AERATION AS A LAKE MANAGEMENT TECHNIQUE

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An Inland Lake Demonstration Project Report

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ABSTRACT

The objective of this project was to demonstrate the feasibility of hypolimnetic aeration as a useful technique for lake restoration. In order to successfully evaluate hypolimnetic aeration, aerators were installed in two eutrophic lakes in central Wisconsin. The major component of the hypolimnetic aerator consisted of a 40-ft long, 18-inch diameter polyethylene tube with an internal longitudinal plate dividing the tube in half and twisted to form a helix. Compressed air or a combination of compressed air and liquid oxygen were supplied to the base of the unit and water was air lifted up the tube to enter a 4-ft by 4-ft by 8-ft bubble separation box at the surface of the lake, where the air bubbles were vented to the atmosphere. The bubble-free oxygenated water was returned to the hypolimnion via two 18-inch diameter flexible return tubes. An evaluation of the unit was completed in a eutrophic, clear, hard water lake (Mirror) in 1972 and 1973 and in a dystrophic soft water lake (Larson) in 1973. The intial studies indicated that all of the oxygen transfer from the compressor occurred in the bottom half of the unit, with further transfer occuring in the surface separation box as the water momentarily came in contact with the atmosphere.

Under operating conditions at Mirror Lake with an air supply of 16 cfm and a water flow moving through the aerator at 4.2 cfs, the dissolved oxygen transfer efficiency of the entire unit (including oxygen transfer in the separation box) was 20 percent. A combination of compressed air at 16 cfm and liquid oxygen at 5.5 cfm was supplied to the aerator giving a water flow of 5.3 cfs and an oxygen transfer efficiency of 23 percent. The oxygen transfer efficiency at Larson Lake with compressed air only was between 12 and 14 percent.

Both Mirror and Larson lakes had anoxic hypolimnia during the summer months. Attempts at satisfying the very high oxygen demands in Mirror Lake (maximum biological oxygen demand in the bottom water was 39 mg/l before aeration) were unsuccessful during limited aeration in 1972 and extended operation in 1973. However, the operation of the aerator in Larson Lake proved successful. Dissolved oxygen concentrations in the hypolimnion increased from 0.0 to 7.0 mg/l. At present, establishment of a cold water fishery appears possible in Larson Lake and current research has indicated a trout population can be maintained in the hypolimnion.

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INTRODUCTION

Semi-annual periods of dissolved oxygen depletion are a common characteristic of many eutrophic lakes in temperate regions. During summer stratification, thermally induced density gradients preclude deep mixing of oxygenated surface water. Decomposition of organic material and bacterial respiration can deplete the store of dissolved oxygen in the hypolimnion. Even in lakes too shallow to stratify, low dissolved oxygen concentrations can occur during surface algal blooms which shade out the light necessary for photosynthesis and exert a high oxygen demand. Under winter ice cover when photosynthetic activity and chances for atmospheric replenishment are minimal, the dissolved oxygen content of the entire lake may also reach critical levels.

Artificial aeration is a common method of alleviating the problem of dissolved oxygen depletion and has a long history of use in lakes and reservoirs. Although it is generally viewed as a cosmetic treatment of the symptoms of eutrophication, it also has the potential for improving the nutrient status of lakes and retarding or reversing the process of eutrophication.

To demonstrate aeration as a lake renewal technique, the Inland Lake Demonstration Project has installed and monitored aeration equipment in two small Wisconsin lakes, Mirror Lake and Larson Lake. These lakes typify many of the problems associated with lake eutrophication throughout the Upper Midwest, and generally conform to the criteria we established for an aeration demonstration project, with emphasis on hypolimnetic aeration. These criteria are: (1) a stable summer metalimnion, (2) a moderate to severe oxygen deficit in the hypolimnion, and (3) a hypolmnion volume suitable for manipulation. In addition, both lakes experience a high rate of winter oxygen depletion, providing an opportunity to test "hypolimnetic" aeration in an ice-covered lake without creating an open water hazard (snowmobile trap).

Although the results from aeration studies on these two lakes can be considered preliminary in that they have been underway for little more than one year, they have successfully demonstrated the use of hypolimnetic and total aeration in small, deep, stratified lakes. In addition, valuable information has been acquired concerning the design of lake aeration systems and the effects of aeration on the physical, chemical, and biological regime of lakes.

BACKGROUND

EFFECTS OF OXYGEN DEPLETION AND BENEFITS OF AERATION

Fish

The effect of low dissolved oxygen concentrations on the biocoenosis of an aquatic ecosystem is not completely understood, but fish exhibit the most noticeable and immediate response. A number of investigators have documented the effects of dissolved oxygen depletion on the distribution and survival of fish during periods of stratification (Mayhew 1963; Eley, Carter, and Dorris 1967; MacCullum and Regier 1970; and others) and winter ice cover (Schneberger 1970). The minimum dissolved oxygen requirements for fish vary with many factors, including species, age, water temperature, and feeding rate (McKee and Wolf 1963), and restriction of activity, growth, and production can occur at any concentration below the saturation level (Doudoroff and Shumway 1967). For this reason, fish biologists are understandingly hesitant to set a general standard, but a minimum dissolved oxygen concentration of 5 mg/l for warm water fish and 6-7 mg/l for cold water fish is widely accepted (Doudoroff and Shumway 1967).*

However, most fish can survive fairly long periods of exposure to oxygen concentrations as low as 2 mg/l at low water temperatures, and some can live at concentrations as low as 1 mg/l (Doudoroff 1957). This capability enables at least some fish to overwinter in marginal winterkill lakes, but the quality of the fishery is drastically reduced (Selbig 1970).

In addition to low dissolved oxygen levels, toxic end products of anaerobic decomposition also have an important effect on the aquatic community. Summerfelt and Lewis (1967) demonstrated that fish were repelled by high ammonia levels, and above a concentration of about 1 mg/l, hydrogen sulfide is lethal to many game fish as well as some zooplankton (McKee and Wolf 1963). Black, Fry, and Black (1954) found that carbon dioxide, which is frequently present in high concentrations in the anoxic hypolimnion of eutrophic lakes, greatly reduced the tolerance of fish to low dissolved oxygen levels.

In stratified lakes and reservoirs, low hypolimnetic dissolved oxygen concentrations frequently restrict fish

*All of the field measurements, with the exception of flows and pressures (i.e., cfs and lbs/inch^2), were recorded using the metric system. In most instances, the metric measurements have been converted to their english equivalents to facilitate the readability of this report. There are, however, certain metric measurements which have not been converted because of their universal acceptance, e.g., chemical concentrations in mg/l. Metric equivalents to the english measurements used in this report are given in Appendix 4.

habitat to the upper water layers, where persistent high temperatures may preclude the development of a cold water fishery. Brook trout, *Salvelinus fontinalis* (Mitchill), a typical cold water fish, prefer temperatures in a range of 57-61° F, and do not inhabit waters where the temperature rises much above 68° F (Mihursky and Kennedy 1967). In many eutrophic lakes, this limits cold water fish habitat to a narrow zone in the metalimnion. Hile (1936) reported that in several lakes in Wisconsin, habitat of cisco, *Coregonus artedii* Lesueur, was limited to a thin layer in the metalimnion, bounded below by cold anoxic water and overlain with well-oxygenated, but lethally warm water. A similar reduction in trout habitat during the summer was observed by Tanner (1960) in four artificially fertilized Michigan lakes. Colby and Brooke (1969) attributed a summer mortality of cisco in a Michigan lake to hypolimnetic oxygen depletion coupled with lethal epilimnetic temperatures. In the lakes and reservoirs of the South and Southwest, the problem is accentuated by lake surface temperatures which frequently exceed 77° F, and there is considerable pressure to provide cold water fisheries, especially in water bodies near large population centers (Whalls 1968).

Aeration can enlarge the habitat available to fish in eutrophic lakes (Hooper, Ball, and Tanner 1952; Irwin, Symons, and Robeck 1967; Wirth and Dunst 1967; Fast 1971), but few studies have documented beneficial effects. A notable exception is the work of Johnson (1966), who reported greatly increased survival and production rates of coho salmon, *Oncorhynchus kisutch* (Walbaum), fry during artificial destratification. In an attempt to provide suitable temperature and dissolved oxygen conditions for rainbow trout, *Salmo gairdneri* Richardson, Fast and St. Amant (1971) operated a destratification system at night in a southern California reservoir, but temperatures rose above critical levels. In a later study, Fast (1971) demonstrated the use of hypolimnetic aeration to increase the living space available to rainbow trout in a Michigan lake, but he did not investigate any potential long-term response.

Zooplankton and Zoobenthos

Compared to reported effects on fish, there is a relative paucity of information regarding the oxygen requirements and the effects of aeration on zooplankton and benthos. In addition to dissolved oxygen, diverse environmental factors such as predation, food abundance, and light intensity limit population distribution (Hutchinson 1957), making it difficult to assess the direct effects of anoxia or aeration. Tubificids can survive for more than four months on totally anoxic lake bottoms (Inland Fisheries Branch 1970). Certain species of midge larvae and oligochaetes can also tolerate extended periods of low dissolved oxygen concentrations (Pennak 1953; Curry 1965). However, given the environmental importance of dissolved oxygen to the zooplankton and zoobenthos of the profundal zone (Ruttner 1963), aeration should promote increases in both the density and diversity of the lower food chain organisms.

Fast (1971) found that aeration resulted in a rapid invasion of the profundal zone by zoobenthos and an extended vertical distribution of zooplankton. Lackey (1971) noted no significant changes in benthic populations during the aeration of a Colorado lake, but he reported a change in the dominant species of zooplankton. Linder and Mercier (1954) found that hypolimnetic aeration resulted in the appearance of species characteristic of oligotrophic conditions.

Phytoplankton

The reduction or elimination of nuisance algae blooms is frequently cited as a major objective of aeration projects, but the direct effects of aeration on phytoplankton populations are related more to the circulation patterns which result from aeration rather than the addition of oxygen to the water. Haynes (1971) found that total aeration (destratification) destroyed blue-green algae scums by circulating the cells throughout the water, even though there was little effect on the total biomass. Malueg et al. (1971) also noted a decrease in the total standing crop of blue-green algae during total aeration. However, increased numbers of green algae have been observed during several aeration studies (Robinson, Irwin, and Symons 1969; Haynes 1971; Hooper, Ball, and Tanner 1952) and Ridley (1971) found that the density of blue-green algae also increased during partial destratification. He suggested that the timing of the onset of destratification with respect to seasonal production was of great importance in determining algal response. MacBeth (1973) suggested that changes in pH and carbon dioxide concentrations were responsible for changes in algal types in several destratification projects in Ontario, Canada.

Water Chemistry

From the standpoint of domestic and industrial water supply, aeration can also produce desirable results. Oxygenation of botton waters leads to a general increase in the oxidation state and a reduction in the concentrations of the reduced forms of iron, manganese, nitrogen, and sulfur (Irwin, Symons, and Robeck 1966; Wirth and Dunst 1967; Symons, Carswell, and Robeck 1970; Haynes 1971). The elimination of these chemical species and their associated taste and odor problems has been the goal of many aeration projects in water-supply reservoirs (Symons, Carswell, and Robeck 1970). Aeration can also improve the pH levels and carbon dioxide concentrations in water from the anaerobic zone, increasing the efficiency of chemical treatment and reducing corrosion in the distribution system (Riddick 1957).

In addition to the oxidation of dissolved chemical constituents, aeration can increase the rate of oxidation and decomposition of bottom sediments and organic matter in the water column (Fast 1971; Mercier 1955). However, circulation and suspension of sediments and decomposing plant cells may increase the oxygen demand (Fast 1971).

Sediments

Maintaining aerobic conditions over lake bottom sediments may also help improve the nutrient status of a lake. Fitzgerald (1970) found that aerobic lake muds can effectively sorb phosphorus and Mortimer (1941) demonstrated that a thin oxidized zone at the sediment surface retarded the movement of phosphorus from the sediments. Unfortunately, the yearly cycle of phosphorus exchange between the sediments and the water and the relative importance of sedimentary phosphorus releases to the overall trophic state remain poorly understood. Fast (1971) attempted to improve the phosphorus status of a small eutrophic lake by hypolimnetic aeration but eventually destratified the lake due to improper equipment design. He postulated that the increased bottom temperatures due to destratification accelerated sediment nutrient release, offsetting the benefits from improved dissolved oxygen concentrations.

AERATION TECHNIQUES

The objective of virtually all aeration projects is to improve dissolved oxygen conditions for fishery or water quality management purposes, but because of differences in technique and the effects of aeration on the thermal regime of a lake, it is convenient to recognize two separate categories—total aeration and hypolimnetic aeration.

The terms *total aeration* and *destratification* are frequently used interchangeably. They refer to the technique of increasing the dissolved oxygen content of the bottom waters of lakes by eliminating thermal gradients and mixing the entire water volume. Destratification is usually accomplished by lifting cold hypolimnetic water to the lake surface where it mixes with the warmer epilimnetic water and absorbs oxygen before sinking back to a new equilibrium depth. A very large volume of lake water can be circulated and aerated from a single site, and the lake will eventually become almost isothermal. The basic design of destratification equipment has undergone little change since Scott and Foley (1919) destratified a small water-supply reservoir by releasing diffused compressed air at the lake bottom. Mechanical water pumps have been used more recently to provide the energy required to lift the denser water to the surface, but, as Symons et al. (1967) noted, they are usually less efficient than air-lift systems. With either method, atmospheric oxygen transfer at the lake surface and photosynthetic oxygen production play an important role in the aeration process. Symons et al. (1967) could not detect any appreciable direct oxygen uptake from a diffused air destratification system installed in a Kentucky reservoir, and Riddick (1957) concluded that the aerating effect of the rising stream of bubbles from a destratification system was negligible compared to atmospheric exchange at the lake surface.

One disadvantage of total aeration is the change in the lake's seasonal heat content. Thermal gradients are eliminated and the temperature of the entire water mass may approach the normal surface temperature. This is a serious problem during the summer; destratification can completely eliminate potential cold water fish habitat and the cool hypolimnetic water preferred for municipal and industrial water supplies. By eliminating the cold water hypolimnetic sink, destratification can also permit a more rapid recycling of nutrients within the lake.

In recognition of the shortcomings of total aeration, several types of aeration devices have been designed to improve dissolved oxygen conditions in the hypolimnion of stratified lakes without disrupting thermal stratification. With these devices which result in *hypolimnetic aeration*, the bottom water is airlifted up a vertical tube, the rising bubbles are vented to the atmosphere, and the oxygenated bubble-free water is returned to the hypolimnion (Bernhardt 1967; Fast 1971; and Björk et al. 1972). One notable exception to this design is the hypolimnetic aerator described by Mercier and Perret (1949), in which water was pumped from the hypolimnion to a shore facility where it was sprayed into the air, collected, and returned to the hypolimnion. A similar system, using oxygen injection, has been developed by Union Carbide (1973). Speece (1971) described several other approaches to hypolimnetic aeration, all of which are in the experimental stage, including U-tube aeration, deep bubble injection, and down-flow bubble-contact aeration.

Various types of aeration devices have also been used in an attempt to prevent dissolved oxygen depletion and fish winterkill in lakes during periods of ice cover. Although both total and hypolimnetic aeration devices have been tried, the most popular methods are similar in design to destratification equipment. This type of aeration is called winter aeration, but does not represent a third separate aeration category, since the aeration is usually accomplished by means of the same devices used to produce total aeration. Compressed air is released from the lake bottom and the rising bubbles carry the slightly warmer bottom water to the surface to maintain an ice-free area. Winter aeration attempts have met with varying degrees of success (Greenbank 1945; Patriarche 1961; Seaburg 1966; Wirth 1970); however, most failures are probably due to undersized systems (Toetz, Wilhm and Summerfelt 1972).

Detailed descriptions of total and hypolimnetic aeration devices are found in Appendix 1.

We began background investigations at Mirror Lake in the latter part of 1971 and installed both hypolimnetic and total aeration equipment in the summer of 1972. During 1972 and 1973, the lake was managed with a complete aeration "package'–i.e., hypolimnetic aeration during summer stratification and winter ice cover, and total aeration during the spring and fall mixing periods. Although we had only limited success with hypolimnetic aeration, we did gain valuable insight into the chemical and biological response of Mirror Lake to aeration.

In conjunction with the aeration project, a study was carried out to determine the effects of urban runoff at Mirror Lake and the influence of storm sewer drainage on lake management (Peterson and Knauer 1975). A few preliminary results from this concurrent study are reported herein.

SITE DESCRIPTION

Mirror Lake (Fig. 1) is located within the city limits of Waupaca, Wisconsin (Sections 29 and 30, T22N, R12E, Waupaca County). Surface area of the lake is 13 acres, and maximum depth is 43 ft. Of the 0.7 mile of shoreline, about three-fourths is in private ownership, with 29 year-round residences. The remainder is owned by the city, which maintains two municipal water supply wells and a park on the lake frontage.

The lake is situated in a kettle hole near the pitted eastern margin of the Cary outwash plain (Possin 1973), and was presumably formed by an ice block stranded in the melt water flood from the receding Green Bay lobe of the Cary ice sheet during Pleistocene glaciation. In the vicinity of Mirror Lake, the outwash consists of a 50- to 100-ft thick sequence of medium- to coarse-grained sand with gravel lenses. It overlies 50 ft of glacial till, which in turn rests on granite bedrock (Possin 1973).

No surface streams enter Mirror Lake, and the outline of the drainage basin is controlled to a great extent by street curbs and gutters. Because of the relatively high percentage of impervious surface in the watershed, storm sewer drainage makes up a significant portion of the water budget. In a comprehensive study of the hydrology of Mirror Lake, Possin (1973) concluded that storm sewers contribute about 26 percent of the yearly water input; a d diffuse surface flow, ground water, and direct precipitation on the lake's surface contribute 10, 21, and 43 percent, respectively.

The outlet from Mirror Lake drains into Shadow Lake, a 40-acre lake about 500 ft downstream, but during most of the year the channel is either weed choked or nearly frozen solid. As a result, ground water seepage and evapotranspiration account for most of the water losses.

During the years, 1908-13, Mirror Lake was the main source of municipal drinking water for the City of Waupaca, but since the completion of urban development and the construction of storm sewers around the lake in the late 1930's, the condition of the lake has steadily deteriorated (Fig. 2). As early as 1948, there is evidence for dissolved oxygen depletion in the hypolimnion, and by 1955, a

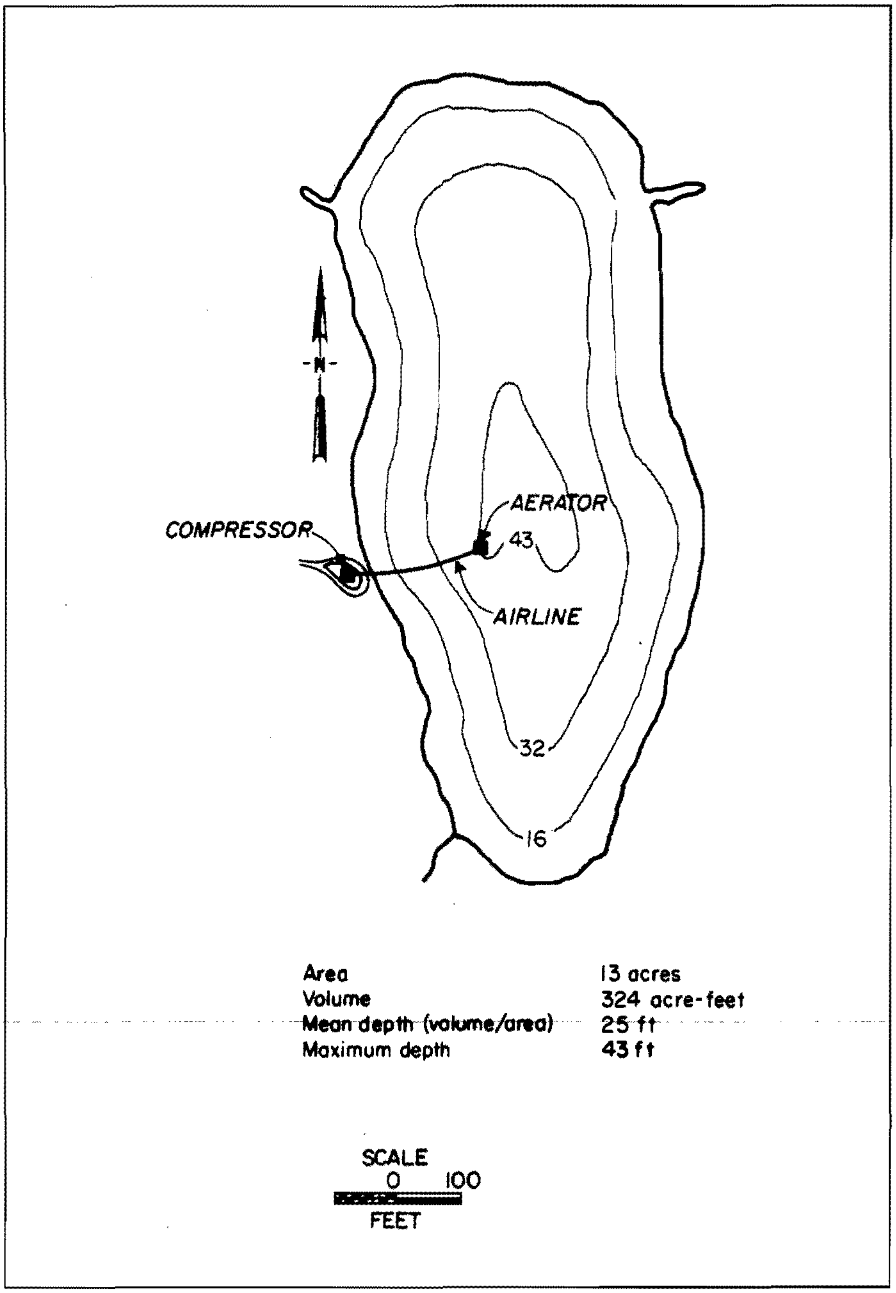

FIGURE 1. *Bathymetric map of Mirror Lake.*

TABLE 1. *Selected water chemistry data for Mirror Lake, 1971-72.*

Lake Condition and Date	Depth (ft)	Tot-P (μg/l)	Dis-P (μg/l)	Org-N (mg/l)	NH_4-N (mg/l)	$CaCO_3$ (mg/l)	pH
Fall turnover (12-2-71)	6.5	60	24	0.88	0.40	100	8.2
	20	70	24	0.94	0.44	152	8.2
	32	90	21	0.95	0.45	152	8.3
	43	880	729	1.22	8.78	248	7.9
Winter stratification (3-16-72)	6.5	70	8	0.92	0.56	157	7.5
	20	40	<5	0.84	0.58	162	7.5
	32	90	33	0.83	0.82	261	7.4
	43	710	648	2.36	4.65	244	7.1
Spring turnover (4-26-72)	6.5	50	5	0.84	0.04	130	8.3
	20	80	28	1.20	0.10	144	7.5
	32	40	15	0.69	0.91	150	7.3
	43	540	467	0.97	4.96	214	6.8
Summer stratification (8-9-72)	6.5	20	0.0	0.69	0.26	110	8.8
	20	20	19	0.74	0.14	151	8.7
	32	220	149	0.88	4.13	200	7.4
	43	550	515	1.32	7.53	244	7.3

