Improving raw water quality with hypolimnetic oxygenation

By

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Introduction

Summertime hypolimnetic anoxia is a common phenomenon in productive drinking water reservoirs. It can result in a number of negative environmental consequences. Anoxic sediment tends to release ammonia and orthophosphate, a phenomenon known as internal nutrient loading, which can reinforce eutrophication (Boström et al. 1988, Ahlgren et al. 1994). Entrainment of nutrients from the hypolimnion to the epilimnion can support summer blooms of blue-green algae which may produce objectionable and difficult-to-remove taste and odor compounds. Anoxic conditions can also lead to hypolimnetic accumulation of iron, manganese and sulfides that can degrade the aesthetic quality and treatability of drinking water (Sartoris and Boehmke 1987). Elevated concentrations of toxins (e.g., sulfide and ammonia) in the hypolimnion as a result of anoxia may impair aquatic biota within the reservoir and in tail-waters released from the hypolimnion (Cooper and Koch 1984, Horne 1989). Finally, anoxic conditions may also increase mercury contamination in lake biota by stimulating the release of methylmercury from sediment (Herrin et al. 1998).

Hypolimnetic oxygenation is a relatively new management technique that averts hypolimnetic anoxia and its harmful consequences by oxygenating the hypolimnion using pure oxygen gas. This paper discusses a number of issues related to hypolimnetic oxygenation including advantages of hypolimnetic oxygenation systems over traditional aeration methods (e.g., destratification, aeration). It also discusses facility requirements and costs associated with various types of oxygenation systems, and the effects of oxygenation on water quality.

Hypolimnetic Aeration Systems

Techniques employed to solve hypolimnetic anoxia can be broadly grouped into three categories: artificial destratification, hypolimnetic aeration, and hypolimnetic oxygenation. 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). 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 temperatures in bottom water. Higher temperatures degrade cold-water fishery habitat, and warm discharges from destratified reservoirs may impair downstream biota. In drinking water reservoirs, 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 an oxic hypolimnia while preserving thermal stratification (McQueen and Lean 1986). 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 the hypolimnion. Lake managers have utilized both full-lift systems that raise the water to the surface and partial-lift system that raise water up to around the metalimnion.

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 are low (Smith et al. 1975). Thus, aeration units may need to operate at high recirculation rates and/or multiple units may be required. This leads to elevated levels of turbulence within the hypolimnion which can increase sediment oxygen demand (Smith et al. 1975, Ashley 1983, Moore et al. 1996) or result in accidental destratification (Heinzmann and Chorus 1994). 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). The introduction of compressed air which 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

Hypolimnetic oxygenation is a relatively new aeration technique used to prevent hypolimnetic anoxia. Lake oxygenation systems generally consist of a liquid oxygen storage facility on shore. Evaporators transform the liquid oxygen to gas, and the gas is dissolved into lake water through an on-shore contact chamber, a system of diffusers located under water, or a contact chamber submerged in the lake. Like hypolimnetic aeration, it preserves thermal stratification, however pure oxygen rather than air is used. 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 and the chance of accidental destratification. 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). Additional advantages of hypolimnetic oxygenation include avoidance of hypolimnetic dissolved nitrogen supersaturation (Fast et al. 1975), low energy use (Speece 1994), and low commercial oxygen costs. Four main types of oxygenation systems are currently in use: side stream oxygenation, bubble plume oxygenation, diffuse deep-water oxygenation, and submerged contact chamber oxygenation. These are discussed in detail below.

Side Stream Oxygenation

In side stream oxygenation, hypolimnetic water is pumped onto shore, injected with oxygen, then discharged back into the hypolimnion (Fast et al. 1975, Fast et al. 1977). A major draw back of this system is the high energy costs associated with the maintenance of a pressurized chamber on shore. Thus, this system is not commonly used for hypolimnetic oxygenation. A U-tube side stream oxygenation system has been developed by Speece (1996) for uses in rivers and shallow lakes that avoids this operational cost. Low DO water is diverted on shore and discharged into a 175-foot-deep U-tube. Oxygen gas is then injected into the water at the bottom of the tube. The hydrostatic pressure in the tube promotes the dissolution of oxygen gas into the water and DO concentration in the water discharged back into the river is around 50 mg/L. Use of U-tube systems instead of an on shore pressurized chamber can decrease electrical costs by a factor of 20.

