage tank and 10 evaporator units. Each frame contains buoyancy chambers that can be filled or emptied with water or air from shore. Operators can remotely control the buoyancy of a frame, and easily deploy or retrieve frames as need. Once in position, the buoyancy of a frame is made slightly positive, causing the frame to float above attached weights resting on the reservoir bottom. The system has a massive oxygen delivery capacity of nearly 100 t d^{-1}. Experimental operation of the system increased DO in turbine releases of 475 m^{3} s^{-1} (17,000 cfs) by 2.5-3 mg $\cdot L^{-1}$. Oxygen transfer efficiency above 90% was observed. Oxygenation did not disturb thermal stratification and eliminated sulfide in turbine releases.

Camanche Reservoir, California

Camanche Reservoir (z_{mean} = 17 m; z_{max} = 31 m; v = 5.1x10^{8} m^{3}, 417,100 acre-ft) is a large eutrophic reservoir located in the western foothills of the Sierra Nevada

Mountains. The reservoir is operated by the East Bay Municipal Utility District (EBMUD) and is used for flood control, irrigation supply, protection of instream resources, recreation and hydroelectric power generation. Immediately downstream of the reservoir is a fish hatchery that rears Chinook salmon and steelhead trout. Summertime hypolimnetic anoxia during drought years historically led to poor water quality supplied to the fish hatchery. The main water quality problem was hydrogen sulfide (Horne 1989).

In the spring of 1993, EBMUD installed a DBCS near the Camanche Reservoir dam (Horne 1995, Jung et al. 1998) to improve the quality of water delivered to the hatchery. Since the hatchery required cold water, a DBCS was selected because of the system's low potential for heating the hypolimnion due to metalimnetic entrainment or accidental destratification. The system is similar to that installed in Newman Lake (Fig. 4). The horizontal diffuser is 30 m long, 0.5 m in diameter, and has 150 5 cm diameter discharge ports. Oxygen is supplied from an onshore liquid storage tank. The system supplies up to 8 t d^{-1} of oxygen at a pumping rate of 1 m^3 s^{-1}.

The system maintains DO levels above 5 mg $\cdot$ L^{-1} at the dam and sulfide has not been detected at hatchery since the system began operation in 1993 (Horne 1995). Spatial monitoring of DO in 1993-94 showed that an oxygenated plume of deep water migrated up the reservoir about 3 km after 40 days of oxygenation. Experimental short-term shutoff of the system in the summer of 1996 showed that hypolimnetic oxygen demand increased from 0.07 mg $\cdot$ L^{-1} d^{-1} before oxygenation to 0.12 mg $\cdot$ L^{-1} d^{-1} during oxygenation (Jung et al. 1998). Operation of the system caused a slight degradation of the metalimnion and caused temperature in the bottom of the hypolimnion to increase from 13.5 to 15 °C.

Oxygenation has improved reservoir water quality. Fall deep-water ortho-P levels dropped from 200 ug-P L^{-1} prior to treatment to less than 50 ug-P L^{-1} after oxygenation. Fall deep-water ammonia dropped from 1,000-1,700 ug-N L^{-1} to less than 200 ug-N L^{-1}. Hypolimnetic nitrate appeared to drop slightly after oxygenation. Further data analysis is underway to confirm that sediment mass release rates of nutrients decreased (Beutel et al. in prep.). Since oxygenation was implemented, peak summer chlorophyll *a* has dropped from 40-50 ug $\cdot$ L^{-1} to less than 10 ug $\cdot$ L^{-1}. Average summer secchi disk has increased from 1.5 to 5 m.