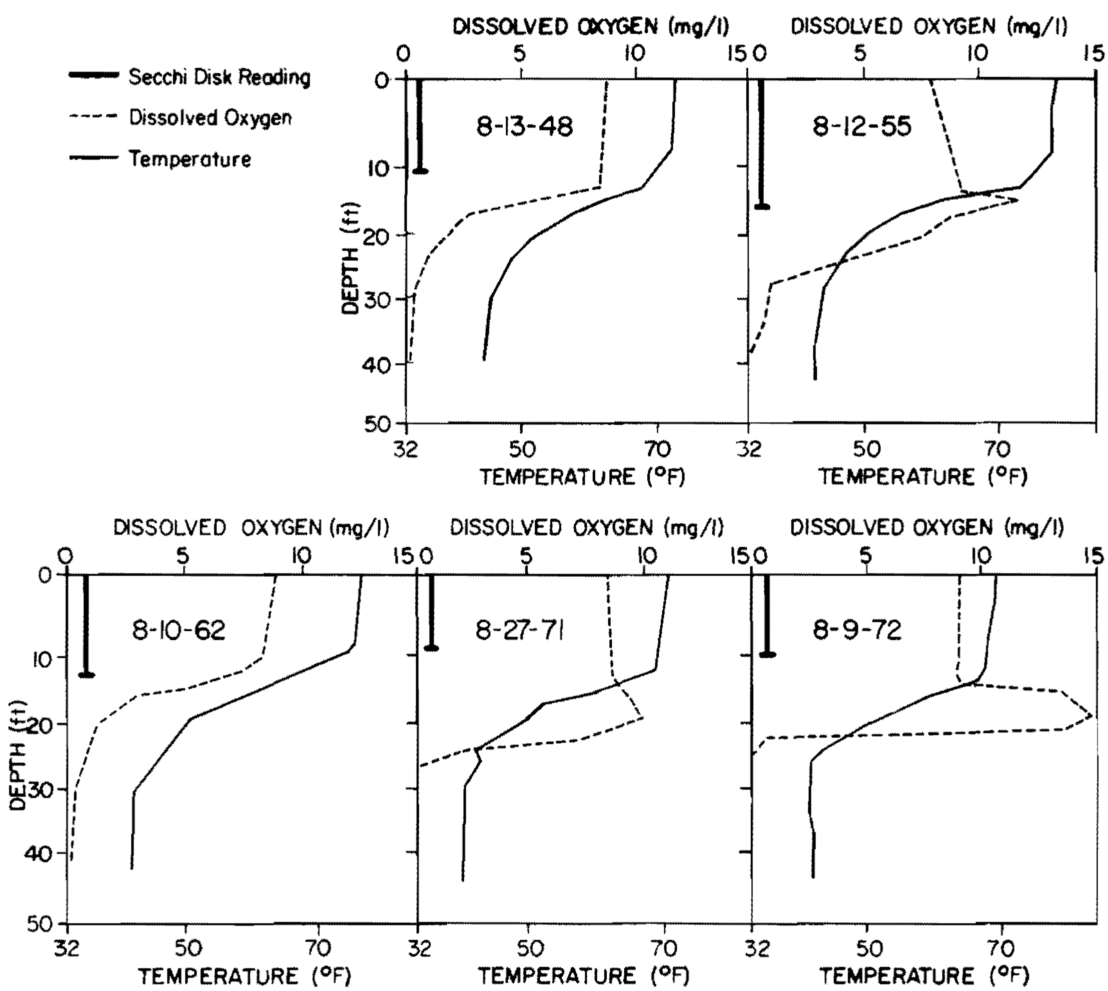

FIGURE 2. *Summer temperature and dissolved oxygen profiles for Mirror Lake for 5 years during the period, 1948 to 1972.*

metalimnetic oxygen maximum was recorded. Similar maxima in later years have coincided with a dense population of *Oscillatoria rubescens*, an oligophotic and oligothermal blue-green algae which is not uncommon in the metalimnion and/or upper hypolimnion of eutrophic lakes (Hutchinson 1967; Ravera and Vollenweider 1968).

Table 1 presents selected water chemistry data for Mirror Lake. Extremely high nutrient concentrations persist in the bottom waters even through the circulation periods, and temperature and dissolved oxygen data indicate that mixing was incomplete during the fall of 1971 and the spring of 1972. Apparently the sheltered location of Mirror Lake and the small surface area relative to depth preclude sufficient wind-induced turbulence to provide thorough mixing.

The Wisconsin Department of Natural Resources has managed Mirror Lake for a trout fishery, but the overwinter survival of the fish population in recent years has been somewhat questionable. During the 1971-72 winter, we recorded a severe oxygen depletion in Mirror Lake; prior to ice-out, dissolved oxygen was completely absent from the 6.5-ft depth to the lake bottom. The biological oxygen demand of the bottom waters was as high as 39 mg/l, which may have been in part due to the persistence of anoxic conditions in the hypolimnion since at least the early summer, and perhaps much longer.

METHODS AND MATERIALS

We installed a hypolimnetic aerator in Mirror Lake in early August 1972. The major component of the aerator consisted of a 40-ft long, 18-in diameter "Helixor,"* an extruded polyethylene tube with an internal longitudinal plate dividing the tube in half and twisted to form a helix. Air was supplied to the base of the "Helixor" via 250 ft of 1.5-in, ID-weighted polyethylene tubing, and two 0.4-in holes in the end of the capped tube released air into each half of the "Helixor." Water and air lifted up the "Helixor" entered a 4-ft by 4-ft by 8-ft styrofoam-covered plywood separation box at the surface of the lake, where the bubbles were vented to the atmosphere. The water returned to the hypolimnion through two 50-ft long, 18-in diameter, neoprene-impregnated flexible nylon tubes. Part d of Figure 26 (Appendix 1) shows a schematic of the aerator in operation.

A skid-mounted, air-cooled compressor rated at 16 cfm, 0 lb/in^2 was used as a primanry air source. It was powered by a 5-hp, 230/460-60-3 electric motor. A larger, trailer-mounted, gasoline-powered compressor capable of supplying up to 42 cfm of air was used for testing the aerator at higher air delivery rates.

We assembled the four-piece "Helixor" on shore and floated it out into position in the lake. After clamping on the airline and about 300 lb of concrete block weights, we lowered the base of the unit to the lake bottom in 42 ft of water. The anchors sank into the bottom sediments and the "Helixor" eventually stablized with the base about 16 in above the lake bottom and the top about 8 in below the lake surface. When attached to the top of the "Helixor," about 1 ft of the separation box was submerged.

For total aeration, we connected the electric-powered compresser to a second air line which was anchored in the deepest part of the lake. The end of the line was capped and we perforated the distal end for a distance of about 16 ft to allow the air to escape.

The biological and chemical methodologies used during this study are presented in Appendixes 2 and 3.

AERATOR PERFORMANCE

In order to test the oxygen transfer characteristics of the hypolimnetic aerator, we constructed a holder for a dissolved oxygen meter probe which could be inserted into holes we had drilled through the wall of the "Helixor" at regular intervals. The probe was held about 2 in away from the inside wall of the "Helixor" with the membrane facing upward. A shield below the probe minimized bubble interference, and a rubber stopper on the probe holder provided a leakproof seal with the wall. A diver inserted the probe into each hole.

The dissolved oxygen content of the water being drawn into the "Helixor" at the bottom was zero throughout the test. At the 10-ft level, the concentration increased to 0.7 mg/l, and at 20 ft above the base, the dissolved oxygen concentration was 2.3 mg/l. Above this point, no further increase in dissolved oxygen was recorded; the concentration at 30 ft and at the top of the "Helixor"—40 ft above the base—remained 2.3 mg/l. Inside the separation box, however, the dissolved oxygen concentration varied from 2.3 mg/l at the center to 3.5-4.0 mg/l at the edges.

Dissolved oxygen levels increased slightly in the separation box as the water moved away from the central boil, but they decreased as the water flowed down the return tubes. From 3.9 mg/l at the top of the return tubes, dissolved oxygen levels dropped to 3.2 mg/l at a distance of about 30 ft and to a 2.7 mg/l at 43 ft. No zone of increased disolved oxygen could be located in the lake at the end of the return tubes, although divers reported that a steady stream of water could be felt coming out of the tubes.

We took several flow measurements inside the return tubes with a horizontal axis flowmeter* to determine water flow rates and the oxygen transfer efficiency. Water was moving through the aerator at a rate of about 4.2 cfs or 8.4 acre-ft/day. (This is a nominal flow rate; we took maximum velocity measurments at the center of the return tubes.) Based on air supply rate of 16 cfm and a dissolved oxygen increase to 3.9 mg/l inside the separation box, the transfer efficiency of the aerator was about 20 percent. These calculations do not take into account the high oxygen demand of the water, indicated by both the presence of particulate manganese oxide in the separation box and the very noticeable odor of hydrogen sulfide.

After operating for about 5 days with the electric compressor, we brought the larger gasoline-powered compressor to Mirror Lake in an attempt to improve the aerator performance. We ran the compressor at four different pressure settings and estimated the air flow rate from standard pneumatic tables and from the orifice diameter at the reuglator. At air flow rates above 25 cfm, the rate of water flow through the aerator began to decrease, apparently due to either the displacement of water by air inside the "Helixor", or because of increased resistance to flow in the return tubes. In addition, we could not achieve dissolved oxygen levels above 5.0 mg/l in the separation box with the

*Polcon Corp., Montreal, Canada.

*General Oceanics Model 2300.

gasoline-powered compressor, even though it could deliver more than twice as much air as the electric compressor. The oxygen transfer efficiency of the aerator decreased from about 20 percent to 14 percent as air flow rates increased, and because of its mediocre performance and the high noise levels associated with the operation of the gasoline compressor, we discontinued its use.

In a further attempt to overcome the high rate of oxygen demand, we began supplying pure oxygen to the aerator on 16 August. A 3,000-ft^3 tank of liquid oxygen was connected to the aerator and we continuously recorded the weight of the tank to determine the rate of oxygen flow. With pure oxygen, the dissolved oxygen concentration in the separation box was about 13.4 mg/l, but measurements inside the "Helixor" indicated that most of the oxygen transfer still took place in the lower half.

Although the use of pure oxygen produced a substantial increase in the dissolved oxygen content of the water, water flow rates through the aerator and transfer efficiencies (about 16 percent) were low. However, by using the electric compressor in conjunction with liquid oxygen, we found that we could maximize aerator performance. With this scheme, about 23 cfm of an air-oxygen mixture was delivered to the aerator, giving a water flow rate of about 5.3 cfs. Dissolved oxygen levels in the separator box were about 8.6 mg/l, and the concentration decreased only slightly during the trip down the return tubes. The transfer efficiency, based on an air supply rate of 16 cfm and an oxygen supply rate of 5.5 cfm was 23 percent. Water flow rates were also near the maximum, based on earlier testing with the gasoline-powered compressor.

RESULTS

The results of the Mirror Lake aeration are presented in chronological order to avoid confusion between periods of hypolimnetic and total aeration. We underestimated the oxygen demand of the hypolimnetic waters; for this reason, the hypolimnetic aerator did not have sufficient capacity to alleviate the anoxic conditions. The results of hypolimnetic aeration are, therefore, a descriptive account of and explanations for the physico-chemical and biological changes that did (or did not) take place.

Hyplolimnetic Aeration, Summer 1972

We ran the hypolimnetic aerator during late summer (10 August-9 September), using both compressed air and pure oxygen. During this period, the total oxygen input as measured by the dissolved oxygen concentration within the separation box and by the rate of water flow through the aerator was 5,512 lb. The oxygen input into the hypolimnion volume of 82 acre-ft was equivalent to a concentration of about 25 mg/l. However, we were apparently unable to meet the rate of oxygen demand; dissolved oxygen concentration in the hypolimnion never exceeded 0.8 mg/l (Table 2). Interestingly, there was little change in the biochemical oxygen demand of the hypolimnion during this period, and manganese and iron concentrations remained relatively high (Table 3).

It is likely that we were introducing oxidizable organic material into the hypolimnion with the aerator. Prior to aeration, a dense population of *O. rubescens* occupied a narrow stratum of water at the metalimnion-hypolimnion interface, with a maximum population biomass of 1.9 mg/l* at the 26-ft level. By the end of August, the aerator had circulated this stratified population throughout the hypolimnion, offsetting any biological oxygen demand decrease due to oxygenation.

Additional chemical data support this conclusion. Total phosphorus in the hypolimnion remained stable from the latter part of August to the end of the aeration period, while at the same time, dissolved phosphorus was effectively reduced (Fig. 3). Apparently the observed loss in dissolved phosphorus was balanced by an input of organic phosphorus from *O. rubescens*. There was also a marked increase in the hypolimnetic organic nitrogen concentration at the time that *O. rubescens* was incorporated into the bottom waters (Fig. 5). Assuming 75 percent of the 135-lb organic nitrogen increase was due to *O. rubescens* and using a nitrogen-phosphorus ratio of 18:1 for blue-green algae (Burns and Ross 1972), the organic phosphorus contribution should have increased by 5.7 lb. (The 75-percent figure corresponds to the sestonic contribution from a similar population during the summer of 1973.) The calculated 5.7-lb increase in organic phosphorus approximates the observed loss of 7 lb in dissolved phosphorus and explains the constant total phosphorus concentration during the latter stages of aeration.

Both ammonium-nitrogen and total phosphorus concentrations increased during the initial stages of aeration, probably due to sediment disruption, and ammonium-nitrogen concentrations decreased only slightly during

*Based on cell volume and assuming one mm^3 is equivalent to one mg fresh weight.

TABLE 2. *Selected dissolved oxygen concentrations and temperatures in Mirror Lake during hypolimnetic aeration, fall 1972.*

Date	Depth (ft)	DO (mg/l)*	Temperature (°F)
12 August 1972	26	0.0	41.5
	39	0.0	41.3
	43	0.0	41.5
20 August 1972	26	0.3	44.0
	39	0.1	43.0
	43	0.1	43.2
29 August 1972	26	0.75	44.6
	32	0.2	44.4
	39	0.1	44.0
	43	0.1	43.7
8 September 1972	26	0.2	44.4
	39	0.2	44.2
	43	0.2	44.2

*Dissolved oxygen determinations by the azide modification of the Winkler method.

the remainder of the aeration period, suggesting that ammonia air-stripping was not occuring. This is reasonable, considering that only 0.16 percent of the ammonium-nitrogen in the hypolimnion would be present in the form of ammonia at the prevailing hypolimnetic temperatures and pH (Trussell 1972). In addition, there was no significant trend in nitrate nitrogen concentrations during aeration, and it is difficult to place emphasis on the minor fluctuations that did occur. Algal assay data from before and after hypolimnetic aeration also indicated no significant change in the biomass response of laboratory algae (Uttormark and Fitzgerald 1973).

TABLE 3. *Selected results of analyses for biochemical oxygen demand, chemical oxygen demand, total manganese, and total iron for Mirror Lake, 1971-73.*

Date	Depth (ft)	BOD_5 (mg/l)	COD (mg/l)	Mn (μg/l)	Fe (μg/l)
2 December 1971	3	2.8			
	39	5.5			
	43	39.0			
20 July 1972	43			400	
9 August 1972	3	1.3			
	30	20.0			
	43	15.0			
8 September 1972	6	3.7		40	40
	26	6.8	25	70	160
	32	15.0	25	100	220
	39	22.0	23	150	220
	43	22.0	23	130	480
20 September 1972	6	3.1		< 40	60
	26	18.0		410	200
	32	15.0		450	200
	39	16.0		380	260
	43	27.0		460	400
30 January 1973	6	2.8		< 40	60
	26	1.8		< 40	40
	32	1.8		60	<40
	39	8.0		460	440
	43	7.1		70	1,120
9 July 1973	6	3.4			
	20	15.0			
	26	3.1	18		
	32	3.4	14		
	39	2.8	19		
	43	2.8	16		
30 July 1973	6	8.6			
	20	9.4			
	26	7.8			
	32	8.2			
	39	8.6			
	43	9.0			

Total Aeration, Fall 1972

Due in part to our inability to increase the hypolimnetic oxygen concentrations with the hypolimnetic aerator, we decided to destratify Mirror Lake prior to winter freeze-up. (The hypolimnetic aerator had virtually no effect on the thermal regime and the lake was still strongly stratified when we shut down the hypolimnetic unit.) We began total aeration on 19 October 1972 and operated continuously through 21 November 1972. The immediate result of destratification was a marked decline in dissolved oxygen levels to a minimum of 0.9 mg/l (Fig. 6), but they gradually increased to a maximum of 12.1 mg/l on 28 November. This represented a substantial improvement over the 3.0 mg/l maximum recorded the previous year and greatly increased the capacity of the lake to withstand the process of winter oxygen depletion.

There was an increase in the phytoplankton crop during the aeration period (Fig. 7), apparently due to several factors. Unusually heavy rainfall contributed to a high nutrient input to the lake via the storm sewers (Peterson and Knauer 1975). Mixing of anoxic hypolimnion water into the trophogenic zone could also be expected to provide available nutrients. *Oscillatoria rubescens* accounted for nearly all of the increased phytoplankton biomass during aeration and a correlation coefficient of 0.97 existed during October and November between cell volumes of *O. rubescens* and organic nitrogen. The data from algal assay experiments on the epilimnion waters indicated an order-of-magnitude increase in laboratory algal production following destratification (Uttormark and Fitzgerald 1973).

Hypolimnetic Aeration, Winter 1973

After the onset of ice cover, there was a rapid depletion in the dissolved oxygen content of the bottom waters of Mirror Lake. A concurrent decline in organic nitrogen suggests that a massive algal die-off occurred (based on the strong correlation between organic nitrogen and *O. rubsecens* during the fall), providing oxidizable material for bacterial degradation. In an attempt to alleviate the anoxic conditions in the bottom waters, we started the hypolimnetic aerator on 30 January 1973 and ran it continuously for the next 37 days.

The separation box remained frozen into the lake ice during the entire period, eliminating the open water hazard usually associated with winter aeration but also decreasing the flow rate by 40 percent. Since the separation box could not sink in response to the flow of water through the "Helixor," the air-lift was forced to act against a pressure head of several inches of water, greatly reducing its efficiency.