Bubble Plume Oxygenation

Bubble plume oxygenation works by injecting pure oxygen through a dense group of diffusers at the lake bottom. Oxygen bubbles dissolve into a surrounding plume of rising water. The oxygenated plume then detrains and spreads out horizontally below the thermocline. The technology was developed in Switzerland in the early 1980s to inhibit high rates of internal phosphorus loading in deep, eutrophic lakes (Imboden 1985, Gächter and Wehrli 1998). In Lake Baldegg (137,900 acre-ft), the system consists of an oxygen tank and an air compressor on shore connected to six diffuser arrays located near the bottom of the lake (Figure 1A). Artificial mixing via compressed air is maintained from November through May by injecting 6 metric tons per day (t/d) of air through 3-4 deep diffusers. Hypolimnetic oxygenation is operated from May through November with

3-4 t/d of oxygen injected through 4-6 diffusers. Phosphorus release is still observed during the summer, but oxygenation did cause a decrease in hypolimnetic accumulation of ammonia and manganese (Gächter and Wehrli 1998). In some lakes, the system appears to have trouble maintaining a well oxygenated sediment water interface because most of the oxygen is distributed to the upper levels of the hypolimnion (McGinnis, personal correspondence). This appears to be a major drawback of the bubble plume oxygenation system.

An experimental bubble plume system was operated in Amisk Lake, Canada (65,000 acre ft) from 1990 through 1993 (Prepas et al. 1997). Summer oxygen input ranged from 0.5-1.1 t/d. Hypolimnetic oxygenation had dramatic and significant effects on water quality. Sediment phosphorus release dropped from 7.7 to 3.0 mg/m^2/d, and hypolimnetic total phosphorus decreased from 123 to 56 ug-P/L. Hypolimnetic ammonia decreased from 120 to 50 ug-N/L with no concurrent increase in hypolimnetic nitrate content. In the epilimnion, average summer total phosphorus decreased from 33 to 28 ug-P/L, ammonia decreased from 28 to 13 ug-N/L, and chlorophyll *a* decreased from 17 to 8 ug/L.

Diffuse Deep-Water Oxygenation

Diffuse deep-water oxygenation consists of an extensive network of linear diffusers that release fine oxygen bubbles that rapidly dissolve into the overlaying water column. In the early 1970s, the Tennessee Valley Authority (TVA) began examining the feasibility of oxygenation for reaeration of hydroelectric reservoir discharges with low DO at Fort Patrick Henry Dam, Tennessee (Nicholas and Ruane 1975). Since then, the TVA has installed diffuse deep-water oxygenation systems in over half a dozen reservoirs ranging in volume from 200,000 to 1.5 million acre-feet. Delivery rates of the system range from 15 to 150 t/d.

A system now in operation at Douglas Dam, Tennessee (1.4 million acre-ft) has successfully oxygenated large turbine discharges since 1993 (Mobley and Brock 1995).

The reservoir is a large power generation reservoir located on the French Broad River. During the late summer, turbine releases from Douglas Dam historically contained low DO and noxious levels of hydrogen sulfide. The system has 16 diffuser lines that include 1,200 m each of porous hose (Figure 1B). The hose is fed pure oxygen from an on shore facility that includes a large capacity liquid oxygen storage tank and multiple evaporator units. Each oxygen line 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 diffuse deep-water oxygenation system has a few advantages over other systems. In contrast to contact chambers, the system does not require the pumping of water. In addition, unlike the bubble-plume oxygenation system, the system does not induce large-scale vertical current of water. Thus, dissolved oxygen tends to stay deeper in the reservoir.

The system at Douglas Dam has a massive oxygen delivery capacity of nearly 100 t/d. Experimental operation of the system increased DO in turbine releases of 17,000 cfs by 2.5-3 mg/L. Oxygen transfer efficiency above 90% was observed. Oxygenation did not disturb thermal stratification and eliminated sulfide in turbine releases. Smaller scale (5-15 t/d) diffuse deep-water oxygenation systems have been installed in a number of California drinking water reservoirs including Los Vaqueros (100,000 acre-feet) operated by the Contra Costa Water District and Upper San Leandro (40,000 acre-feet) operated by East Bay Municipal Utility District). Others systems are being planned for drinking water reservoirs operated by the San Francisco Public Utility Commission and the San Diego Water Department.