Conclusion

Table 2 summarizes the oxygenation systems discussed above. Unlike some hypolimnetic aeration projects (Fast et al. 1973, Heinzmann and Chorus 1994), all oxygenation systems maintained stratification with only minor increases in hypolimnetic temperature. All systems maintained average hypolimnetic DO above 4 mg $\cdot$ L^{-1}. Some hypolimnetic aeration systems have been unable to increase hypolimnetic DO above 0 mg $\cdot$ L^{-1} (Smith et al. 1975, Soltero et al. 1994). Other aerated lakes commonly have hypolimnetic DO levels below 2 mg $\cdot$ L^{-1} by the fall (Smith et al. 1975, Taggart and McQueen 1981, Ashley 1983, Steinberg and Arzet 1984, Soltero et al. 1994). Induced oxygen demand reported at oxygenated lakes and reservoirs is lower than values reported in aerated lakes (Smith et al. 1975, Ashley 1983, Soltero et al. 1994), likely because oxygenation imparts less mixing into the hypolimnion than aeration systems. Table 2 includes the percentage change in hypolimnetic water quality before and after oxygenation. Oxygenation affected the release of nutrients and problematic reduced compounds from sediment. Hypolimnetic levels of P, ammonia, manganese and hydrogen sulfide all dropped from 50-100%. A detailed examination of recent hypolimnetic oxygenation projects over the past decade shows that the management strategy results in numerous water quality benefits.

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Table 2.–Summary of selected hypolimnetic oxygenation systems.

	Morphology		System Description			Hypolimnetic Water Quality Response							
Lake or Reservoir	z_{max} (m)	volume (10^6 m^3)	System type	Years of operation	Oxygen supply rate (t d^{-1})	Mean summer DO (mg L^{-1})	Induced oxygen demand	Temp	P	NH_4	Mn	H_2S	Comments & References
Ottoville Quarry, Ohio	18	0.06	SSPS	1973-74	0.01	4-14							Oxygenation resulted in maintenance of year-round trout fishery (Fast et al. 1975 & 1977).
Lake Ghirla, Italy	14	2.0	SPOS	1976	0.13	4.4		0%					Little post-oxygenation water quality data was reported (Bianucci and Bianucci 1979).
Lake Baldegg, Switzerland	66	170	DOIS	1983-99	3.8	5.0				-95%	-70%		External and internal P controls were implemented concurrently. Decreases in NH_4 and Mn observed in hypolimnetic deep-water (Gachter and Wehrli 1998).
Lake Sempach, Switzerland	87	6.3	DOIS	1984-97	3.0	7.0				-90%	-50%		External and internal P controls were implemented concurrently. Decrease in NH_4 mass accumulation observed in hypolimnion (Hohener and Gachter 1994). Decrease in Mn observed in hypolimnetic deep-water (Gachter and Wehrli 1998).
Russell Lake, Georgia	47	1,270	DOIS	1984-99	100	5-6		0%	-80%	-80%	-50%		Decrease in nutrient and Mn mass accumulation observed in hypolimnion. Decreases aided by higher hypolimnetic flushing and reservoir aging (James et al. 1985 and 1986).
Amisk Lake, Alberta	34	25	DOIS	1990-93	2.0	4.6	+100%	+45%	-55%	-60%		-100%	Decrease in nutrient mass accumulation observed in hypolimnion. Oxygenation also caused drops in epilimnetic P, ammonia and chl a (Prepas and Burke 1997).
Newman Lake, Washington	10	29	DBCS	1992-99	2.0	5.5	+70%						No quantitative reporting on changes in hypolimnetic nutrient content. Oxygenation expended suitable trout fishery habitat (Doke et al. 1995)
Douglas Dam, Tennessee	38	1,700	DOIS	1993-99	96			0%				-100%	Oxygenation used to aerate massive turbine discharges, system is one of many operated by TVA (Mobley and Brock 1995).
Camanche Reservoir, California	31	515	DBCS	1993-99	8.0	5-6	+70%	+10%	-80%	-80%		-100%	Decrease in nutrients observed in bottom water of hypolimnion. Oxygenation also caused drop in epilimnetic chl a and an increase in water transparency (Horne 1995, Jung et al. 1998).

Notes:
SSPS = side stream pumping system, SPOS = submerged pumping oxygenation system,
DOIS = deep oxygen injection system, DBCS = downflow bubble contact system.

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