We apparently added little oxygen directly to the lake during winter aeration, but because of the very small temperature gradients in the lake, the aerator mixed the entire lake from the 6.5-ft level on down, substantially improving the dissolved oxygen condi-

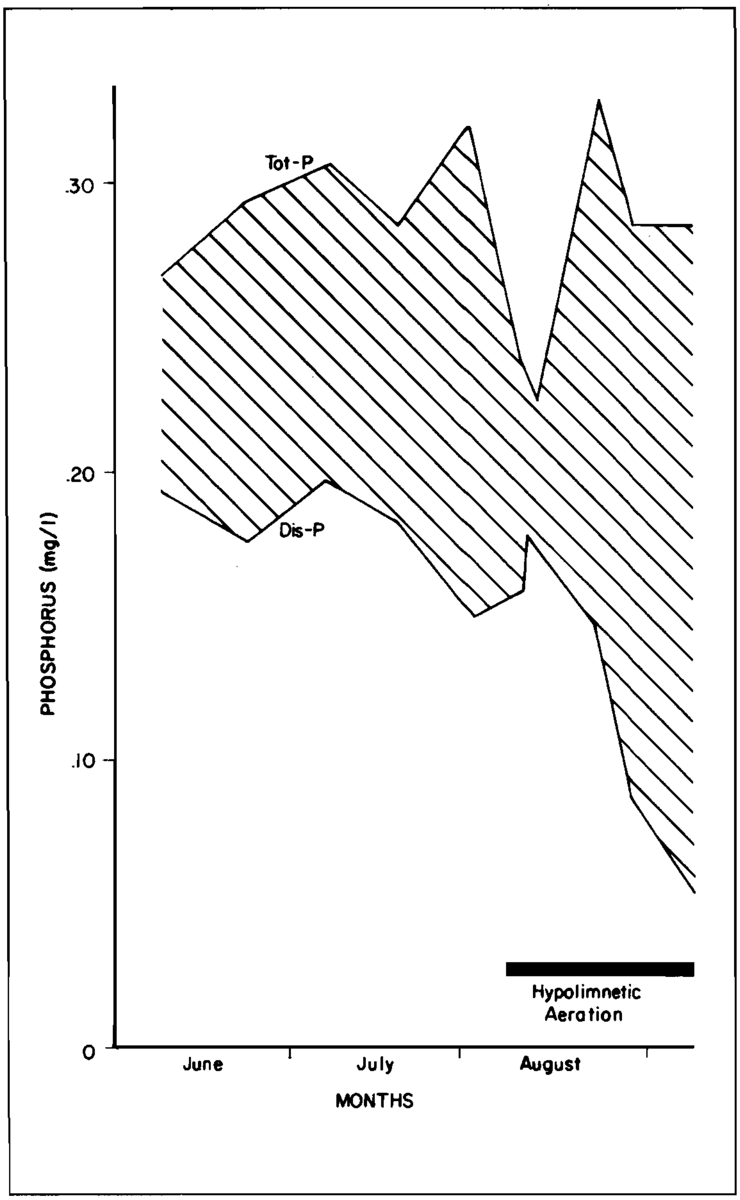

FIGURE 3. *Weighted average hypolimnetic phosphorus concentration in Mirror Lake, 1972.*

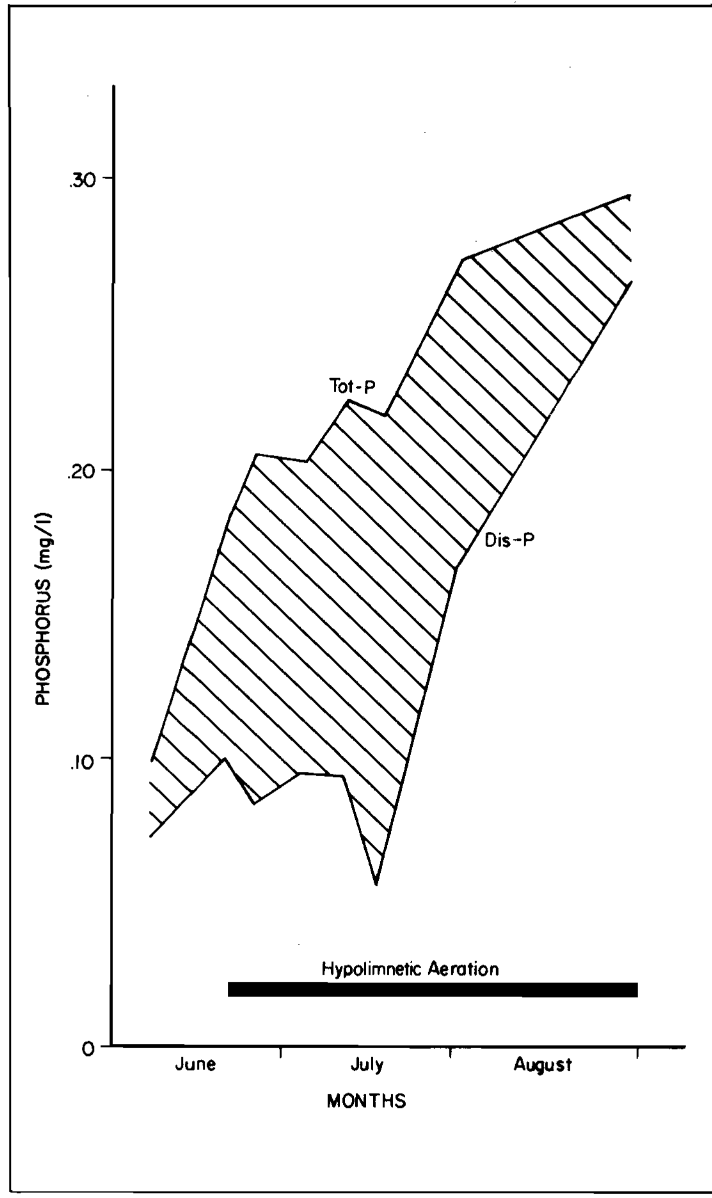

FIGURE 4. *Weighted average hypolimnetic phosphorus concentration in Mirror Lake, 1973.*

tions at the bottom (Fig. 8). However, the aerator was largely ineffective in retarding the rate of oxygen depletion. Based on a weighted average dissolved oxygen concentration decline from 8.2 to 4.0 mg/l during the 110 days of ice cover during the 1972-73 winter, the dissolved oxygen depletion rate for the entire lake was 0.038 mg/l/day, nearly the same as the 0.040 mg/l/day recorded during the previous winter.

Total Aeration, Spring 1973

To maintain oxic waters over the sediments after ice-out, the total aeration system was operated between 30 March and 23 April. By 23 April, 11.2 mg/l of dissolved oxygen were present throughout the lake (Fig. 6), and we shut down the air compressor to let the lake stratify. At the onset of stratification, the hypolimnion was approximately 5° F warmer than the previous year.

During aeration, there was an increase in algal biomass from 1.7 mg/l on 26 March to 5.5 mg/l on 30 April (Fig. 7), with *O. rubescens* again as the dominant phytoplankter. The total increase in the phytoplankton biomass was probably not entirely the result of artificial mixing; dimictic lakes of this region normally have a spring phytoplankton pulse.

Hypolimnetic Aeration, Summer 1973

Hypolimnetic dissolved oxygen conditions were monitored during stratification, and it was evident that complete anoxia would again develop in the hypolimnion by the end of June. From the maximum dissolved oxygen concentration at turnover, 11.0 mg/l, hypolimnetic dissolved oxygen was depleted at the rate of 0.18 mg/l/day. The hypolimnetic aerator was started up on 21 June and operated until 28 August, but as with previous attempts, the results were not completely satisfactory.

Based on the dissolved oxygen concentration within the separator box and the rate of water flow through the aerator, a total of 6,472 lb of dissolved oxygen was supplied to the hypolimnion during the two-month period, or 29.3 mg/l on a volume basis. A maximum increase in the weighted average hypolimnetic dissolved oxygen

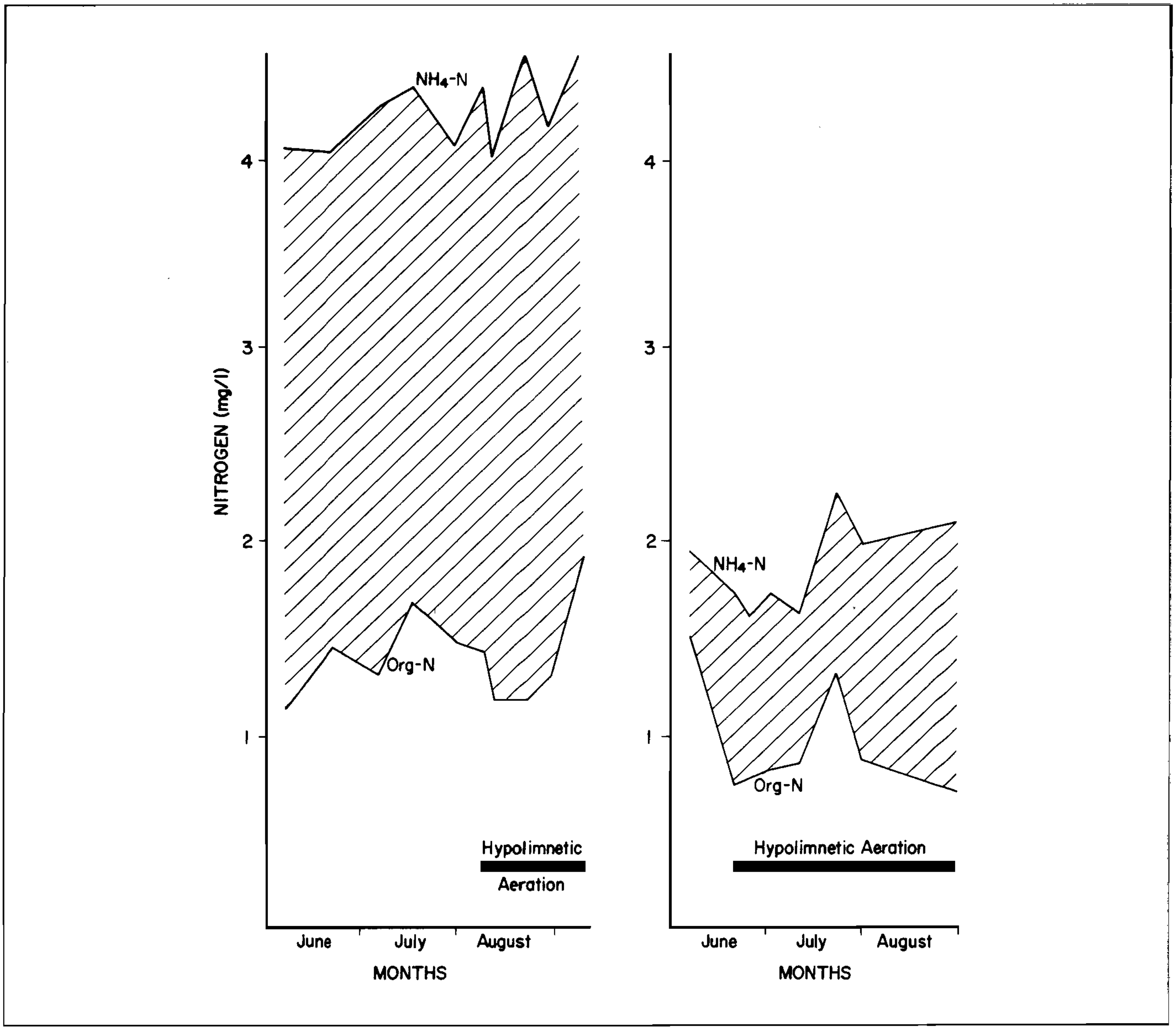

FIGURE 5. *Weighted average hypolimnetic nitrogen concentration in Mirror Lake, 1972 and 1973.*

from 0.0 to 1.7 mg/l was recorded, coincident with the addition of 1,120 lb of pure oxygen between 12 July and 21 July, but after oxygen injection, the compressor alone was unable to meet the rate of oxygen demand. The biochemical oxygen demand of the hypolimnion before aeration was about 80 percent lower than during the previous year and the chemical oxygen demand was 4-11 mg/l less (Table 3); however, a stratified population of *O. rubescens* in the metalimnion prior to start-up once again represented a major source of oxidizable organic material (the biochemical oxygen demand of 15 mg/l at the 20-ft depth on 9 July corresponded to an algal biomass of 14 mg/l). After 39 days of aeration, the biochemical oxygen demand of the hypolimnion had in-

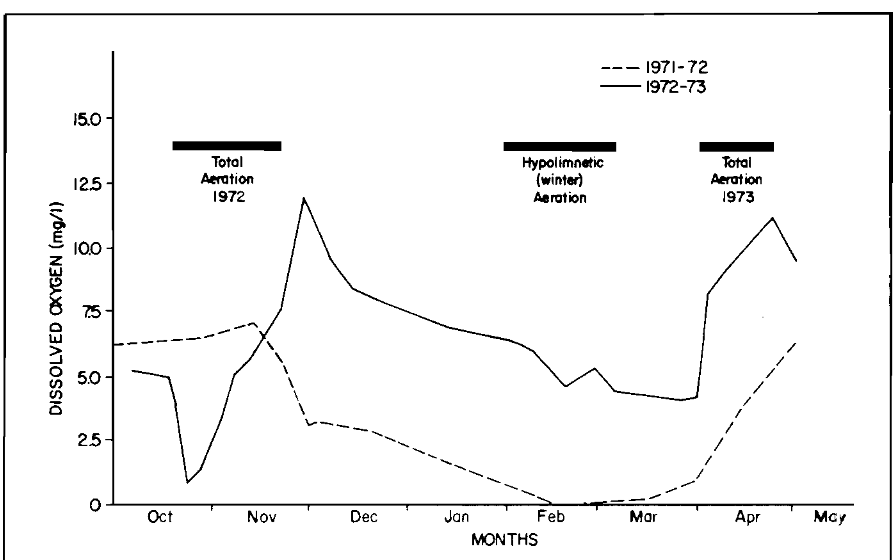

FIGURE 6. *Dissolved oxygen content of Mirror Lake between fall and spring mixing periods, 1971-72 and 1972-73.*

creased by a factor of two or three, suggesting once again that *Oscillatoria* might be contributing to the oxygen demand.

In contrast to the previous summer, dissolved phosphorous increased during the 1973 hypolimnetic aeration from 0.1 mg/l to 0.26 mg/l. An increase in total phosphorous from 0.19 mg/l to 0.29 mg/l was also recorded (Fig. 4). Ammonium nitrogen increased gradually from 0.90 mg/l to 1.5 mg/l, and organic nitrogen declined erratically (Fig. 5).

Algal assay results on hypolimnetic water (Uttormark and Fitzgerald 1973) indicated that laboratory algal production increased by more than an order of magnitude from June to August. The assay procedure also suggested a change from both a phosphorus- and nitrogen-limiting environment to a nitrogen-limiting environment in the Mirror Lake hypolimnion. These data correspond to the measured increase in phosphorus during aeration.

The source of the additional phosphorus is not clear. Schindler et al. (1971) reported that the increase in hypolimnetic phosphorus in ELA* lake 227 could be accounted for by sedimenting seston. It is possible that, over a period of several months, sedimenting *O. rubescens* cells from the metalimnion could account for the increase, either directly as seston or indirectly via decomposition products. The phosphorus product of decomposition could also have supported the earlier vernal phytoplankton bloom. The role of sedimentary phosphorus release is an additional unknown.

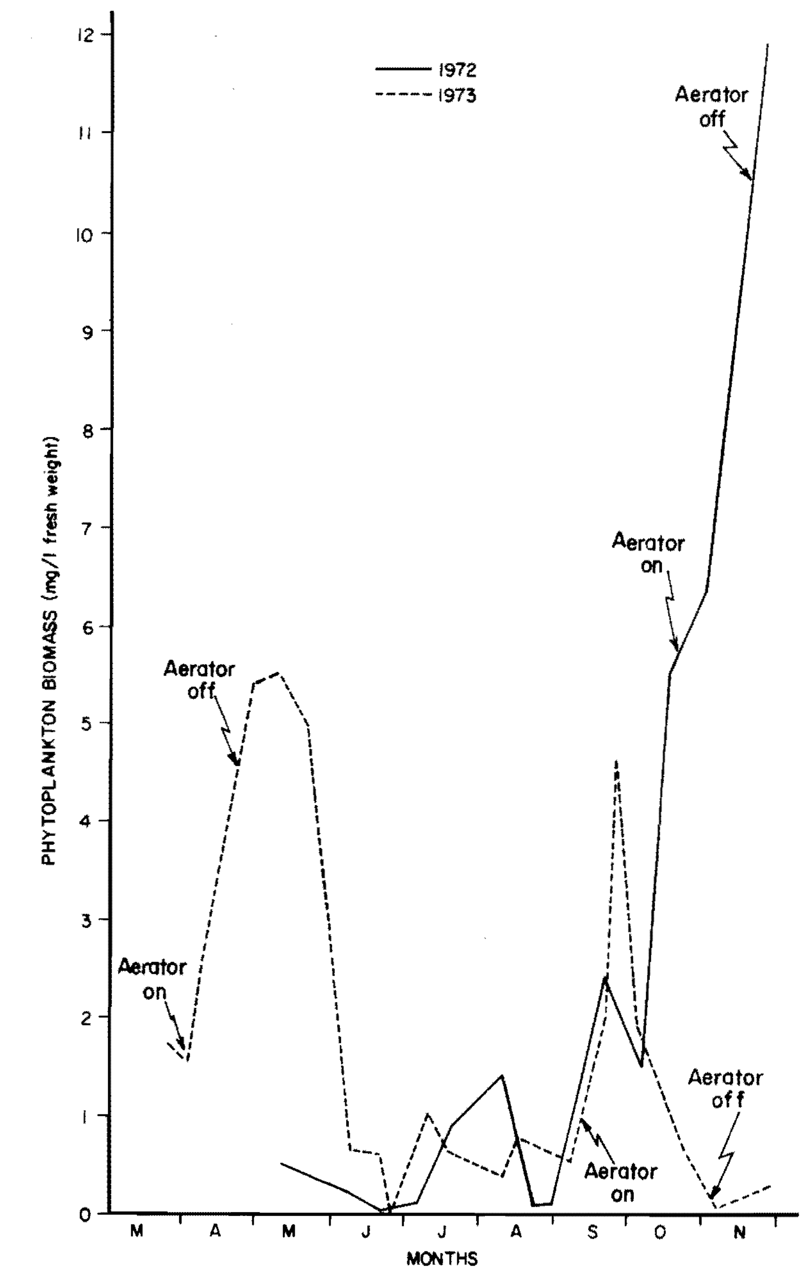

FIGURE 7. *Phytoplankton biomass in Mirror Lake, 1972 and 1973.*

DISCUSSION

Dissolved oxygen depletion in a lake is due to uptake at both the sediment-water interface and in the free water. In a discussion of the depletion process, Hutchinson (1957) lists four factors which influence the rate of uptake: (1) animal respiration, (2) plant respiration at night or when respiring organisms settle below the compensation zone, (3) bacterial respiration, and (4) chemical demand. Studies by Zobell and Stodler (1940), Hutchinson (1957), and Menon, Marion, and Miller (1972) conclude that bacterial respiration could readily reduce the dissolved oxygen in a hypolimnion to very low levels during a period of 3-4 months of summer stagnation, if provided with a continuous supply of respirable organic material. Burns and Ross (1972) have shown that sedimenting phytoplankton supports sufficient bacterial activity to create anoxic conditions in the hypolimnion of Lake Erie.

As the rate of supply of oxidizable material to a lake bottom increases, anaerobic metabolism may be expected to assume a role of increasing importance in the mineralization of the organic matter in the sediments (Pamatmat and Bhagwat 1973). Bacterial degradation of organic matter under anerobic conditions can contribute mineralized by-products that may increase the chemical oxygen demand, as for example, in the biological reduction of sulfates to sulfides:

$$SO_4^{=} + 2CH_2O + 2H^+ \rightarrow H_2S + 2CO_2 + 2H_2O.$$

*Experimental Lake Area.

The chemical oxidation of hydrogen sulfide can be both spontaneous and instantaneous:

$$H_2S + 2O_2 \rightarrow 2H^+ + SO_4^=.$$

The metallic sulfides of iron and manganese may also be involved. The large seasonal blooms of *O. rubescens* that occurred in the late fall of 1972 (12 mg/l), the spring of 1973 (5.5 mg/l), and in the metalimnion during the summer of 1973 (maximum of 14 mg/l during July), indicate a steady supply of renewable organic material sediments into the hypolimnion of Mirror Lake.

Schindler et al. (1971) have demonstrated in artificial nutrient enrichment experiments of ELA Lake 227 that the rate of phosphorus loading, rather than the amount of phosphorus in solution, is responsible for continued increases in phytoplankton biomass. Our data indicate that there is sufficient nutrient loading into Mirror Lake to support a substantial phytoplankton crop. The phosphorus and nitrogen loading rates in Mirror Lake for 1971-72 were high enough, on an annual basis, to exceed Vollenweider's (1968) dangerous limits (Table 4). The sources of external phosphorus loading are diagrammed in Figure 9.

The combination of hypolimnetic and total aeration in Mirror Lake was insufficient to meet the rate of oxygen uptake imposed by the continuous external supply of nutrients and its associated crop of algae. However, even though there was no satisfactory improvement in the dissolved oxygen regime, we were able to successfully eliminate reducing conditions in the bottom waters, based on the dissolved phosphorus-total phosphorus ratio. Anoxic conditions generally favor high concentrations of dissolved phosphorus, whereas oxic conditions generally favor total phosphorus. Figure 10 represents the dissolved phosphorus-total phosphorus ratio at 43 ft from August 1971 through August 1973 for Mirror Lake. With the exception of the hypolimnetic aeration during the summer of 1973, a marked change in the ratio was very evident during periods of aeration. Unfortunately, the improved conditions were only temporary.

In summary, hypolimnetic aeration was unable to maintain satisfactory oxygen levels in the hypolimnion of Mirror Lake during the summer operation of 1972 and 1973. Reductions in biochemical and chemical oxygen demand were evident following fall and spring aeration and mixing period, but there was no positive trend during hypolimnetic aeration, probably due to an increased rate of supply of organic material. Total phosphorus increased in the lake over the aeration period (August 1972 to July 1973) as compared to the control year (August 1971 to July 1972). A statistical evaluation by analysis of variance showed a significant increase in the concentration of total phosphorus between the two periods (Fig. 11). This increase may be allochthonous (storm sewer input) and/or autochthonous (sediment disruption). However, there was also a storm sewer input during the control year, so sediment disruption due to aeration seems to be a likely source. A similar statistical evaluation of organic nitrogen and ammonium-nitrogen showed no significant differences in the concentrations of these nutrients between the two periods (Fig. 12).

RECOMMENDATIONS

Although a comprehensive description of the Mirror Lake environment is not possible, the following recommendations for improving Mirror Lake

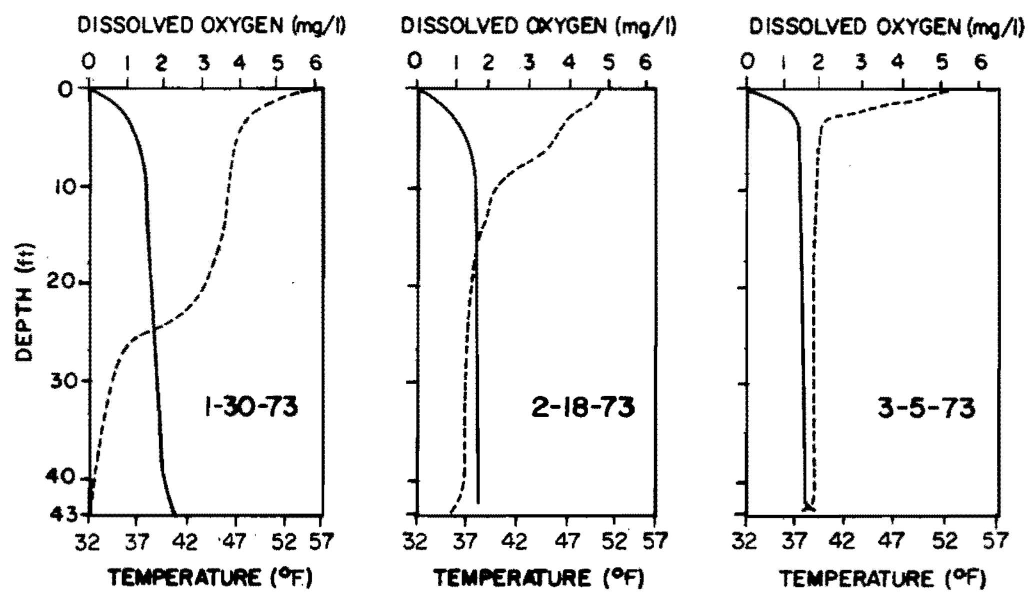

FIGURE 8. *Dissolved oxygen and temperature profiles in Mirror Lake during winter aeration, 1973. (The aerator was in operation from 30 January to 8 March).*

water quality can be made, based on the available data:

(1) To the fullest extent possible, nutrients which support phytoplankton growth must be prevented from entering the lake. Diversion of storm water would reduce the external nutrient loading.