Submerged Contact Chamber Systems

The submerged contact chamber oxygenation systems consist of a submerged cone-shaped contact chamber mounted on the lake bottom. A submersible pump draws water from the hypolimnion into the top of the cone. Oxygen supplied from an on shore facility is injected at the top of the cone. The oxygenated water is discharged through a horizontal diffuser pipe. In an experimental bench-scale chamber, Speece et al. (1971) observed oxygen transfer efficiency in the range of 80-90%. With the proper horizontal dispersion of reoxygenated water, a submerged chamber system can overcome potential limitations of a bubble plume or diffuse deep-water system. These include 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). In addition, in contrast to bubble plume and diffuse deep-water systems, horizontal dispersion sends reoxygenated water out over the sediments of the reservoir, thereby keeping highly oxygenated water in direct contact with the sediments and assuring a well-oxygenated sediment-water interface.

Submerged contact chamber oxygenation system have been installed in two lakes, Newman Lake, Washington and Camanche Reservoir, California (Speece 1994, Horne 1995) to improve cold water habitat for fish (Figure 2). In Newman Lake (23,000 acre-ft), oxygen is piped to the chamber from two on shore molecular sieve oxygen gas 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 of oxygen to the lake. Flow rate through the chamber is 0.6 m^3/s. Oxygenation maintained an hypolimnetic DO of 5.5 mg/L throughout the summer and fall 1992. In the previous year the hypolimnion was anoxic late May through early August. Oxygenation expanded suitable trout habitat and increased benthos diversity (Doke et al. 1995, Moore et al. 1996).

Camanche Reservoir (417,100 acre-ft) is a multi-purpose reservoir operated by the East Bay Municipal Utility District. In 1993, a submerged contact chamber oxygenation system was installed to improve the quality of water delivered to a nearby fish hatchery that rears Chinook salmon and steelhead trout. The system is similar to that installed in Newman Lake but oxygen is supplied from an on shore liquid storage tank and the system is larger. It supplies up to 8 t/d of oxygen at a pumping rate of 1 m^3/s. The system maintains DO levels above 5 mg/L at the dam and sulfide has not been detected at hatchery since the system began operation (Figure 3). Spatial monitoring of DO in 1993-94 showed that a well-oxygenated plume of deep-water migrated up the reservoir about 3 km after 40 days after oxygenation.

Oxygenation has had dramatic effects on water quality in Camanche Reservoir (Jung et al. 1998) (Figure 4). Fall hypolimnetic orthophosphate levels dropped from 200 ug-P/L prior to treatment to less than 50 ug-P/L after oxygenation. Summertime accumulation rates of phosphate in the hypolimnion dropped from 4-5 mg-P/m^2/d to less than 0.7 mg-P/m^2/d. Fall hypolimnetic ammonia dropped from 1,000-1,700 ug-N/L to less than 200 ug-N/L. This is equivalent to a drop in the rate of ammonia accumulation from 25-30 mg-N/ m^2/d to less than 4 mg-N/ m^2/d, with no concurrent increase in the rate of nitrate accumulation. Since oxygenation was implemented, peak chlorophyll *a* has dropped from 40-50 ug/L to less than 10 ug/L. Average summer secchi disk has increased from 1.5 to 5 m.

System Cost, Advantages and Disadvantages

Table 1 below summarizes costs as well as advantages and disadvantages for various oxygenation systems. Capital costs are based on a 5 t/d system and are roughly $1 million dollars for both a submerged contact chamber or a diffuse deep-water oxygenation system. Such a system would be adequate for a mesotrophic to eutrophic reservoir roughly 50,000 acre-feet in volume. Operating costs range from $850 to $3,000 and assume liquid oxygen cost of $150/metric ton and energy costs of $0.10/kWh. Because of its extremely high efficiency in dissolving oxygen gas into hypolimnetic water, the lowest operating costs are associated with a submerged contact chamber. The submerged contact chamber oxygenation system installed in Camanche Reservoir with a capacity of 8 t/d cost around $1.2 million in 1993. Operation costs were around $1,000 per day and the system was operated for roughly 150 days per year.