(2) The high organic content of the sediments must be oxidized. If step one is carried out, aeration could be beneficial in oxidizing the organic content at the sediment-water interface at an accelerated rate.

(3) Methods of reducing autochthonous nutrient release from the sediments, i.e., alum treatment (Peterson et al. 1973; Peterson and Knauer 1975), should be considered.

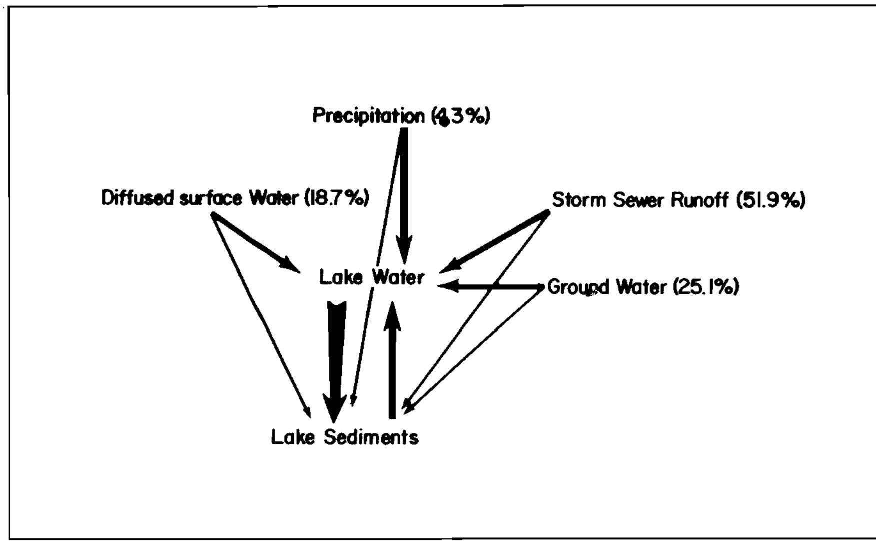

FIGURE 9. *Phosphorus loading in Mirror Lake. (After Possin 1973.)*

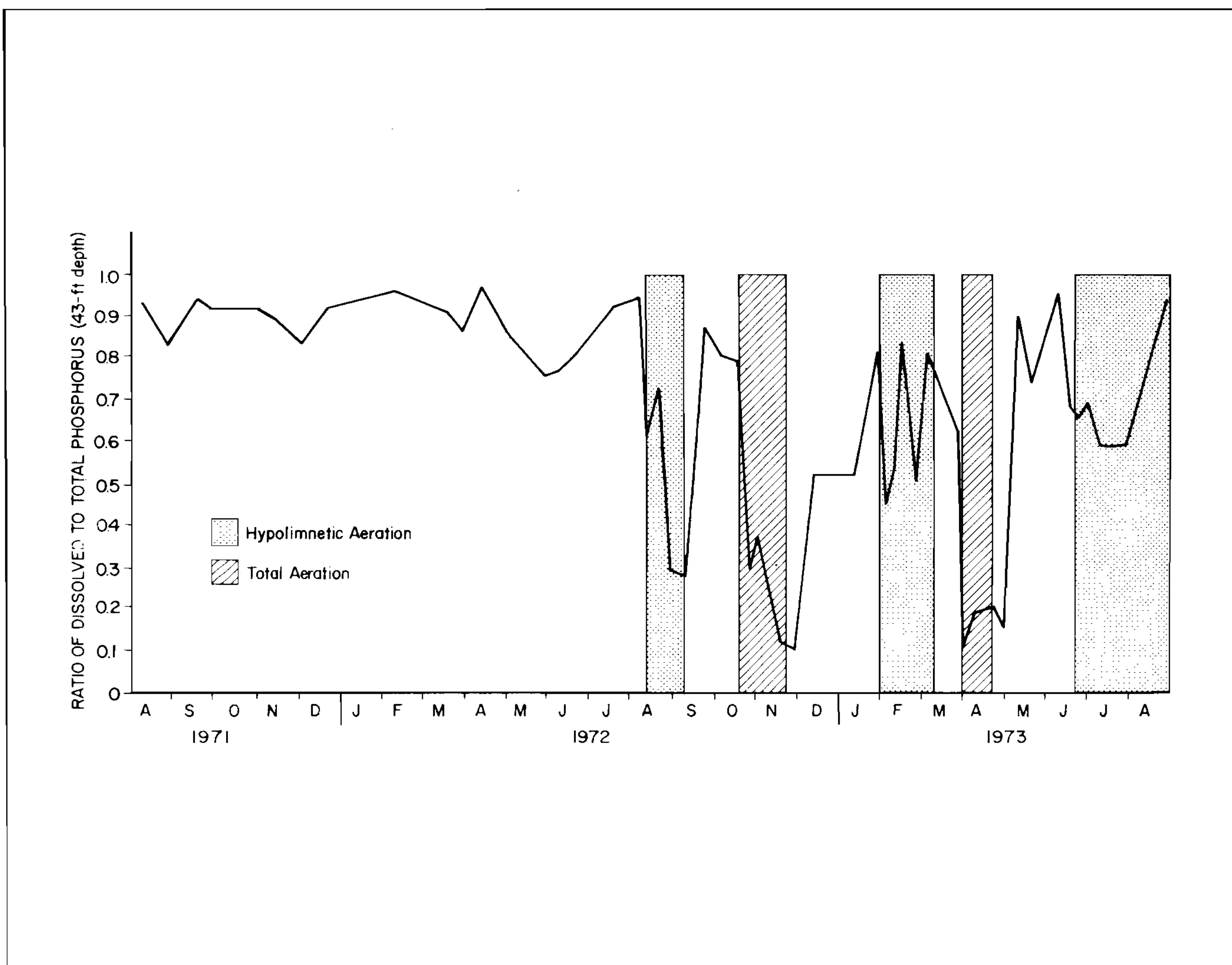

FIGURE 10. *Ratio of dissolved phosphorus to total phosphorus in Mirror Lake, 1971-73.*

TABLE 4. *Comparative nutrient loading rates for Mirror Lake.*

Name of Lake	Mean Depth (m)	P (gm/m^2/yr)	N (gm/m^2/yr)	Ratio of loading rates to dangerous limits* P	N	Reference
Mirror Lake	7.8	0.46	5.14	2.5	2.1	This report
Lake Erie, West Basin	6.7	7.0	45.0	43.8	18.8	Vollenweider (1968)
Lake Ontario	84	0.65	8.3	0.9	1.3	Vollenweider (1968)
Lake Winnipeg	8.4	1.1	7.4	6.1	2.7	Schindler et al. (1971)

*Dangerous loading rates (P_D and N_D) of Vollenweider (1968) as calculated by method of Schindler et al. (1971):

$$\log_{10} P_D = 0.60 \log_{10} \bar{z} + 1.70$$

$$\log_{10} N_D = 0.60 \log_{10} \bar{z} + 2.87$$

where $\bar{z}$ is mean depth in meters.

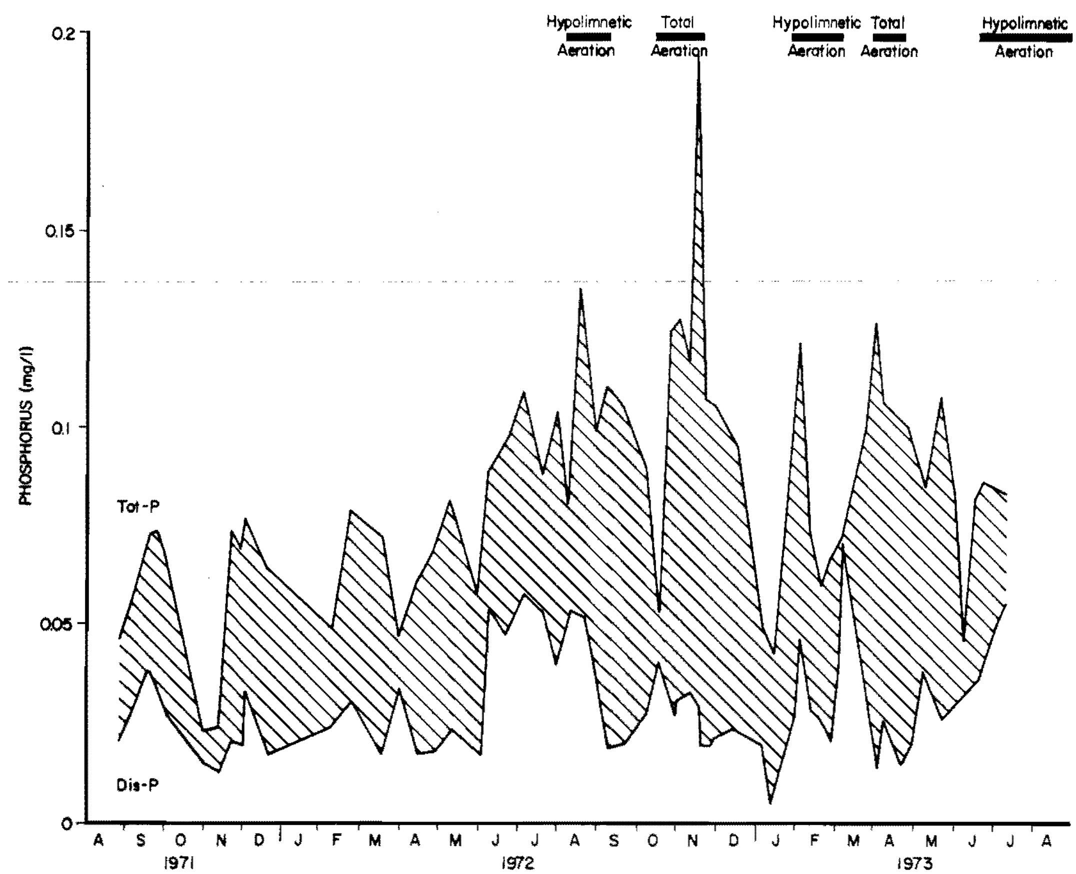

FIGURE 11. *Weighted average phosphorus concentrations in Mirror Lake, 1971-73.*

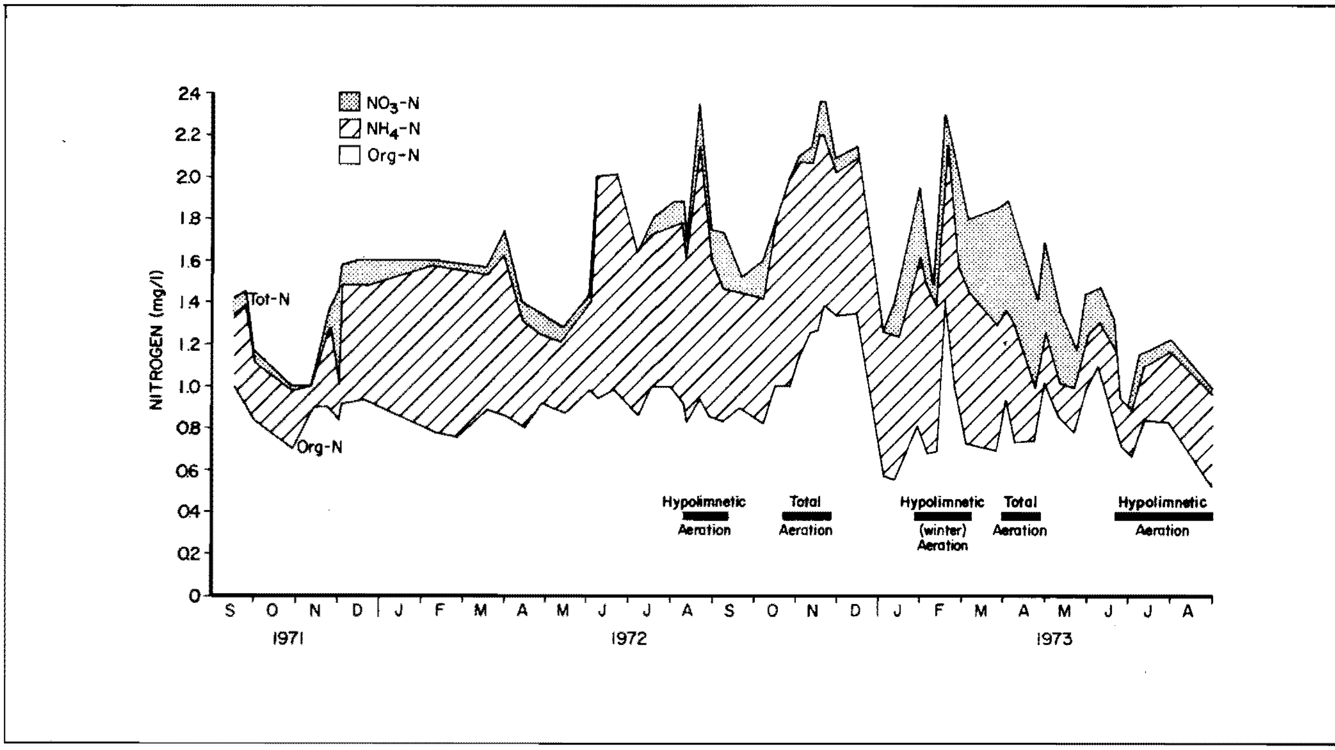

FIGURE 12. *Weighted average nitrogen concentrations in Mirror Lake, 1971-73.*

LARSON LAKE AERATION PROJECT

Although the first year of hypolimnetic aeration was not completely successful, we were confident that our basic design was sound. In retrospect, Mirror Lake was not an ideal choice for initial testing of the aerator; the rate of hypolimnetic oxygen demand, a factor we did not adequately consider in the site selection process, was too high. However, we were able to aerate hypolimnetic water without disrupting thermal stratification, and, encouraged by these results, we extended our operations to a second lake. At the same time, we continued to monitor the operation of the first unit at Mirror Lake.

Larson Lake is nearly identical to Mirror Lake in both surface area and maximum depth, but the volume of the hypolimnion is only one-half the volume of the Mirror Lake hypolimnion, and the biochemical oxygen demand of the lake water is also considerably lower. We began collecting background data on Larson Lake during the 1971-72 winter, but an intensive sampling program was not started until the spring of 1972. We began aerating the lake in February 1973, and as a result, we did not get a full year of thorough background data. However, we did collect sufficient information to suggest that Larson Lake could provide a valuable complement to our demonstration project.

SITE DESCRIPTION

Larson Lake is a small bog lake located in Section 31, T33N, R7E, Lincoln County, Wisconsin. It has a surface area of 12 acres, and a maximum depth of 39 ft (Fig. 13). A narrow bog fringe, 30-60 ft wide, extends around the lake on the south and west sides, and probably made up a greater portion of the shoreline prior to highway construction along the east side of the lake.

The lake is situated near the crest of the Harrison terminal moraine (Nelson 1973), a northeast- to southwest-trending topographic high which marks the southern limit of advance of the Wisconsin Valley lobe of the Woodfordian ice sheet during the Wisconsin stage of Pleistocene glaciation. Numerous small lakes and bogs dot the poorly drained hummocky morainal surface, which has a local relief in the vicinity of Larson Lake of about 50 ft and a total relief of more than 325 ft above the nearby Wisconsin and Prairie River valleys.

The surface drainage basin for Larson Lake is about 50 acre and includes a portion of a roadside park area, mixed upland forest, and cleared pasture land and farm yard. Soils in the basin are developed on a thick (up to 325 ft) sequence of noncalcareous glacial till, with a sand size fraction of about 80 percent (Nelson 1973). The farm southwest of the lake is a small-

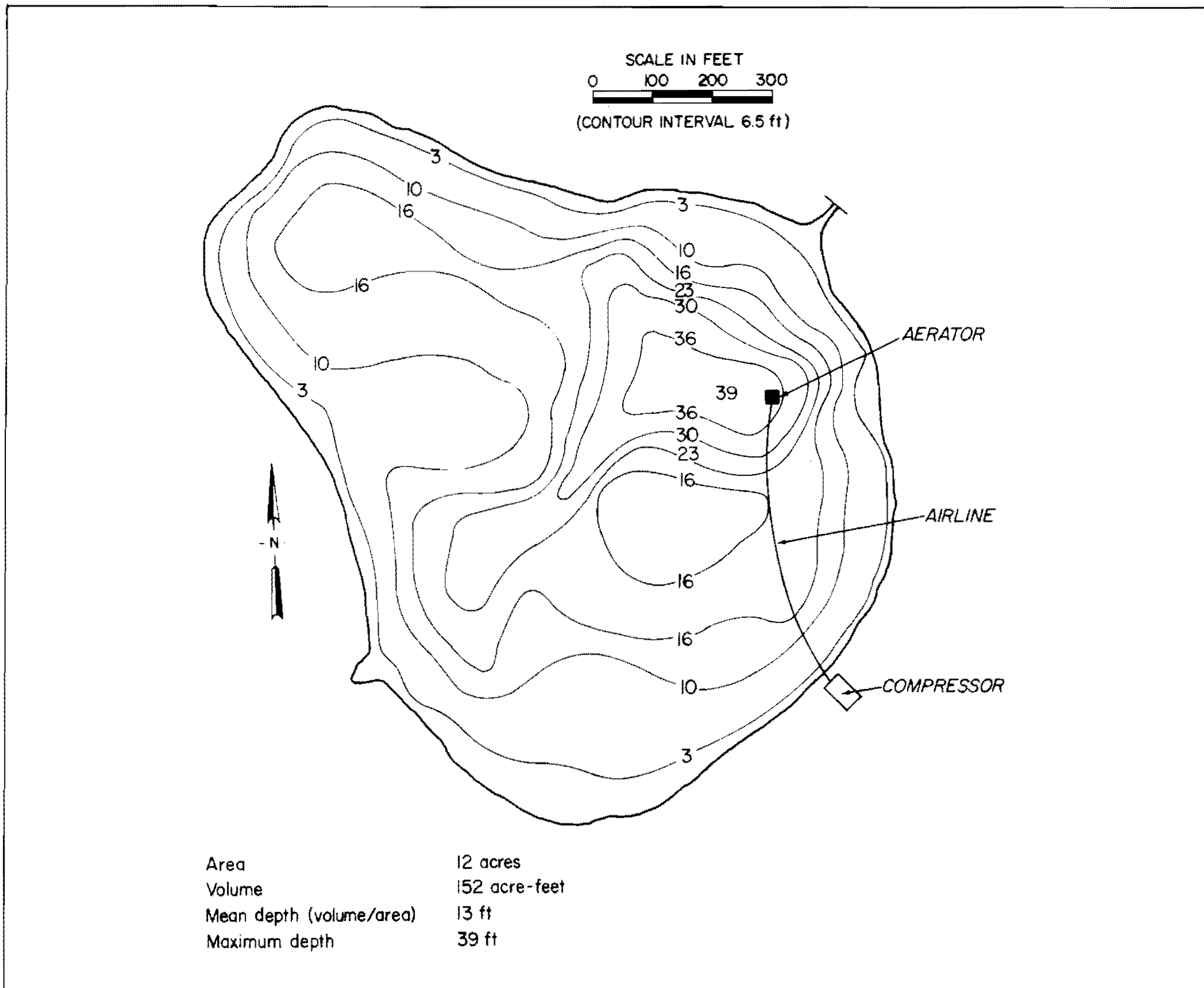

FIGURE 13. *Bathymetric map of Larson Lake.*

scale beef and dairy operation (20 head) and probably does not represent a significant nutrient input to the lake at the present time. The cattle, however, have free access to the lake, and in the past, a larger herd could have made substantial contributions to the lake's fertility.

The lake is drained by a small intermittent stream which passes through two culverts on the east side of the lake. The second culvert serves as a partial level control, and during periods of heavy precipitation or snowmelt preceded by a low lake stage, runoff from the state highway and park area northeast of the lake can enter the lake through the outlet channel. These periods of reversed flow are usually of short duration, however. The lake level quickly responds to the increased inflow and overtops the sill on the second culvert, allowing outflow to proceed normally.

Direct precipitation on the lake's surface, combined with intermittent channelized and diffuse surface runoff from the small watershed make up the major water inputs to Larson Lake. The results of shallow test drilling, the depth of water supply wells in the lake's vicinity, and the surface elevation of Larson Lake with respect to nearby major rivers and lakes suggest that ground water does not contribute significantly to the water budget. Evapotranspiration and intermittent flows through the outlet probably represent the major fraction of the output; seepage to the regional ground water flow system is limited by the great thickness of relatively impermeable bottom sediments which cover the entire lake bed.

During the 1972 control year, Larson Lake mixed normally in the spring and fall and was stratified at a shallow depth during most of the summer. A metalimnion was present between 6.5 ft and 11.5 ft from about 1 June to 30 September. Epilimnetic temperatures normally varied from 66 to 72° F, with a maximum of 81° F recorded on 27 August. Hypolimnetic temperatures varied from about 41° F in June to 44° F at the end of September.

During the 1971-72 and early 1972-73 winters, a shallow inverse stratification developed; temperatures increased from near 32° F at the surface to about 39° F at 10 ft. In the 23-ft to bottom interval, temperatures were generally slightly higher, and a maximum bottom temperature of 40° F was recorded in mid-January 1973.

In 1972, hypolimnetic dissolved oxygen was depleted rapidly after the onset of summer stratification; by 23 June, dissolved oxygen was detected only in the upper 7 ft of the lake, and the entire metalimnion and hypolimnion, representing about 60 percent of the lake volume, were anoxic. Dissolved oxygen concentrations follow-

TABLE 5. *Background chemical data for Larson Lake, 1972.*

Constituent*	Epilimnion	Hypolimnion
pH (units)	6.2 - 7.0	6.1 - 6.8
$CaCO_3$	9 - 36	9 - 26
NO_2-N	0.000 - .009	0.00 - .034
NO_3-N	.07 - .48	.10 - .59
NH_4-N	0.00 - 3.5	0.00 - 1.29
Org-N	.59 - .128	.50 - 1.12
Dis-P	<.005 - .069	.015 - .221
Tot-P	.02 - .13	.03 - .26
Na	2 - 10	1 - 9
K	1 - 4	1 - 4
Mg	2 - 4	2 - 4
Ca	2 - 9	2 - 10
Cl	5 - 12	4 - 8
SO_4	5 - 14	5 - 13
Conductivity (μmhos/cm at 25°C)	44 - 98	43 - 97
Color (standard units)	42 - 70	42 - 75
BOD_5 at 20°C	1.2 - 3.8	1.4 - 2.5
COD	44 - 55	57 - 93

*All concentrations in mg/l except as noted.

TABLE 6. *Results of chemical analysis of Larson Lake sediments.**

Constituent	Depth below sediment surface (in)					
	0 - 2	2 - 4	4 - 6	8 - 10	14 - 16	20 - 22
N (%)	1.98	1.45	2.03	1.72	2.83	2.52
P (%)	1.02	0.90	0.87	0.76	0.58	0.52
K (%)	0.69	0.58	0.69	0.77	0.67	0.65
Ca (%)	0.44	0.40	0.46	0.44	0.44	0.46
Mg (%)	0.30	0.42	0.25	0.30	0.15	0.19
Na (%)	0.171	0.139	0.152	0.167	0.137	0.111
Al (ppm)	15,700	17,720	15,060	18,860	11,600	12,780
Fe (ppm)	18,000	18,640	13,120	13,480	5,720	6,970
B (ppm)	169	177	136	125	68	75
Cu (ppm)	36.2	32.1	31.4	29.4	27.7	30.6
Zn (ppm)	322	224	262	185	126	133
Mn (ppm)	744	692	743	581	363	317
Ba (ppm)	174	169	175	182	131	148
Sr (ppm)	48.4	41.8	51.9	44.4	40.4	44.0
Cr (ppm)	34.1	34.8	32.7	38.6	27.9	25.0
Cl (ppm)	-	68.5	76.0	42.0	56.0	40.0
Solids (%)	4.69	9.15	6.75	8.55	8.79	7.95

*Core obtained in water 32 ft deep. Constituents expressed on a dry weight basis except for percent solids, which are on a wet weight basis. Analyses performed by Soil and Plant Analysis Lab, University Wisconsin Extension.

ing a similar pattern during the early part of the 1972-73 winter. One week after freeze-up, dissolved oxygen concentrations were near saturation levels throughout the lake, but one month later, dissolved oxygen was absent at the 36-ft and 39-ft depths. By February, the weighted average concentration for the entire lake had decreased to 7 mg/l, and in the 20-ft to bottom interval, the weighted average concentration was only 2 mg/l. Based on limited observations during the previous winter, a continued decline in dissolved oxygen concentrations would have been expected to a weighted average concentration of 3-4 mg/l for the entire lake and complete absence in the 6-m to bottom interval by the spring thaw.

Based on the results of water chemistry analyses, Larson Lake can be classified as an acid, soft water, highly colored, moderately fertile lake. With the exception of nitrogen and phosphorus, most dissolved chemical constituents showed little spatial or temporal variability during the control year. Table 5 presents the range of epilimnetic and hypolimnetic concentrations for 1972, and the results for sediment analyses are shown in Table 6. There is evidence of cultural disturbance (perhaps related to the close proximity of the highway to the lake) in the most recent sediments (0-10 in), particularly with regard to heavy metals and, in the upper 6 in, chlorides.

METHODS AND MATERIALS

The aeration unit installed in Larson Lake was nearly identical to the one installed in Mirror Lake with the exception that the "Helixor" had been shortened by 20 in and was constructed in two pieces, rather than four. Total length of the "Helixor" was 38.4 ft and it was anchored in 39 ft of water using concrete blocks for weight. Initially, the top of the "Helixor" was about 4 in below the water level; however, the anchors continued to sink into the soft bottom sediments after installation, and the unit eventually stabilized at a depth of about 12 in below the water surface.

The air line connection at the bottom of the "Helixor" and the separation box at the top were identical to

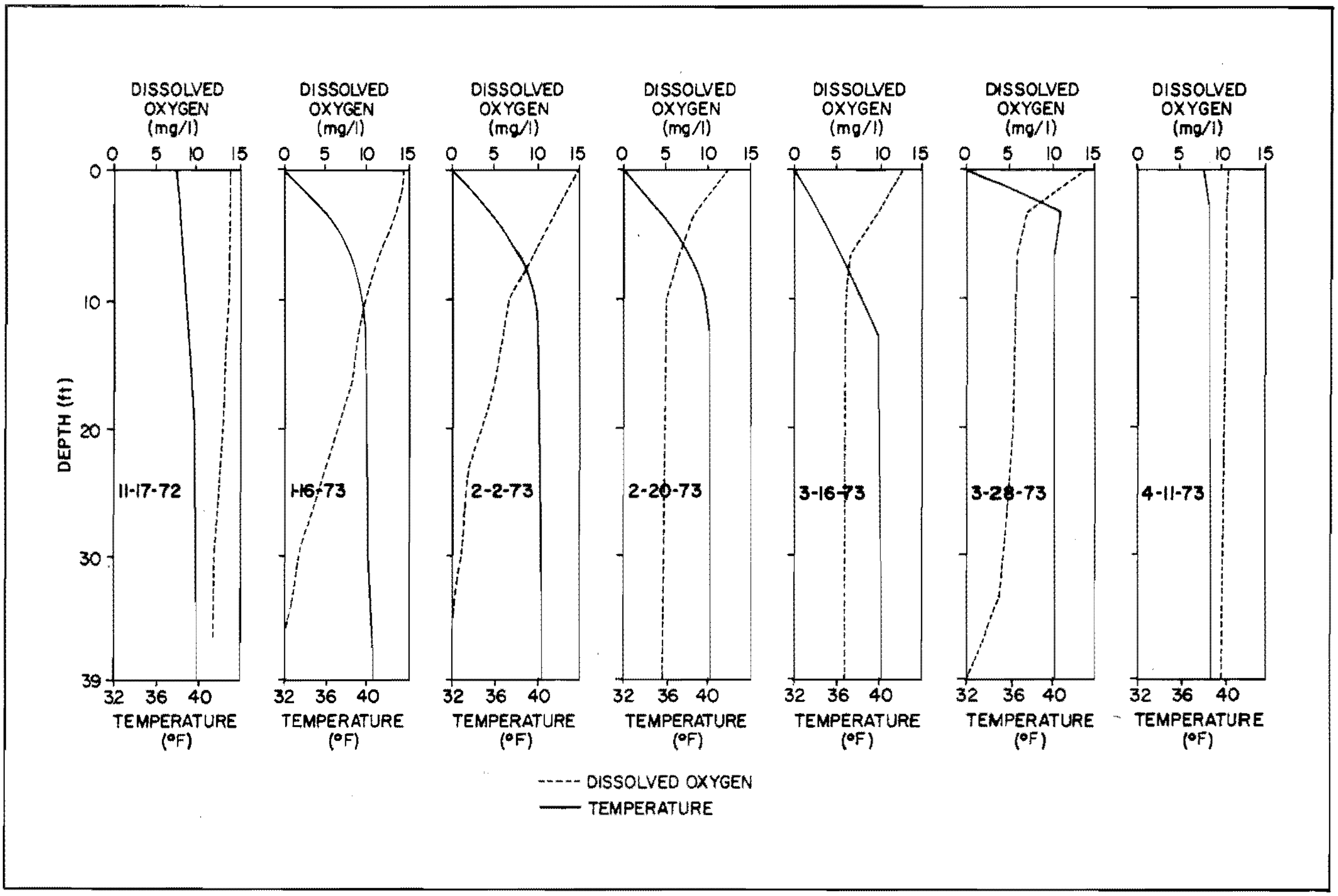

FIGURE 14. *Selected dissolved oxygen and temperature profiles in Larson Lake during the 1972-73 winter. (The aerator ran from 2 February to 16 March. The lake was ice-covered from 12 November to 1 April.)*

the installation at Mirror Lake (see Part d of Fig. 26, Appendix 1). However, the return tubes were shorter and unequal in length; one 33-ft long tube discharged towards the center of the lake and a 20-ft tube discharged towards the east shore. Initially, both tubes hung nearly vertically from the separation box and were displaced laterally from the "Helixor" by no more than 10 ft. An electic-powered compressor, rated at 16 ft^3/min at 0 lb/in^2, 3.7 kw was connected to the aerator via 500 ft of 1.5 in ID-weighted plastic tubing.

We installed the aerator on 1 February 1973 through about 27 in of lake ice using chain saws to cut slots for the "Helixor" and air line. The aerator operated from 2 February to 16 March, when an unusually early spring thaw made it impossible to safely monitor the operation. After the aerator was shut down, the lake stage increased by about 8 in, and the separation box, which was frozen into the ice, was lifted off the top of the "Helixor". Without the surface support of the buoyant, styrofoam-covered box, the "Helixor" fell over on its side on the lake bottom. However, by turning on the compressor and injecting air into the "Helixor", we brought it back to a vertical position and clamped the box back on the top on 25 April. The lake had already begun to stratify, so the unit was left running and operated continuously through the summer until 20 September, when natural destratification was nearly complete.

Water chemistry samples and temperature-dissolved oxygen profiles were obtained at a point about 200 ft west of the aerator. Numerous temperature and dissolved oxygen profiles obtained at sampling stations up to 650 ft away from the aerator confirmed that this was a representative sampling point. Sampling was conducted at 7- to 10-day intervals during aeration, and once every two or three weeks when the aerator was not operating. Appendixes 2 and 3 list the methods of chemical and biological analyses.

RESULTS

Dissolved Oxygen and Temperature

Winter. Selected dissolved oxygen and temperature profiles for Larson Lake during the 1972-73 winter are shown in Figure 14. After freeze-up, dissolved oxygen was depleted rapidly from the bottom water and by 2 February, when aeration started, the concentration of dissolved oxygen was less than 2 mg/l from 23 ft to the bottom. During the first 18 days of aeration, the dissolved oxygen concentration at the lake bottom increased to 4.6 mg/l and by 16 March, the last day of aeration, the dissolved oxygen concentration at the bottom was 6.0 mg/l.

Figure 15 shows the progressive increase in the dissolved oxygen content of the water at selected depths during the aeration period. For thoses depths below 20 ft, the dissolved oxygen levels increased rapidly. After 10 days, it became apparent that even the water above the level of the

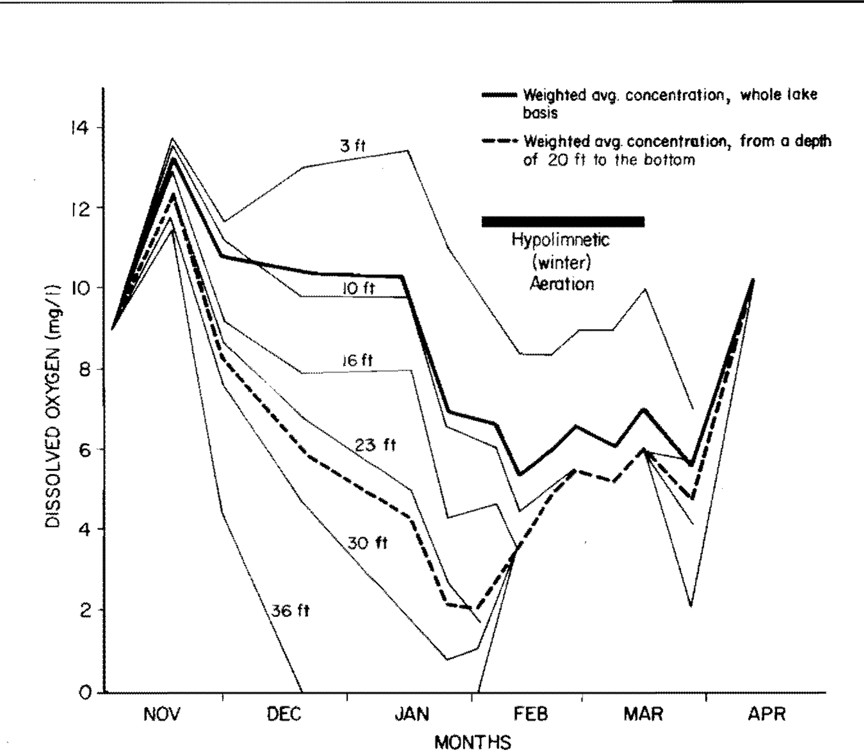

FIGURE 15. *Dissolved oxygen concentrations at selected depths in Larson Lake during the 1972-73 winter.*

TABLE 7. *Winter dissolved oxygen depletion rates for Larson Lake.*

Period	Depletion Rate* (mg/l/day)	Ice Thickness (in)	Snow Cover (in)
28 Dec 71 - 31 Jan 72	0.084	4 - 6	?
31 Jan 72 - 12 Apr 72	0.037	6 - 30	?
17 Nov 72 - 30 Nov 72	0.25	1 - 4	0 - 1
30 Nov 72 - 16 Jan 73	0.012	4 - 8	0 - 1
16 Jan 73 - 2 Feb 73	0.22	8 - 27	1 - 2
16 Mar 73 - 28 Mar 73	0.11	0 - 27	0 - 1

*Based on the weighted average dissolved oxygen concentration for the whole lake.

shorter return tube was being affected by the aerator (similar to the results obtained during winter aeration at Mirror Lake). Since the 20-ft to bottom interval at Larson Lake only contains about 16 percent of the total lake volume, the weighted average dissolved oxygen concentration for the whole lake was not greatly influenced by aeration until the dissolved oxygen concentration in the upper levels began to increase.

Dissolved oxygen concentrations fell off rapidly at all levels during the 15 days between aerator shutdown and ice-out. From 6.0 mg/l, the dissolved oxygen concentration at the bottom decreased to 0.6 mg/l, and at the 3-ft levels, the concentration decreased from 10.0 to 7.0 mg/l. Within 10 days after ice-out, however, near-saturation levels were recorded at all depths.

The aerator had little effect on lake temperature, and the separation box froze into the lake ice shortly after installation. Below the 13-ft level, the operation of the aerator caused water temperatures to fluctuate slightly between 38.8 and 39.6° F in apparent response to ambient air temperature, but there was never any measurable difference between the temperature of water in the separation box and the temperature of the water at the lake bottom.

To determine the actual rate of oxygen input by the aerator, we took several flow measurements inside the return tubes. These measurements indicated a nominal flow rate of 5.5 acre-ft/day. (Actual flow rates were somewhat less; we measured the maximum velocity in the center of the return tubes.) The increase in the dissolved oxygen content of water moving through the aerator, as indicated by the difference between the dissolved oxygen concentration at the lake bottom near the aerator and the dissolved oxygen concentration in the return tubes, was 2.8 mg/l. This value remained remarkably constant throughout the 42-day aeration period despite the continual increase in the oxygen level of the water being pulled in at the bottom of the "Helixor". Assuming no oxygen uptake by the sediments or lake water and uniform mixing, the aerator was adding about 42 lb oxygen/day to a lake volume of 154 acre-ft, or about 0.1 mg oxygen/l/day. Based on actual air flow measurements at the compressor (which confirmed the manufacturer's rating table), about 9 percent of the oxygen pumped to the aerator was actully transferred to water moving through the unit.

From 12 February to 16 March, the weighted average dissolved oxygen concentration for the whole lake increased by an average of 0.05 mg/l/day, compared to an input rate of 0.1 mg/l/day. The difference between the two values, 0.05 mg/l/day, represents the rate of oxygen uptake. Although this oxygen uptake rate falls within the range of depletion rates determined for Larson Lake during the 1971-72 and 1972-73 winters and is only slightly greater than that determined for the corresponding time period during the previous winter, Table 7 shows that the range varies greatly from a low of 0.012 mg/l/day to a high of 0.25 mg/l/day.

The decline in the weighted average dissolved oxygen concentration for the whole lake for the first 10 days of aeration indicates that in fact the oxygen uptake rate was much higher than the rate calculated for the last 32 days. During this early period, the dissolved oxygen content of the lake decreased by 0.08 mg/l/day, which, combined with the aerator input of 0.1 mg/l/day, gives an uptake rate of 0.18 mg/l/day. A partial explanation for the higher rate is sediment disturbance during the early stages of aeration. Suspended sediments were visible in the separation box when the aerator was first started up; until these settled out of the water column, they may have exerted a significant demand. Unfortunately, no biochemical oxygen demand samples were taken during this period, and samples taken 18 days after start-up indicated that biochemical oxygen demand of the lake water was at pre-aeration levels (Table 5).

Summer. Summer hypolimnetic aeration began on 25 April with the compressor running at about one-half of full capacity. On this date, the lake was sharply stratified at a shallow depth; the temperature decreased from 59° F at the surface to 48° F at 5 ft and then fell off gradually to 43° F at the bottom. Stratification broke down in early May, but the lake was re-stratified by 15 May with a weak thermocline between 10 and 16 ft. From 17 May to 26 June, we ran the compressor at full capacity. During this period, stratification proceeded normaly with the exception that the hypoliminion was about 5° F warmer than during the previous control year (45° F as opposed to 40° F). This temperature increase cannot be attributed solely to aerator operation, however. When aeration was first started on 25 April, the weighted average temperature in the 20-ft to bottom interval was already more than 4.5° F higher than during the previous year.

Figures 16 and 17 show the weighted average temperatures and temperature isopleths for Larson Lake during the 1972 and 1973 summers, and Figures 20 and 21 show the weighted average dissolved oxgyen concentrations and dissolved oxygen isopleths for the same periods. During the early summer, the effect of aeration on hypolimnetic dissolved oxgyen concentrations is quite evident in the 20-ft to bottom interval. By the end of June, the weighted average dissolved oxygen concentration in this interval was about 7 mg/l, compared to 0 mg/l for the previous year. From 26 June to 17 July, we ran the compressor at about one-half of full capacity to evaluate the aerator performance at a decreased rate of air flow. As a result, the weighted average dissolved oxygen concentration in the 20-ft to bottom interval decreased from 7 mg/l to less than 5 mg/l in about 3 weeks.

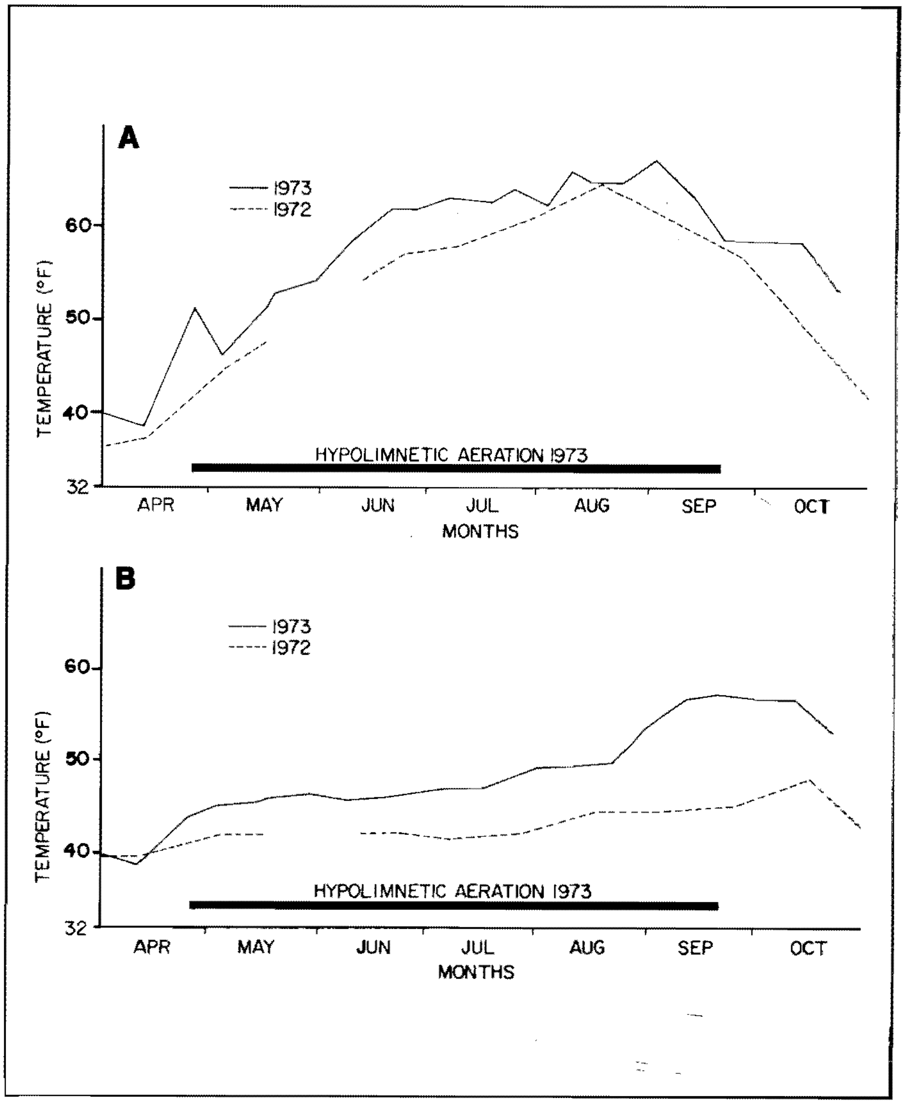

FIGURE 16. *Weighted average temperature in Larson Lake, 1972 and 1973 (a) for the whole lake and (b) from a depth of 20 ft to the bottom.*

By mid-July, it was apparent that we could maintain high hypolimnetic dissolved oxygen concentrations without significantly affecting the thermal regime of Larson Lake. The average hypolimnetic temperature was increasing at a rate of less than 1° F/month (due mainly to heat transfer through the walls of the "Helixor" and return tubes; we put a lid on the separation box early in the summer), and by running the compressor at full capacity, we could maintain high dissolved oxygen levels in the bottom waters. However, the metalimnetic oxygen levels had developed an undesirable pattern.