Table 1. Oxygenation Systems

System (reference)	Capital Cost ($)	Operating Cost ($/d)	Advantages	Disadvantages
Pure oxygen submerged chamber	~$1 million	~$850	Very high oxygen transfer efficiency. Oxygen discharged horizontally over sediment-water interface. System efficiency independent of lake depth.	Need for a submerged pump and chamber.
Deep pure oxygen U-tube	Not reported	~$1,000	Low operating cost compared to on shore chamber. System efficiency independent of lake depth.	Need to construct 175-foot deep u-tube. Pumping involved.
Diffuse deep-water oxygenation	~$1 million	~$1,000	No pumping. Good horizontal distribution of oxygen.	Oxygen released above and away from sediment-water interface. System efficiency decreases with lake depth. May impact thermal stratification.
Shallow pure oxygen U-tube	Not reported	~$1,200	Tube only 20-30 feet deep. System efficiency independent of lake depth	Pumping involved. Compared to deep U-tube, less oxygen delivered per unit flow through the system.
Bubble plume oxygenation	Not reported	Not reported	By pumping air through the diffusers, it can also be used as destratification system.	System efficiency decreases with lake depth. Oxygen released above and away from sediment-water interface. System can impact thermal stratification.
Pure oxygen on shore pressurized chamber	Not reported	~$3,000	Most facilities on shore. System efficiency independent of lake depth	High pumping cost.

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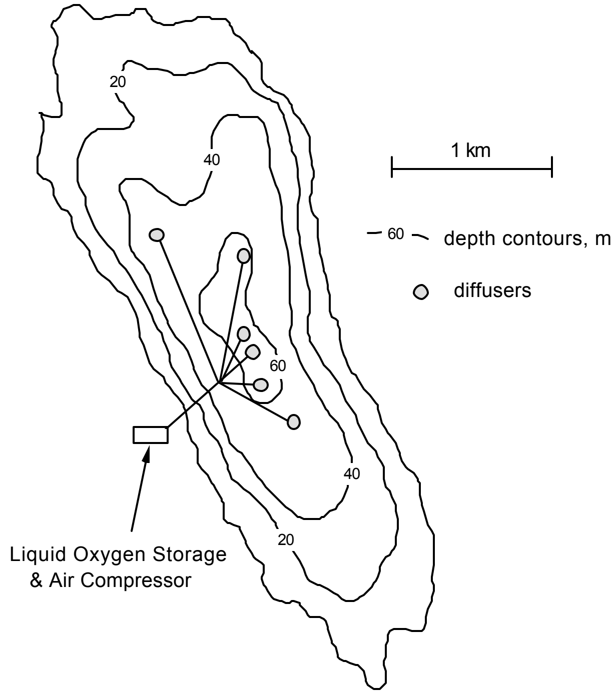
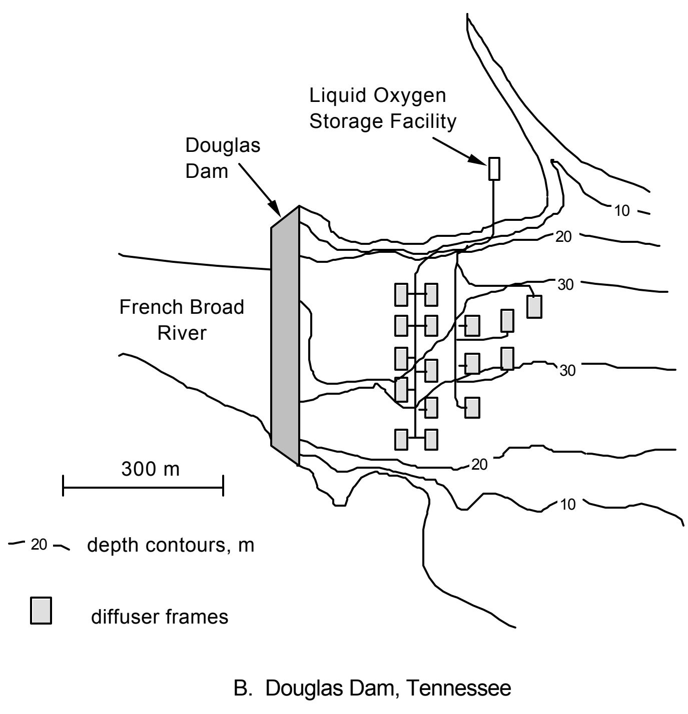


A. Lake Baldegg, Switzerland



B. Douglas Dam, Tennessee

Figure 1 - Arrangement of diffusers for a bubble plume oxygenation system (A), and a diffuse deep-water oxygenation systems (B). Modified from Imboden (1985) and Mobley & Brock (1995).