As early as mid-May, a zone of low dissolved oxygen was apparent in the region of the metalimnion, and the mid-July, the 8- to 13-ft interval was anaerobic. In an attempt to increase the dissolved oxygen levels in this interval, we left the long return tube in place and raised the shorter return tube from the 20-ft to the 7-ft level on 17 July. This had the immediate effect of increasing the hypolimnetic temperature (Figs. 16 and 17), and by 1 August, the weighted average temperature in the 20-ft to bottom interval was 48° F. The thermocline dropped from the 7- to 13-ft interval to the 13- to 20-ft interval, and as the metalimnion dropped, the anaerobic zone shifted, decreasing the dissolved oxygen content of the 20-ft to bottom interval from 3.6 mg/l to 1.1 mg/l.

The drop in the level of the metalimnion between 17 July and 1 August was apparently due to transfer of water from the hypolimnion into the epilimnion and metalimnion. During this period, about one-third of the total flow through the aerator was discharged through the upper return tube (raising the tube to the 7-ft level created some kinks and reduced the flow rate), for a total flow of 38 acre-ft during the 14-day period. The bottom of the metalimnion dropped from the 13-ft level to the 20-ft level, reducing the volume of the hypolimnion by 24.3 acre-ft. Although some of the water discharged through the upper tube sank back to the hypolimnion, most of it was permanently removed.

We lowered the return tube back down to the 20-ft depth on 1 August and the dissolved oxygen concentration in the bottom waters showed an immediate response (Figs. 18 and 19). In three weeks, the weighted average concentration was back up to 3.6 mg/l and the concentration at the 39-ft depth was up from 2.7 to 5.0 mg/l. However, the metalimnion had now stabilized in the 8- to 20-ft interval (Fig. 17), and the increased thickness of the metalimnion produced a corresponding increase in the volume of the anaerobic zone to about 30 percent of the total lake volume.

On 22 August, we again attempted to increase the metalimnetic oxygen levels by raising the shorter return tube to the 13-ft level in the hope that we could erode away the bottom of the metalimnion and reduce its thickness. However, this merely divided the metalimnion and pushed the lower half down to the 26-ft level (Fig. 17), with a concurrent increase in bottom temperatures and a decline in dissolved oxygen concentration (Figs. 16 and 18). The upper portion of the metalimnion remained stable and anaerobic until it mixed with the epilimnion as the lake surface began to cool during the first weeks in September.

Because we had nearly succeeded in mixing the entire lake during the last attempt at improving metalimnetic oxygen levels, we shut down the aerator on 20 September (the top to bottom temperature differential was only 3.8° F). With the aerator off, dissolved oxygen disappeared from the lake bottom for the first time all summer, but by 22 October, the lake had mixed completely and near saturation levels of dissolved oxygen were present at all depths (Fig. 19).

The rate of water flow through the aerator during the summer was considerbly greater than that during the winter. When the separation box was frozen into the ice, the airlift through the "Helixor" produced a 2- to 4-in head of water above the lake level. However, during the summer, the separation box sank about 12 in, nearly eliminating this head and increasing the flow rate. With the compressor running at full capacity, the nominal flow through the aerator was 8-9 acre-ft/day. The equivalent of the entire volume of the 20-ft to bottom interval passed through the aerator once every 2.4 days. Increasing the aerated interval to the 13-ft depth more than doubled the residence time, and when the return tube was lifted to the 6.5-ft level, we were attempting to aerate a volume of about 80 acre-ft, with a theoretical residence time of about 10 days.

During the early summer, when the compressor was running at full capacity and the dissolved oxygen concentration of the water being pulled in at the bottom of the aerator was about 7.5 mg/l or less, water passing through the unit gained about 2.6 mg/l of dissolved oxygen. (At one-half capacity, the difference between the oxygen content of the bottom water and the oxygen content of the water in the return tubes was about 2.0 mg/l.) During this period, with the return tubes at the 20-ft and 33-ft depths, we were adding about 57 lb/oxygen/day to an interval volume of 19 acre-ft, or slightly more than 1 mg/l/day. The rate of addition was lower in early May because of the higher dissolved oxygen levels of the bottom water being drawn into the aerator, but not enough data were obtained for a reliable estimate. Based on an increase of 2.6 mg/l, the oxygen transfer efficiency of the aerator with the compressor running at full capacity was about 12 percent. At the lower air delivery rates, the transfer efficiency was slightly higher, about 14 percent.

The weighted average dissolved oxygen concentration in the 20-ft to bottom interval fluctuated only slightly for most of this period; it is likely, therefore, that the rate of uptake closely matched the rate of input. A hypolimnetic oxygen depletion rate of 1 mg/l/day is about three times as great as that estimated for the previous year during stratification. Although the exact date of vernal mixing in 1972 cannot be determined from the limited data, the lake probably did not mix much sooner than mid-May. By mid-June, the hypolimnion was completely devoid of oxygen. Assuming a hypolimnetic dissolved oxygen concentration of 10 mg/l during turnover, the average rate of depletion was 0.33 mg/l/day.

A better estimate of the depletion rate in the 20-ft to bottom interval can be derived from the data obtained in early October, after the aerator was shut down but before the lake mixed. In the 10-day period from 2 October to 12 October, the weighted average oxygen concentration decreased from 2.8 mg/l to 0.2 mg/l, for a depletion rate of 0.26 mg/l/day. This figure is in fairly good agreement with the depletion rate estimated from the 1972 data, and suggests that the depletion rate during aeration was as much as three to four times as great as the normal depletion rate.

Nitrogen

Figure 20 shows the temporal distribution of nitrogen in Larson Lake in 1972 and the relative abundance of the various forms. (Nitrite-nitrogen concentrations rarely exceeded 0.01 mg/l and are not plotted.) For the lake as a whole, there was little variation in total nitrogen levels during the year, and organic nitrogen made up a fairly constant portion of the total. Of the inorganic fraction, nitrate-nitrogen predominated during the winter and spring, but ammonium-nitrogen made up an increasingly greater percentage as the summer progressed.

In the 20-ft to bottom interval, the concentrations and relative proportions of the various species of nitrogen did not differ greatly from the whole lake values during the winter and spring. However, during the summer stagnation period, there was a large increase in ammonium-nitrogen. Just prior to the fall mixing period, the weighted average concentration of ammonium-nitrogen in the bottom waters exceeded 0.80 mg/l, and inorganic nitrogen made up about one-half of the total nitrogen content. After fall turnover, in October, nitrogen concentrations in the hypolimnion dropped sharply, but the weighted average for the whole lake remained about the same.

Aeration had a marked effect on the nitrogen levels in Larson Lake in 1973 (Fig. 21). Shortly after startup in

February, organic nitrogen levels sharply increased and then declined, but nitrate-nitrogen levels remained high until ice-out. Similar peaks in organic nitrogen occurred in late July and early August, coincident with raising one of the return tubes into the metalimnion, and another increase was recorded in late September, after the aerator was shut down and the upper strata of the lake began to mix. The last three peaks were all characterized by blooms of *Anabaena circinalis*, a blue-green algae capable of nitrogen fixation (surface cell counts exceeded 12,000 cells/ml). The temporary increase in organic nitrogen in February was not marked by any noticeable algae bloom (algae analyses were not part of our regular sampling program), but coincided with a substantial amount of sediment disruption that took place during aerator installation and startup. Sediment disruption may have also played a role in producing the increases in organic nitrogen in July and August. When we first raised the return tube, we lifted the tube anchor and dragged it across the lake bottom several times in an attempt to eliminate kinks and increase the flow rate. This procedure was not necessary when we raised the tube the second time.

Although there were sporadic increases in organic nitrogen concentrations during aeration, ammonium-nitrogen levels were greatly reduced. During winter aeration, ammonium-nitrogen was virtually eliminated, and summer hypolimnetic aeration also held ammonium-nitrogen well below the 1972 levels. In the 20-ft to bottom intervals, the reduction in ammonium-nitrogen greatly reduced the amount of inorganic nitrogen, and despite the increased organic nitrogen concentrations, total nitrogen was also reduced.

Phosphorus

Phosphorus concentrations during the 1972 control year are shown in Figure 22. For the lake as a whole, total phosphorus concentrations were at a minimum during the winter (0.023 mg/l) and increased erratically to a high of almost 0.1 mg/l prior to freeze-up. In the bottom waters, phosphorus concentrations showed a nearly classical response to periods of stagnation and mixing. Dissolved and total phosphorus concentrations reached a maximum in the late winter and declined sharply after ice-out. A very large increase again occurred during summer stratification, and the dissolved phosphorus concentration reached nearly 0.15 mg/l by late September. Phosphorus levels fell dramatically during the fall mixing period, and by mid-November, the weighted average dissolved phosphorus concentration in the bottom waters was less than one-tenth of the September peak.

Figure 23 presents the phosphorus data from Larson Lake during 1973. Aeration had a very noticeable effect on dissolved phosphorus levels in the bottom waters. Although there was a temporary increase in dissolved phosphorus during aerator startup, dissolved phosphorus remained well

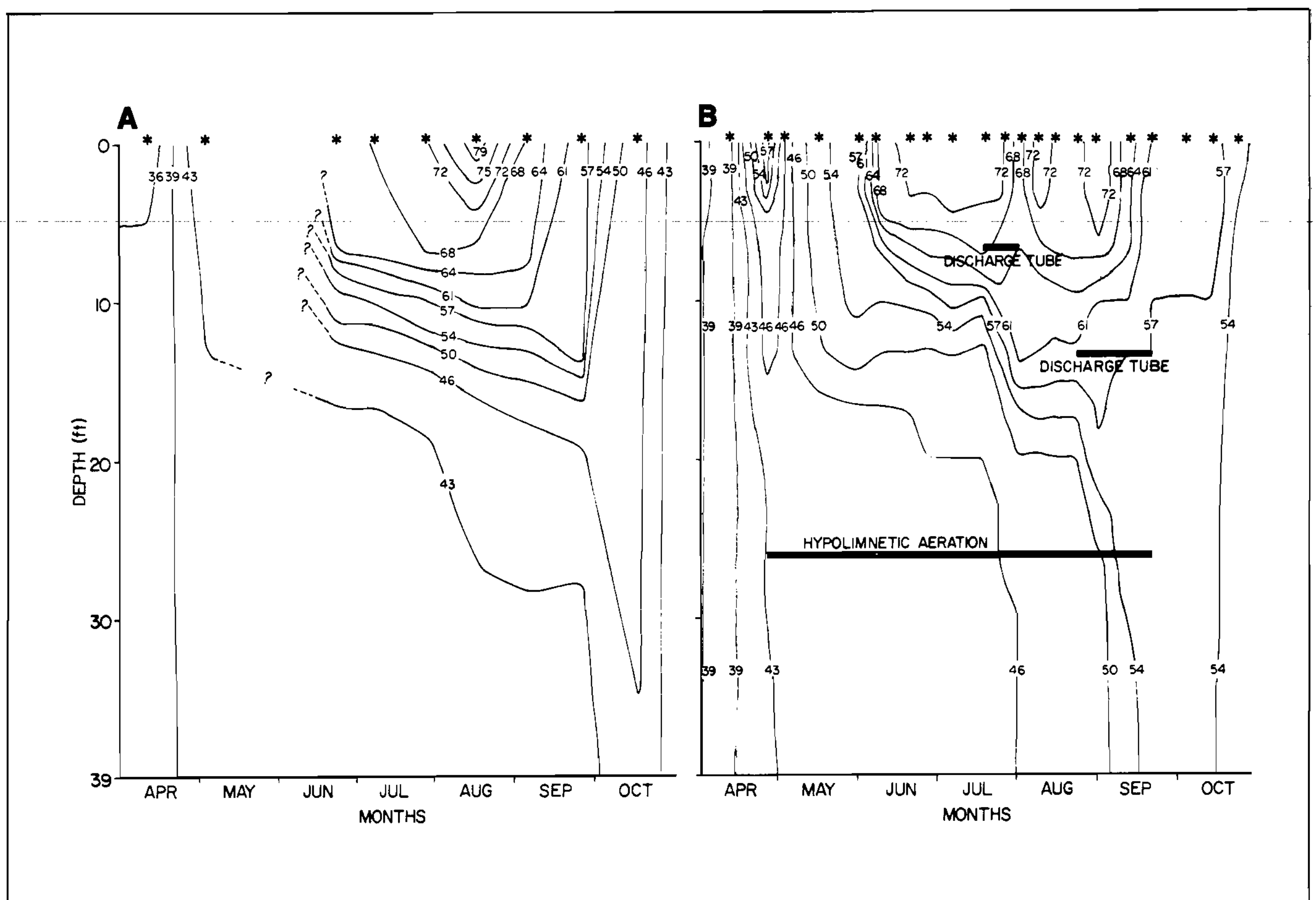

FIGURE 17. *Larson Lake temperature isopleths (in° F) for (a) 1972 and (b) 1973. (Sampling dates are indicated by asterisks.)*

below the 1972 levels during most of the summer despite an increase which was recorded in August.

For the lake as a whole, the effects of aeration are less evident. Dissolved and total phosphorus levels during winter were generally higher than during the previous year, but during the early summer, they were lower. The February and August peaks in total phosphorus occurred within a few days of similar peaks on the nitrogen plots, and suggest that sediment disruption was probably responsible for the increases. The September peak in nitrogen coincides with the virtual disappearance of dissolved phosphorus, suggesting a rapid algal uptake of phosphorus as the lake began to mix.

Other Chemical Constitutents

With the exception of nitrogen and phosphorus, aeration apparently had little effect on the chemistry of Larson Lake. A small temporary decline in pH and a slight increase in alkalinity occurred a few days after the start of winter aeration, but no permanent change was recorded. Hypolimnetic pH and alkalinity levels were essentially unaffected by summer aeration.

Despite the presence of significant amounts of chloride in the bottom sediments, there was no measurable increase in chloride concentrations, in spite of the fact that sediment disruption is suspected as a likely cause of several temporary increases in nutrient levels. However, sediment nitrogen and phosphorus levels are very high in relation to chlorides (by a factor of more than 100), and a very large sediment disturbance would be required to create a detectable increase in chloride levels.

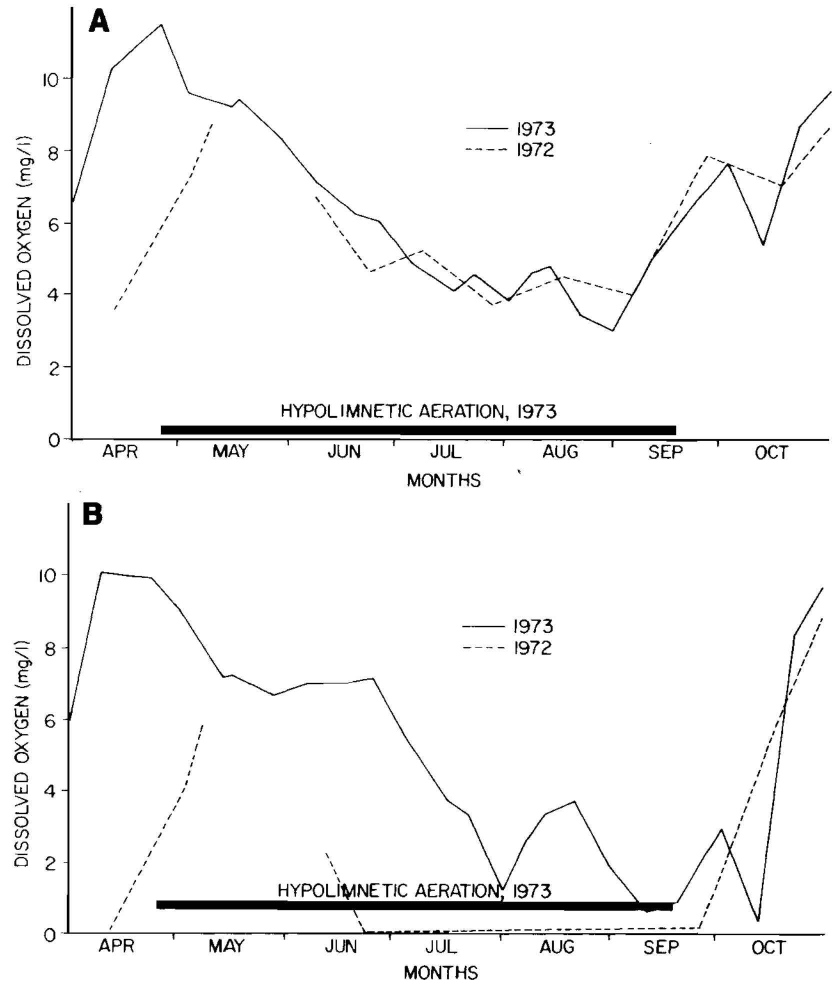

FIGURE 18. *Weighted average dissolved oxygen concentration in Larson Lake, 1972 and 1973 (a) for the whole lake and (b) from a depth of 20 ft to the bottom.*

DISCUSSION

The Larson Lake aerator was much more effective in overcoming the various processes of oxygen depletion than the Mirror Lake hypolimnetic aerator, due in part to the smaller hypolimnion volume. At Larson Lake, the turnover rate of the hypolimnion through the aerator was about twice as fast as that at Mirror Lake. In addition, we had no large additions of oxidizable organic material during aeration, and although the chemical oxygen demand of the Larson Lake water was much higher than Mirror Lake water, the biochemical oxygen demand was lower. The great difference between the biochemical and chemical oxygen demand at Larson Lake (Table 6) is probably due to the presence of humic substances which are fairly resistant to biological degradation.

Based on the observed rates of winter oxygen depletion for the whole lake and summer hypolimnetic oxygen depletion, the Larson Lake aerator was oversized, but the actual performance of the unit indicated that it was just adequate in maintaining satisfactory dissolved oxygen levels. When compared to the measured rate of oxygen addition by the aerator, the rate of increase of the lake's oxygen content indicates that the dissolved oxygen uptake rate increased substantially when the aerator was in operation. The increase in the rate of uptake was probably due in part to sediment suspension and a longer settling period for sestonic material due to the turbulence created by the aerator, but increased circulation at the sediment-water interface was also undoubtedly responsible. At a dissolved oxygen content of 7 mg/l in the hypolimnion, we were operating in a steady state, but at lower concentrations we could effect an increase. Since the increase in the dissolved oxygen content of the water passing through the aerator was

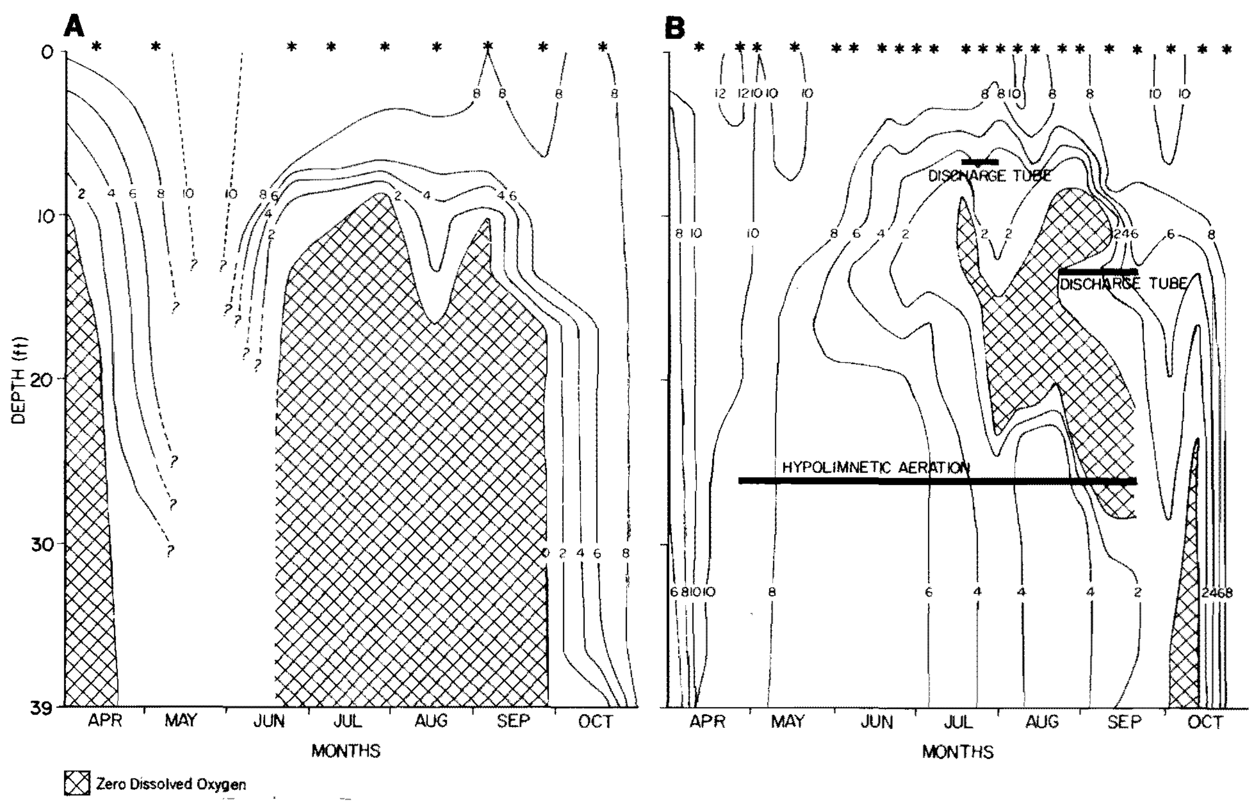

FIGURE 19. *Larson Lake dissolved oxygen isopleths (in mg/l) for (a) 1972 and (b) 1973. (Sampling dates are indicated by asterisks.)*

fairly constant over a wide range of concentrations, it seems that the depletion processes operating in the lake were nonzero order, i.e., oxygen dependent. This is indicative of sediment, rather than water, uptake. During the winter aeration period, the rate of increase of the dissolved oxygen content of the bottom waters was also distinctly nonlinear (Fig. 15).