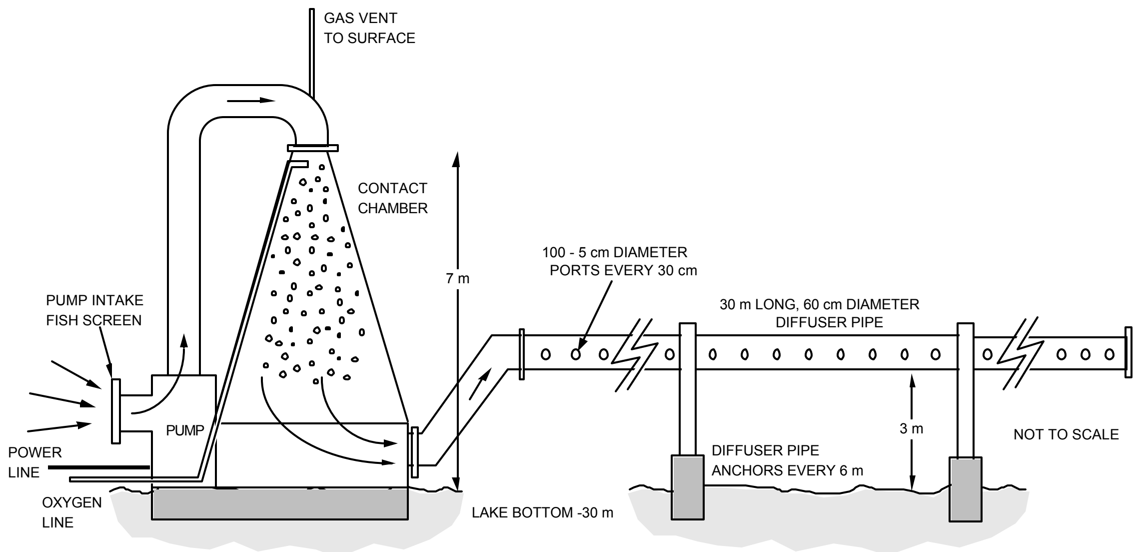


Figure 2 - Schematic of submerged contact chamber oxygenation system used in Camanche Reservoir, California and Newman Lake, Washington.

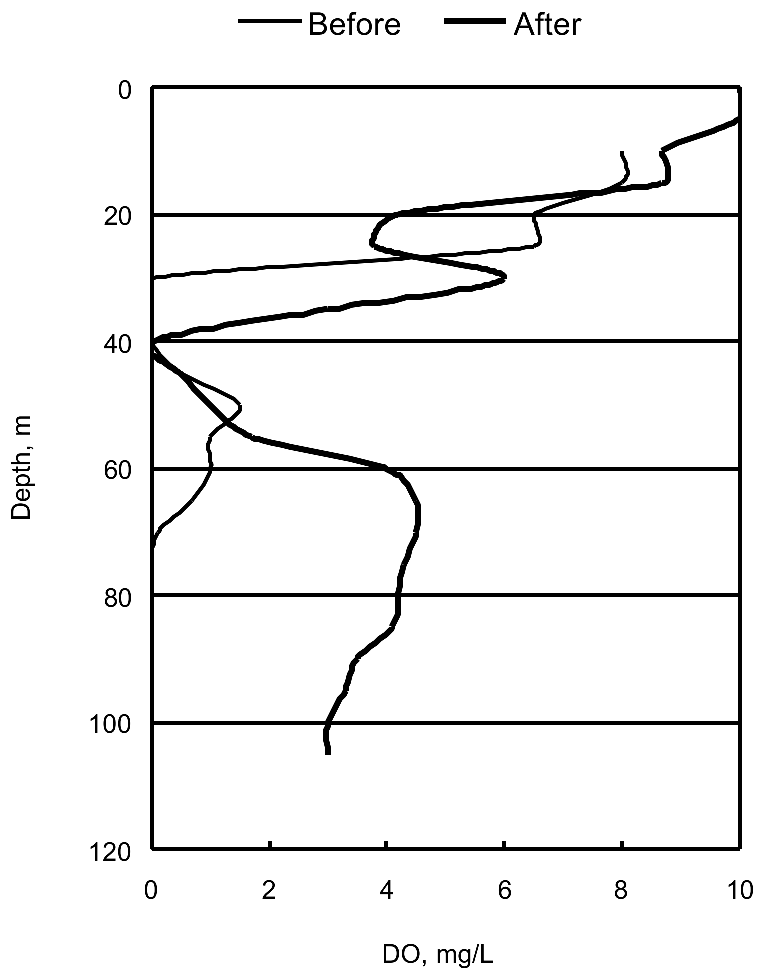


Figure 3 – DO before and after hypolimnetic oxygenation in Camanche Reservoir. Modified from Jung et al. (1998).