The metalimnetic oxygen minimum that developed during the hypolimnetic aeration of Larson Lake presents a potentially serious problem. At Jarlasjon, Sweden, a similar zone developed during hypolimnetic aeration which was thought to have served as a vertical barrier to fish movement (Bengtsson undated), and a metalimnetic minimum also developed during the hypolimnetic aeration of Lake Waccabuc (Dorr 1973). In Larson Lake, the zone of low dissolved oxygen eventually comprised about 30 percent of the lake volume, although this could probably have been reduced somewhat by maintaining one return tube at a higher level from the start. We were not able to make a substantial short-term improvement by introducing oxygenated hypolimnetic water into the metalimnion. Apparently, most of the displaced water was permanently transferred out of the hypolimnion, lowering the metalimnion.

A metalimnetic aerator does not seem feasible due to the difficulty that would be involved in adjusting the temperature of the discharge water to specific depths within the metalimnion. This would require numerous inlet and outlet ports at various depths, each designed to aerate a specific stratum. However, in conjunction with a hypolimnetic aerator, a carefully adjusted total aeration system placed at a shallow depth could probably reduce the thickness of the metalimnion without affecting the hypolimnion temperature.

We made no fish studies in Larson Lake, although anglers report that there are abundant bullheads (*Ictalurus* spp.) and stunted bluegills (*Lepomis macrochirus macrochirus Rafinesque).** It is likely that they

*Since this was written, fish studies have been initiated by S. Serns. Serns (1974, personal communication) has obtained data that indicate trout will penetrate the low dissolved oxygen zone of the metalimnion to gain access to the colder oxygenated hypolimnion waters.

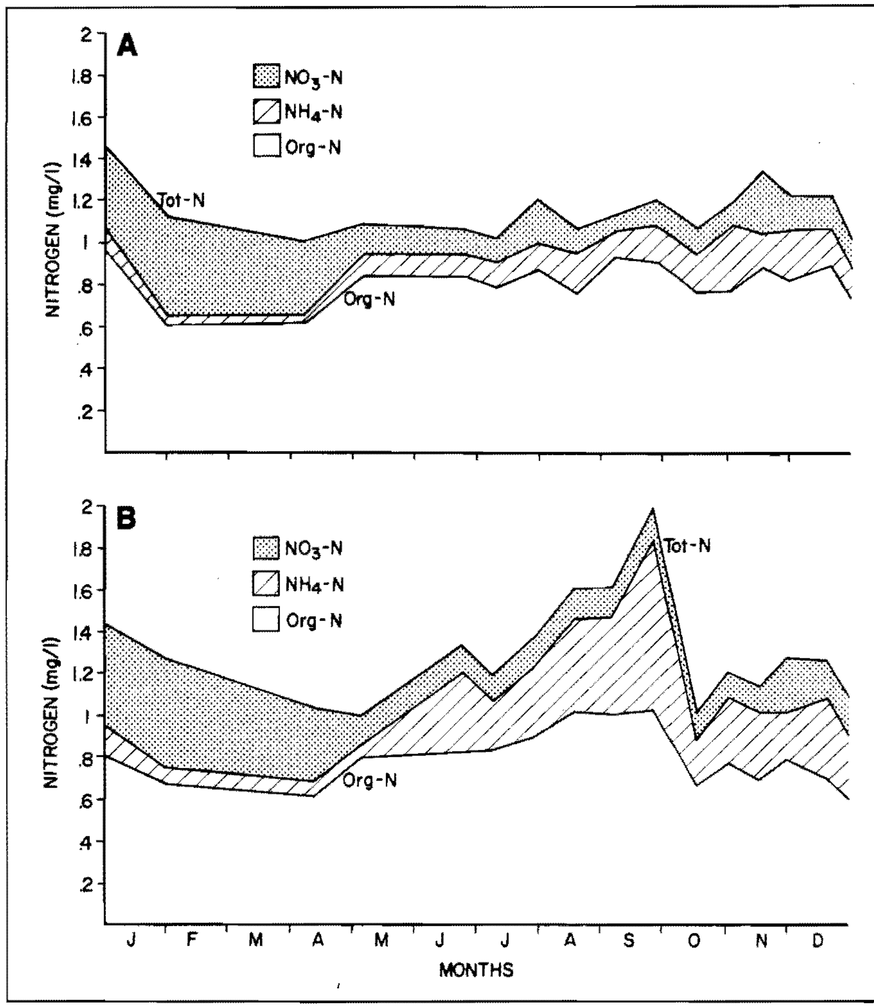

FIGURE 20. *Weighted average nitrogen concentration in Larson Lake, 1972 (a) for the whole lake and (b) from a depth of 20 ft to the bottom.*

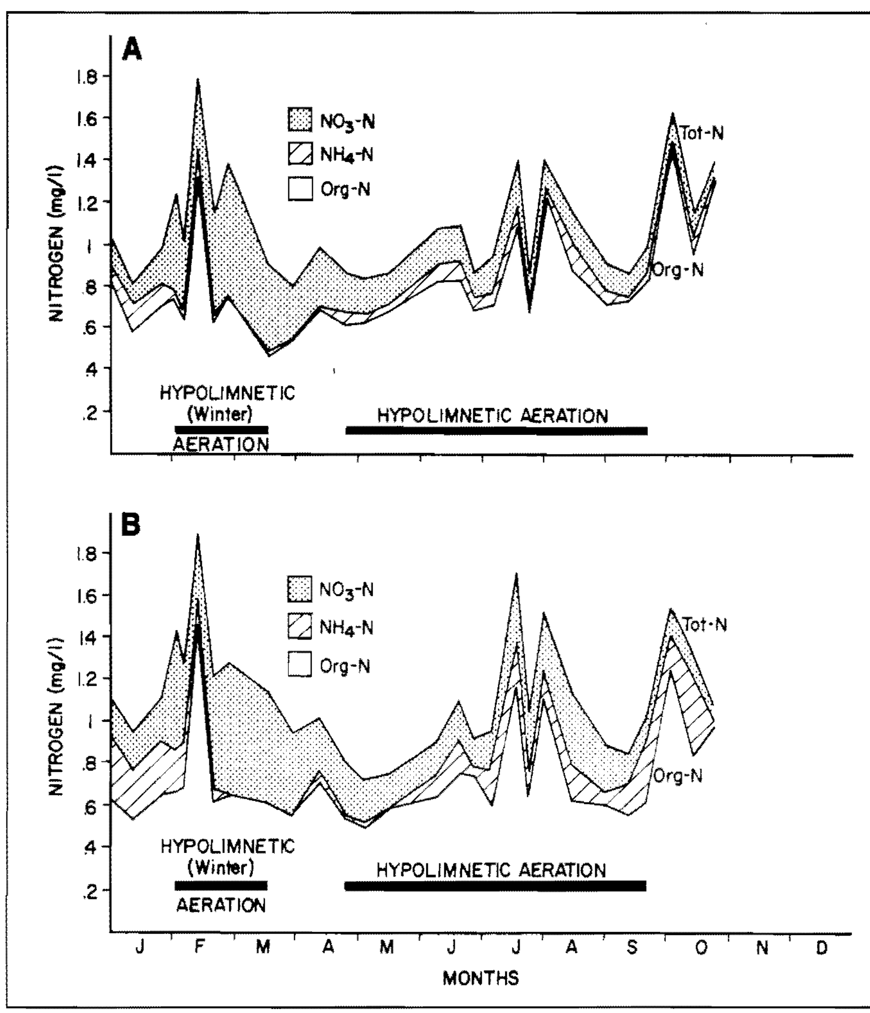

FIGURE 21. *Weighted average nitrogen concentration in Larson Lake, 1973 (a) for the whole lake and (b) from a depth of 20 ft to the bottom.*

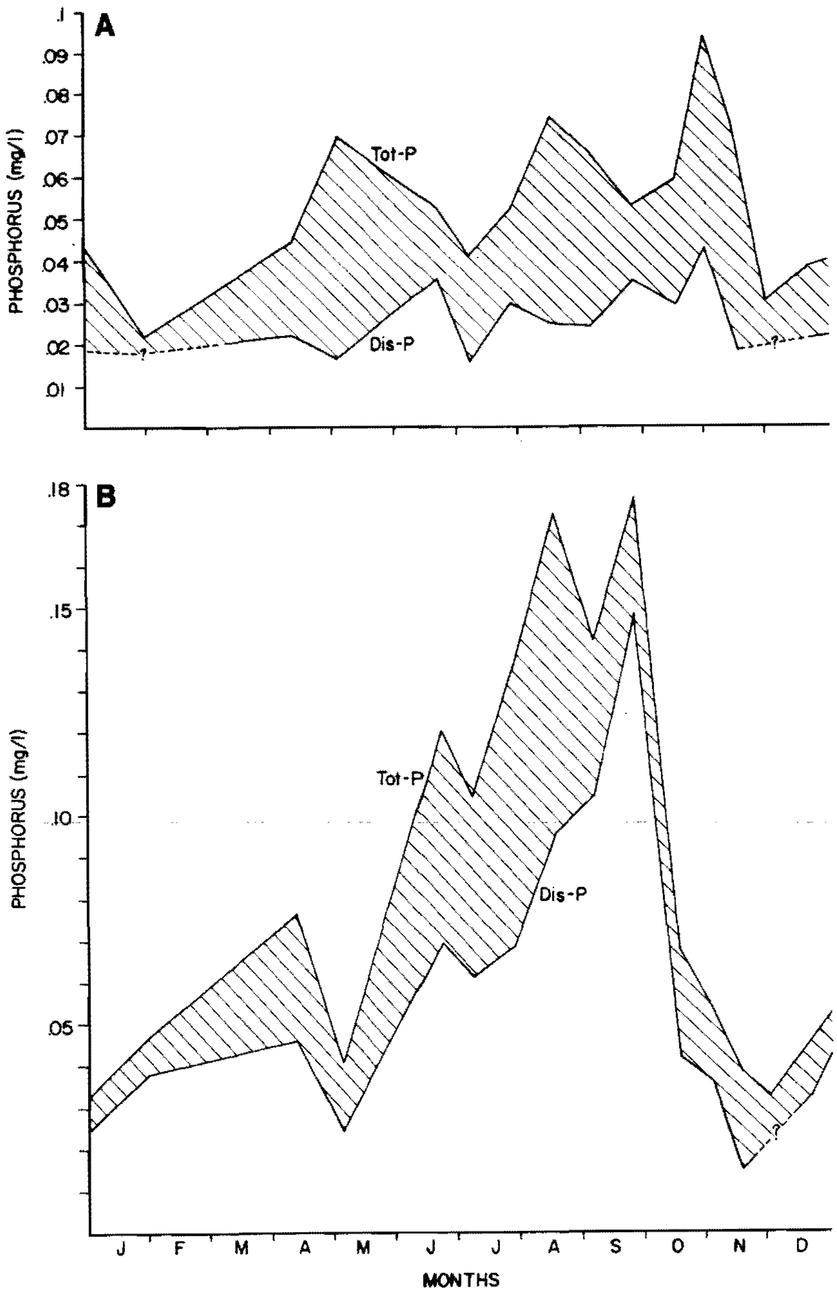

FIGURE 22. *Weighted average phosphorus concentration in Larson Lake, 1972 (a) for the whole lake and (b) from a depth of 20 ft to the bottom.*

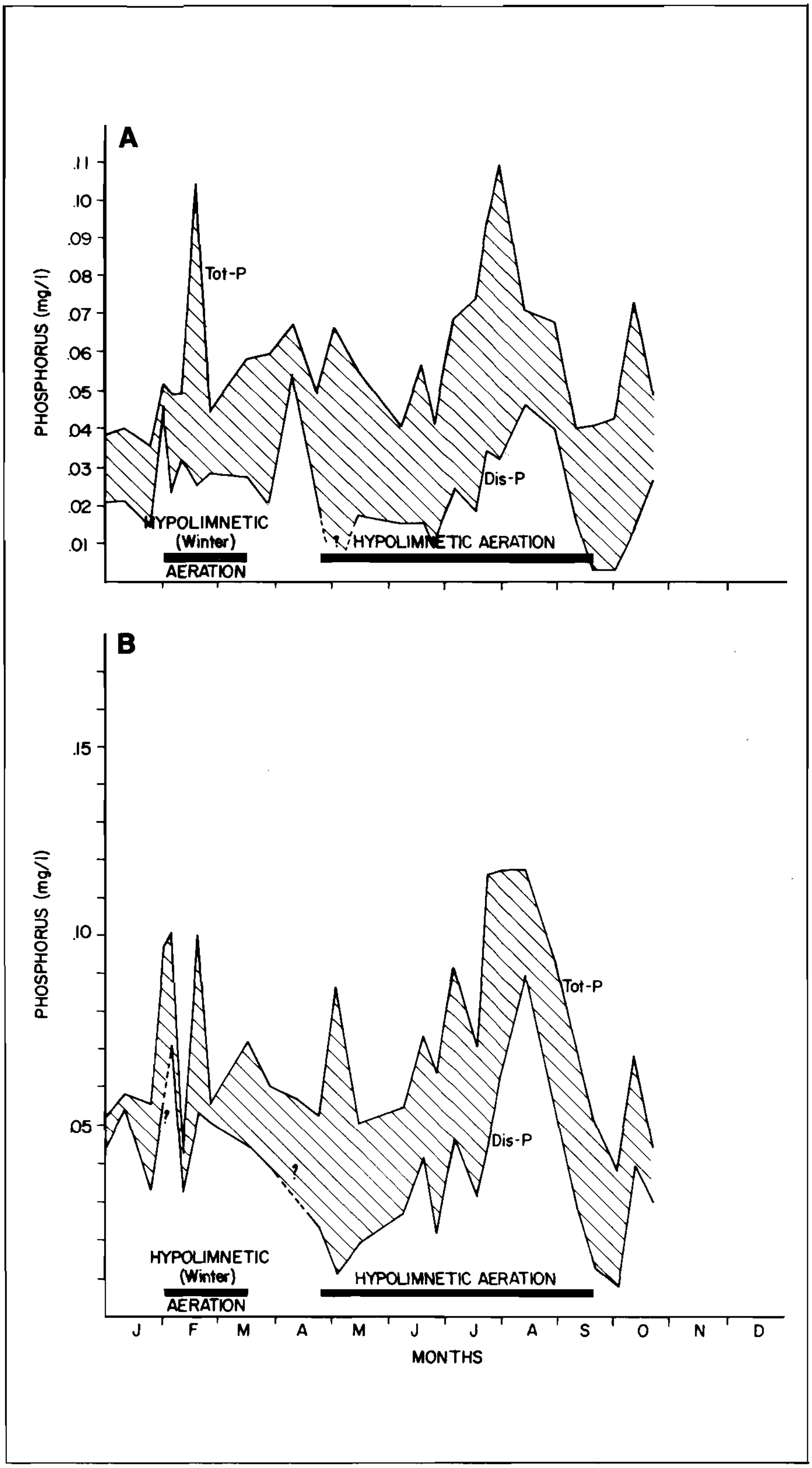

FIGURE 23. *Weighted average phosphorus concentration in Larson Lake, 1973 (a) for the whole lake and (b) from a depth of 20 ft to the bottom.*

were confined to the epilimnion during the summer, but winter aeration may have produced more favorable conditions throughout the entire lake.

We considered stocking the Larson Lake hypolimnion with trout (this could have been done easily by flushing them down the aerator return tubes), but survival and growth would have been doubtful. Unfavorable epilimnetic temperatures (almost 76° F for nearly the entire month of July) combined with low dissolved oxygen in the metalimnion might have trapped them in the hypolimnion. Although the hypolimnetic temperature and dissolved oxygen conditions were favorable, we suspected that there were few fish food organisms available. Feeding forays into the more productive upper waters would have been restricted.

In addition to improved dissolved oxygen conditions, the reduction of ammonium-nitrogen and phosphorus concentrations are positive benefits of hypolimnetic aeration; both play an important role in the process of eutrophication (see, for example, Stewart and Rohlich 1967; Vollenweider 1968; National Academy of Sciences 1969; Lee 1970). Although Larson Lake does not exhibit many of the characteristics of eutrophic lakes (in fact the lack of primary producers would be cause for concern from the fish management standpoint), it does have high nutrient levels. In lakes where high hypolimnetic nutrient concentrations or the presence of reduced chemical species create water quality problems, these additional benefits may help justify aeration. In Mirror Lake, a similar reduction in phosphorus was noted, although the total effects were masked somewhat by suspected sediment and storm sewer inputs.

The oxygen transfer efficiency of the Larson Lake aerator and the Mirror Lake aerator with only the compressor in operation were about the same, 10 to 12 percent, which is not surprising considering that the units were nearly identical. This is a greater rate of oxygen transfer than that predicted on the basis of a simple air injection system operating at a 39-ft depth with the same orifice size. However, similar transfer efficiencies could probably have been attained at a much lower cost by using smaller bubbles and a simple tube without a helix. Part of the advantage of the helix for promoting a long travel time (about twice the straight-line length) may be lost due to channeling of bubbles along the helix surface. Even with the compressor operating at full capacity, the bubbles emerging from the "Helixor" at Larson Lake were definitely concentrated at the helix surface and were not distributed uniformly throughout the available space. Channeling of the bubbles along the helix may also help explain the results of the dissolved oxygen measurements inside the Mirror Lake "Helixor." Virtually all of the oxygen transfer took place inside the lower half of the unit with both air and oxygen injection. Although the greater solubility of oxygen with depth partially explains these results, it is possible that the bubbles coalescenced as they moved up the unit, reducing the effective transfer surface.

CONCLUSIONS

Lake aeration, either hypolimnetic or total, is a valuable lake restoration technique. The importance of dissolved oxygen to the aquatic community–fish, plankton, and benthos–is well-documented, and aeration is an effective means of improving dissolved oxygen conditions. In addition, aeration can lead to improved water quality by eliminating reduced chemical species such as ferrous iron, manganese, ammonia, and hydrogen sulfide. Aeration has little direct effect on aquatic nuisances such as rooted macrophytes or algae, but the circulation patterns developed by a total aeration (destratification) system may be useful in eliminating nuisance algal blooms or causing a shift to more desirable algal species. Aeration may also lead to a reduction in phosphorus concentrations, a critical plant nutrient.

In the past, little effort has gone into efficient aerator design. A number of systems have proven inadequate (see Dunst et al. 1974), and probably a substantial number of installations are oversized. Research is needed in this field, particularly with regard to: (1) the flow rate of water and the rate of oxygen transfer in free and confined bubble swarms as a function of bubble size, length of rise, and bubble density; (2) the relative efficiencies of various low-head, high-volume water pumps such as air-lift, eductors, and low-rpm mechanical pumps; and (3) cost energy, and maintenance trade offs for hypolimnetic aeration using compressed air and liquid oxygen.

The Mirror Lake and Larson Lake demonstration projects have shown:

1. A reliable means of estimating the oxygen uptake rate in lakes needs to be developed. The standard 5-day biochemical oxygen demand provides only a qualititative estimate, and the depletion rate during aeration can be several times the "normal" depletion rate observed during stratification or ice cover.

2. With hypolimnetic aeration, it is possible to make substantial improvements in hypolimnetic dissolved oxygen concentrations without altering the thermal regime of a lake. This preserves the cold-water resource for fish habitat, and at the same time eliminates rapid nutrient recycling from the hypolimnetic sink.

3. During periods of ice cover, "hypolimnetic" aeration can improve dissolved oxygen conditions in a lake without creating the open-water hazard associated with total aeration systems.

4. In both Mirror and Larson Lakes, hypolimnetic aeration had a positive effect on nutrient concentrations. The long-term effects are unclear.

5. In lakes such as Mirror Lake, where the oxygen demand is great and vernal and autumnal mixing may be incomplete, total aeration in the spring and fall can provide a valuable supplement to hypolimnetic aeration. In Larson Lake, a depth-adjusted total aeration system operated in conjunction with the hypolimnetic aerator may have helped reduce the thickness of the anoxic metalimnion.

APPENDIX 1: AERATOR DESIGN FACTORS

Basic Design

Mechanical aeration of lakes consists of two basic steps: (1) oxygen transfer across some air-water interface, and (2) distribution of the oxygenated water in the lake (Hogan, Reed, and Starbird 1970). The basic equation for predicting the rate of oxygen transfer across an interface (bubble surface or lake surface) into water can be written in the general form:

$$\frac{dm}{dt} = K_L A\,(C_s - C) \qquad (1)$$

where dm/dt = time rate of oxygen mass transfer (gm/sec), K_L = liquid film coefficient (cm/sec), A = area of the interface (cm^2), C_s = concentration of dissolved oxygen at saturation (gm/cm^3)*, and C = concentration of dissolved oxygen in the water (gm/cm^3).

In terms of the rate of change of the concentration of oxygen, Equation 1 can be rewritten as:

$$\frac{dC}{dt} = K_L \frac{A}{V}(C_s - C) = K_L a\,(C_s - C) \qquad (2)$$

where dC/dt = time rate of change of the dissolved oxygen concentration (gm/cm^3 sec), V = unit volume of water (cm^3), and a = interfacial area per unit volume of water (per cm). These equations indicate that the rate of oxygen transfer is proportional to the dissolved oxygen deficit, $C_s - C$, or the "driving force" of the system. When the concentration of dissolved oxygen in the water is zero, the rate of oxygen transfer is at a maximum.

In terms of the dissolved oxygen deficit, Equation 2 can be rewritten as:

$$\frac{dD}{dt} = -K_L a D \qquad (3)$$

*mg/l = 10^{-6} gm/cm^3

where D = dissolved oxygen deficit (mg/l). This equation can be integrated to give the solution:

$$t = -ln \frac{\frac{Dt}{D_o}}{K_L a} \qquad (4)$$

where t = time, D_o = initial dissolved oxygen deficit (mg/l), and D_t = dissolved oxygen deficit at time t (mg/l). The above equation provides a means of solving for either t or D_t, providing that $K_L a$ is known. For commercial wastewater aerators, $K_L a$ is usually evaluated by full-scale testing. Water with a low dissolved oxygen content is aerated, and the slope of a semilogarithmic plot of D_t vs. t gives $K_L a$ (Technical Practice Committee 1969).