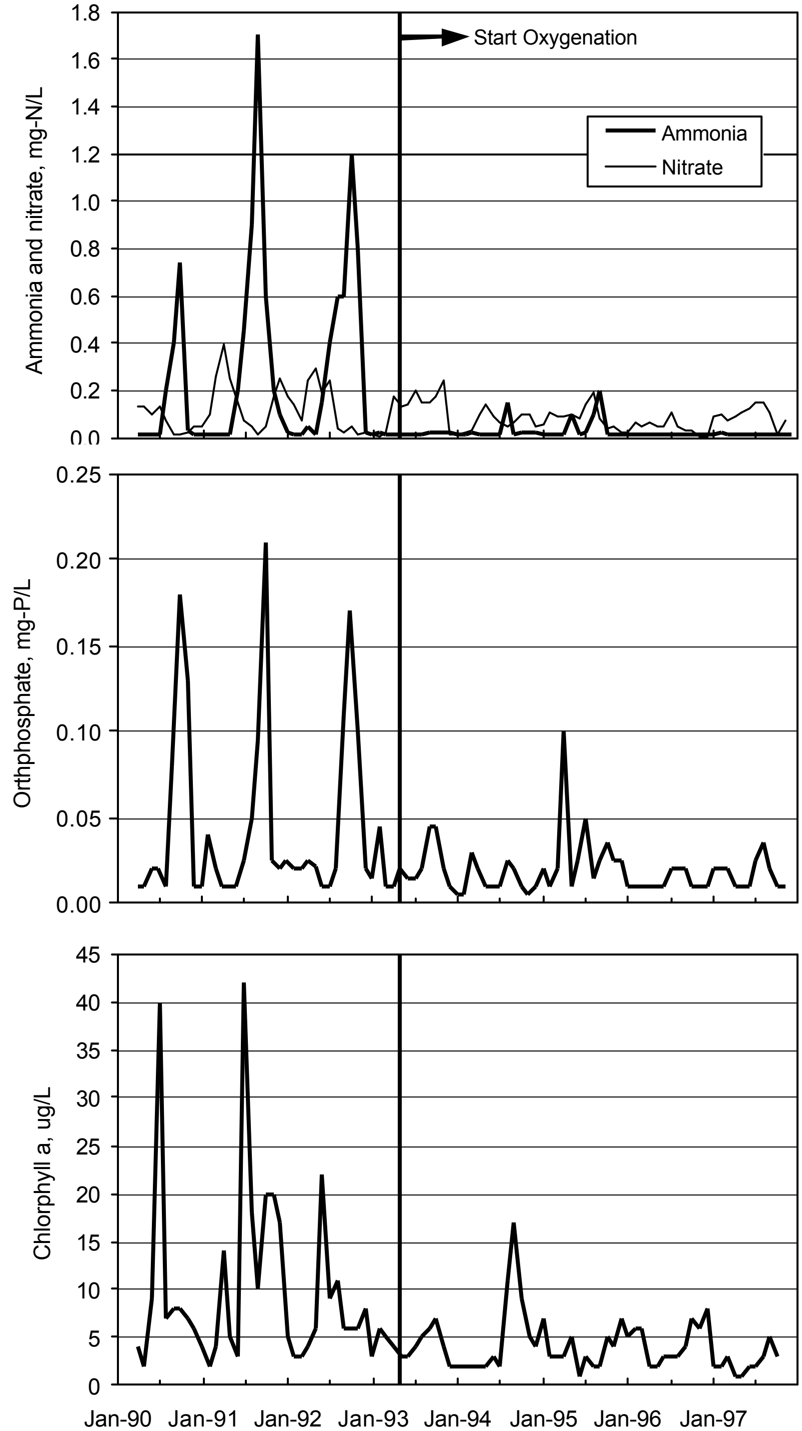


Figure 4 – Nutrients in bottom water and algae in surface water after hypolimnetic oxygenation in Camanche Reservoir. Modified from Jung et al. (1998).