The efficiency of both commercial wastewater and shop-built lake aerators is commonly expressed in terms of oxygen added per unit of energy input, or:

$$OC = \frac{D_o - D}{E}\, V \qquad (5)$$

where OC = oxygenation capacity (kg/kWh) and E= energy input (kWh).

The efficiency of aerators can also be expressed as the ratio of the amount of oxygen absorbed to the amount supplied (transfer efficiency). For wastewater aerators, which operate in essentially a steady state, the theoretical oxygenation capacities fall within the range of 3.3 to 7.7 lb/kWh, and transfer efficiencies of about 10 percent are common (Technical Practice Committee 1969). For several types of lake aerators (total aerators), King (1970) lists oxygenation capacities of 1 to 5 lb/kWh and transfer efficiencies of 2 to 8 percent. Since the transfer efficiency and oxygenation capacity of an aerator is usually based on the measured increase in the dissolved oxygen content of the aerated water, atmospheric and photosynthetic oxygen additions are included in the calculation. The true transfer efficiency, based only on the direct transfer of oxygen from the aerator, is undoubtedly less than the above values.

Adaptations

Total Aeration—Aeration by Destratification. The most efficient aeration devices maximize the area of the air-water interface and/or turbulence in order to achieve the greatest amount of oxygen transfer. (The value of the transfer coefficient, K_L, is related to the degree of turbulence.) The effectiveness of aeration by destratification is readily apparent when one considers that the surface area of the entire lake becomes the site of oxygen transfer, and wind-induced turbulence, aided by the destratification equipment itself, is used to circulate oxygenated water away from the interface (Fig. 24).

For most realistic aeration situations where compressed air is used to destratify the lake, the surface area of the lake far exceeds the surface area of the bubbles present in the lake at any given time. For instance, assume that a destratification system is installed in a small lake with a maximum depth of 26 ft and a surface area of 20 acres. With an air flow rate of 27.5 cfm and an average bubble diameter of 0.8 in, the total surface area of all the bubbles in the lake at any given instant is, at the most, only 0.14 percent of the lake surface area.* Decreasing the size of the bubbles slows their rate of rise, but even at a bubble diameter of 0.2 in, the surface area of the bubbles is still less than one percent of the surface area of the lake. Although turbulence is great at the bubble site, most oxygen is transferred at the lake surface. Riddick (1957) reached the same conclusion during the destratification of a water-supply reservoir and suggested that an aerator should simply be regarded as a cheap, uncomplicated, and relatively efficient device for pumping water. In a comparison of

*This is a maximum percentage based on the terminal rising velocity of single bubbles in water (Haberman and Mortan 1954). Bubbles in swarms rise faster than single bubbles, with a corresponding decrease in residence time.

lake destratification using a mechanical water pump and compressed air, Symons et al. (1967) noted that the oxygenation capacity (Equation 5) of the diffused air "pump" was greater, not because of oxygen transfer from the bubbles, but because it was more efficient in moving bottom water to the surface (in terms of energy input).

The minimal time required to oxygenate a completely mixed lake by natural aeration at the surface can be approximated by (Hutchinson 1957):

$$C_t = C_o + (C_s - C_o)(1 - e^{-tb/\bar{z}}) \quad (6)$$

where C_t = oxygen concentration at time t (mg/l), C_o = initial oxygen concentration (mg/l), C_s = oxygen concentration at saturation (mg/l), t = time (days), b = exchange coefficient (m/day), and $\bar{z}$ = mean lake depth (m). Or, in a more convenient form, this equation can be expressed as:

$$t = \left(-ln \; \frac{D_t}{D_o}\right) \frac{\bar{z}}{b} \quad (7)$$

where D_o = initial dissolved oxygen deficit (mg/l) and D_t = dissolved oxygen deficit at time t (mg/l).

The value of the exchange coefficient, b, varies according to the degree of turbulence in the lake, but as Hutchinson (1957) points out, the value determind by Adeney and Becker (1919) for a continuously reformed surface is not likely to be exceeded (18 ft/day at 39° F). Since t is inversely related to b in Equation 7, D_t/D_o can be plotted against t to determine the probable minimum rate of natural aeration in a totally mixed lake (Fig. 25). The net rate of natural aeration decreases with time, but even so, only slightly more than 4 days are required to reduce the oxygen deficit in a lake with a mean depth of 16 ft to one percent of its initial value. The corresponding period of time for a lake in which $\bar{z}$ = 49 ft is 3 times as great, or about 12.5 days.

Since b increases with temperature, a longer period of time is required to satisfy an oxygen deficit at temperatures above 39° F. At 68° F, b = 25 ft/day, compared to 18 at 39° F. This increases the time required to overcome the oxygen deficit proportionally. In other words, about 6 days would be required to overcome 99

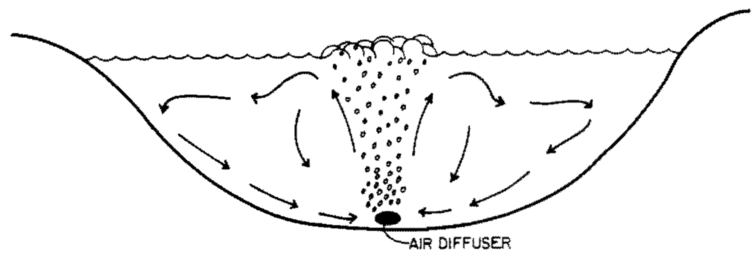

FIGURE 24. *Diagram of water flow during lake destratification.*

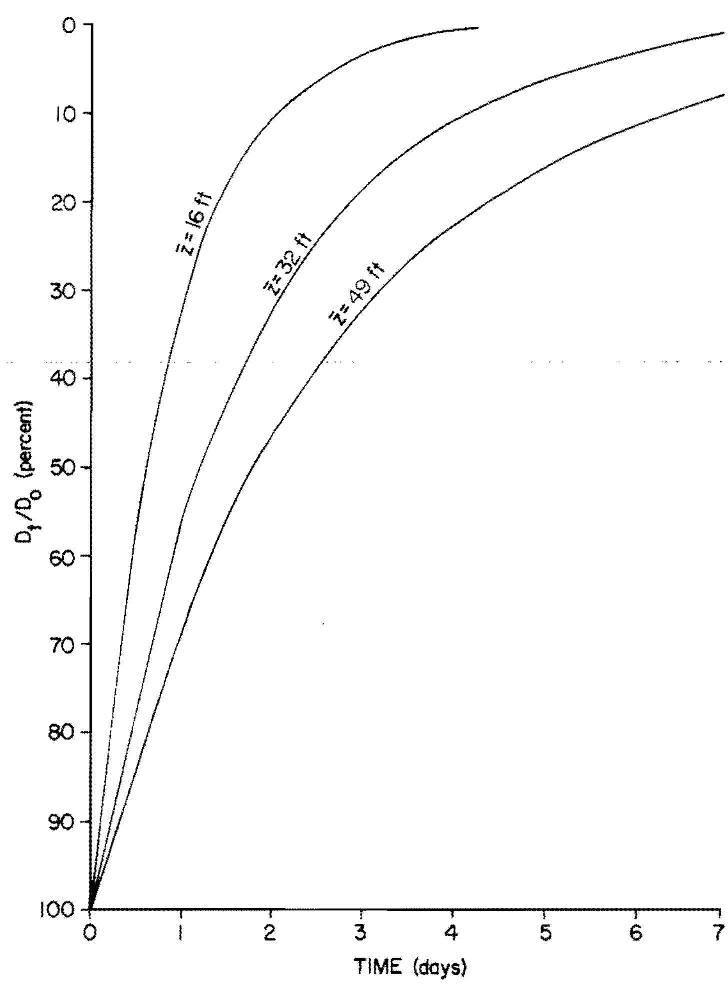

FIGURE 25. *Natural (atmospheric) aeration of totally mixed lakes. (D is the initial dissolved oxygen deficit in mg/l, D_t is the dissolved oxygen deficit at time t in mg/l, and $\bar{z}$ is the mean lake depth in m.)*

percent of the deficit in a lake with $\bar{z}$ = 16.4 ft at 68° F, as opposed to 4 days at 39° F (Fig. 25). The period is increased correspondingly for deep lakes.

Natural surface aeration of a completely mixed lake is, therefore, a rather rapid process, a conclusion which is a little surprise to most fish managers. In fact, the limiting step in artificial aeration by destratification in most lakes is the time required to effect destratification. Provided that the oxygen demand of the water is not too great, natural surface aeration will raise the oxygen content to satisfactory levels as destratification is proceeding, or the lake will be oxygenated soon after destratification is complete. However, a destratified lake can also quickly restratify, cutting short the natural aeration process, and destratification can also introduce a large pulse of oxygen-depleting materials from the bottom waters. It is usually necessary, therefore, to operate destratification equipment at least intermittently after a lake is destratified in order to permit continual mixing and aeration.

The theoretical energy input required for destratification can be easily calculated from the thermal stability. The thermal stability of a lake represents the work required to lift the entire water mass from the center of gravity of the stratified lake to its center of volume (the center of gravity in a completely mixed state). However, there is no highly efficient method of lake destratification. Destratification schemes used in the past have reported efficiencies ranging from 0.1 percent to 2.0 percent (Symons et al. 1967), based on the energy input relative to change in stability. Air injection is probably the most efficient method of destratification, with an approximate average efficiency of about 1 percent; the average destratification efficiency of mechanical pumping is about 0.5 percent (Symons et al. 1967).

It is not generally necessary to pump the entire water volume to destratify a lake. Irwin, Symons, and Robeck (1966) destratified four small reservoirs in Ohio after pumping only 4-17 percent of the lake volume and 6-26 percent of the volume of "cold water" (presumably the hypolimnion and at least part of the metalimnion). Bryan (1964) reported that Blelham Tarn was destratified after 26 percent of the lake volume was pumped through the "Bubble-Guns," and Zieminski and Whittemore (1970) found that they could completely mix a stratified laboratory tank by pumping 28-33 percent of the tank volume with their diffused air system. Using dye tracers, Van Ray (1968) found that Stockade Lake was destratified after pumping only 23 percent of the lake volume.

It should be possible, therefore, to reasonably estimate the time required to destratify a lake if the water flow rate through the destratification system is known. The flow rate through a mechanical pump can be easily determined, but it is much more difficult to calculate the rate of water flow from a diffused air injection system. Smith and Wegener (1971) have calculated that a spherical cap bubble* rising through water can theoretically transport no more than 15 times its volume of water, but several field studies have shown the water-air ratio to be much larger. These results are summarized in Table 8, and vary from a low of 27 for Bernhardt's hypolimnetic aerator to a high of 1100 for Buchanan Lake. Bernhardt's results are not strictly applicable, however, since the rising bubbles were confined inside of a vertical pipe and the water inside the pipe built up a pressure head. The water flow rates for the Buchanan Lake aeration system may be unreasonably high as well. They were apparently based on the assumption that the entire lake volume was pumped during the destratification process. (Water flow measurements were made but later rejected.)

It seems that a water-air ratio of about 100 is a reasonable estimate for a destratification system. Using this figure, and 25 percent as an estimate of the amount of water that must be pumped to destratify a lake, it should be possible to calculate the time required to destratify a lake. Table 9 lists the results of this calculation for several lakes which have been destratified and for which data are available (lake volume, air flow rate, and actual time to destratify). Although there is fairly good agreement between the calculated and observed destratification time, the calculated time is generally less than the observed time, indicating that either one or both of the underlying assumptions is in error. A water-air ratio of 100 may be too great, and/or more than 25 percent of the lake volume may have to be pumped. Of course, there are numerous additional factors which affect the time required to destratify a lake, and these were not considered. Morphometry, severity and degree of stratification, climatic conditions, and the efficiency of the system itself all affect the destratification time. Zieminski and Whittemore (1970) and Knoppert et al. (1970) both found that small bubbles are more effective at moving water than large bubbles (Table 8). The method used in calculating destratification time probably has built-in compensating errors for some of these factors, but there are not enough data to test them effectively. At any rate, the technique gives a means of at least estimating the size of a destratification system needed for a given lake. However, all of the additional factors should be considered in the design process.

*Above a diameter of about 0.4 in, bubbles rising in water assume the shape of a spherical cap, with a rounded upper surface and an irregular, flattened lower surface (Haberman and Morton 1954).

Hypolimnetic Aeration. To date, little design data have been accumulated for hypolimnetic aerators. Typically, hypolimnetic aerators have been less efficient than total aerators (destratification equipment) in terms of both oxygenation capacity (Equation 5) and the ratio of water flow rate to air flow rate. However, in terms of oxygen transfer, hypolimnetic aeration is somewhat more efficient than total aeration. Table 10 lists the performance characteristics of hypolimnetic aeration units for which data are available.

Figure 26 shows the basic design features of the different units. All of the aerators incorporate the air-lift principle to circulate and oxygenate hypolimnetic water. The relatively poor performance of hypolimnetic aeration compared to total aeration (in terms of oxygenation capacity and water-air ratio) is probably in part due to the confinement of the bubbles inside the vertical stack (riser). In his analysis of air-lift pumps, Andeen (1974) notes that efficiency losses in a riser are due to the slip velocity between the bubbles and the liquid, or:

$$n = \frac{V}{V + V_r} \qquad (8)$$

where n = riser efficiency, V = velocity of the water, and V_r = slip velocity,

TABLE 8. *Water flow rate/air flow rate (W/A) for aeration systems.*

Name of Lake or Res.	W/A	Comments	Reference
Buchanan Lake	1100	Probably too high, see text	Brydges (1972)
Indian Brook Reservoir	89	None	Riddick (1957)
Maarseveen	53-318	Ratio decreased as orifice diameter and/or over-pressure increased	Knoppert et al. (1970)
Loch Turret Reservoir	150	"Aero-Hydraulic Guns"	Bryan (1964)
Bench Testing	48-200	Ratio decreased as air flow rate increased	Zieminski and Whittemore (1970)
Pfäffikersee	75	Confined in pipe	Bernhardt (1967) and Thomas (1966)
Wahnbach Reservoir	27	Hypolimnetic aerator, see text	Bernhardt (1967)
Stockade Lake	84	None	Van Ray (1968)
Cox Hollow Lake	71	"Aero-Hydraulic Guns"	Wirth and Dunst (1967)

TABLE 9. *Observed and computed destratification times for lakes and reservoirs using air injection.*

Name of Lake or Reservoir	Reference	Max. Depth (ft)	Time Required For Destratification: Actual Time	Time Required For Destratification: Calculated Time (In Days)*
Babson Reservoir	Nickerson 1961	30	14 days (interrupted)	5.5
Boltz Lake	Symons et al. 1967	62	3 - 5 days	2.0
Buchanan Lake	Brydges 1972	43	1 - 3 days	2.6
Lake Cachuma	Busby 1973	200	unsuccessful	17.5 - 23.8
Casistas Reservoir	Barnett 1971	270	successful**	16.0 - 16.2
Corbett Lake	Halsey 1968	64	<1 day	0.7
El Capitan Reservoir	Fast 1968	203	10 days	5.3
Escondido Reservoir	Burns 1966	43	successful**	1.2
Falmouth Lake	Symons et al. 1967	43	3 - 5 days	4.0
Indian Brook Reservoir	Riddick 1957	28	4 - 6 days	6.5
Lafayette Reservoir	Laverty and Nielsen 1970	79	partial destratification***	5.3
Parvin Lake	Lackey 1971	32	successful**	0.7
Roberts Lake	Leach and Harlin, Jr. 1970	30	3 days	0.8
Stockade Lake	Van Ray 1968	43	1.7 days	1.5
Waco Reservoir	Biederman and Fulton 1971	75	partial destratification****	8.0
Wahnbach Reservoir	Bernhardt 1967	141	unsuccessful	48.0
Wahnbach Reservoir	Bernhardt 1967	141	21 days	15.3

*Calculated from 25% of the volume divided by 100 times the daily air input.
**Actual time not given.
***Operated 30 hrs/wk.
****Operated intermittently.

TABLE 10. *Performance characteristics of hypolimnetic aerators.*

Name of Lake or Reservoir	Reference	Oxygenation Capacity (lb/kWh)	Oxygen Transfer Efficiency (In Percent)	Water:Air Ratio
Hemlock Lake	Fast 1971	–	–	8 - 12
Larson Lake	this report	0.7	9 - 14	10
Mirror Lake	this report	0.7*	14 - 23	9 - 23
Waccabuc Lake	Union Carbide 1973	0.1**	10.6	3.8
Wahnbach Reservoir	Bernhardt 1967	0.1	50	27

* Oxygenation capacity (OC) and transfer efficiency are based on the increase in dissolved oxygen content while the water was in contact with the bubbles. Due to the high oxygen demand of the water, the dissolved oxygen was depleted rapidly after the bubbles were separated from the water. The actual OC and transfer efficiency were nearly zero.

** OC is based on compressor rating, not power consumption. The actual OC is probably somewhat greater.

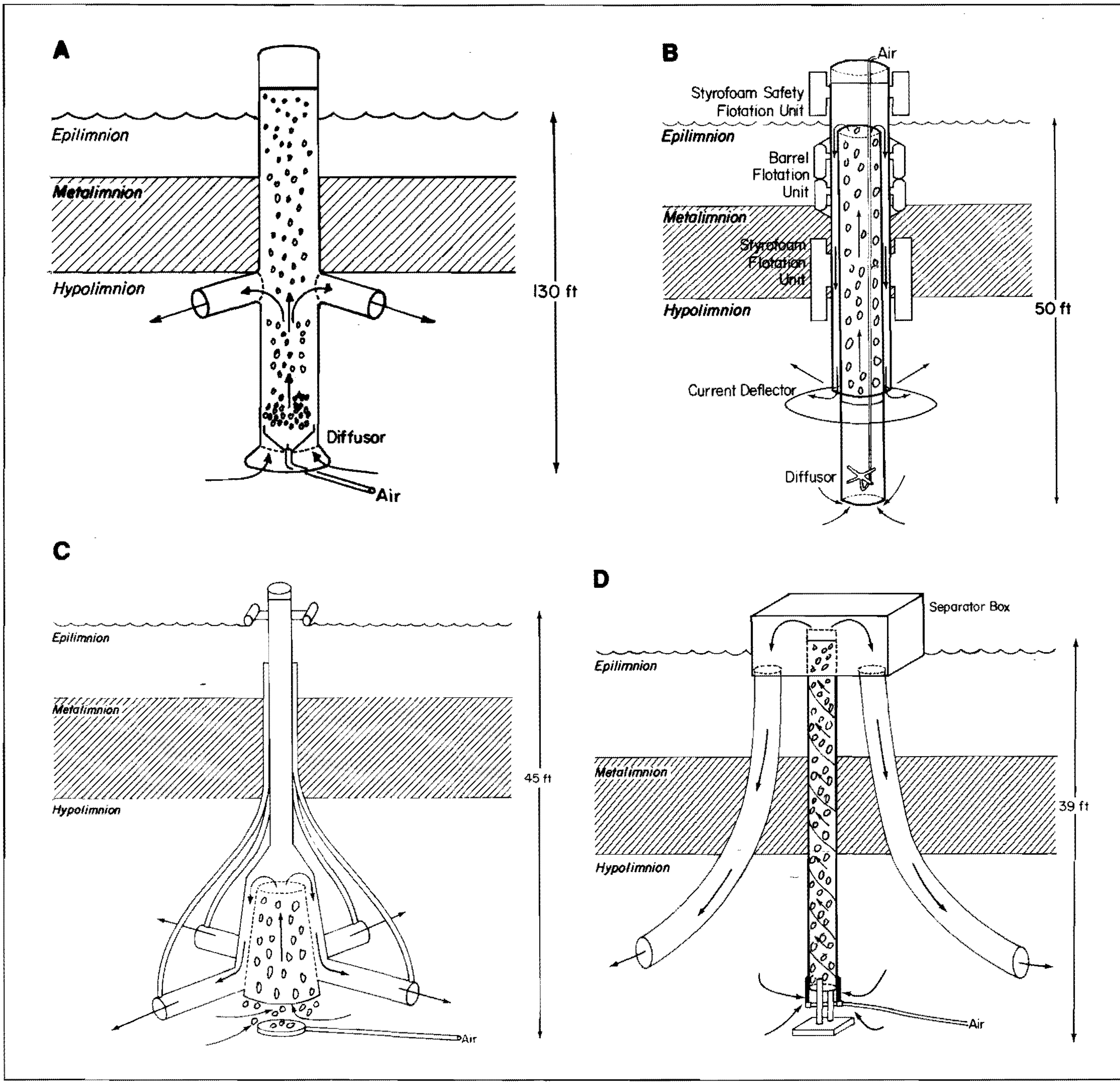

FIGURE 26. *Hypolimnetic aeration units: (a) Bernhardt 1967, (b) Fast 1971, (c) Union Carbide 1973, and (d) this report.*

or the relative velocity between the bubbles and the liquid. Obviously, for maximum riser efficiency, it is desirable to minimize the slip velocity (if the bubbles and the water are moving at the same velocity, the riser efficiency is 100 percent).

As a first approximation, the slip velocity is the rise velocity of a free bubble in an unbounded fluid (Andeen 1974). Small bubbles generally have a lower rise velocity than large bubbles (Haberman and Morton 1954), so in order to minimize slip velocity, it is advantageous to produce small bubbles. This also maximizes the rate of oxygen transfer (Higbie 1935; Eckenfelder 1959; Johnson, Besik, and Hamielec 1969; Hogan, Reed, and Starbird 1970; and others). Although small bubbles are desirable, they are difficult to achieve. Small bubbles require a small diffuser orifice, which in turn leads to clogging problems and high overpressures at the orifice. At very small bubble diameters, the energy required just to overcome surface tension and form a bubble can cause drastic reductions in aerator efficiency (Andeen 1974).

It is possible, of course, to minimize the slip velocity by completely filling the riser tube with a single, large bubble. This is the basic principle of the "Aero-Hydraulics Gun," which has been used in several lake destratification projects (Water and Water Engineering 1961; Bryan 1964; Kolbe 1964; Wirth et al. 1970). However, with few exceptions, slug flow is less efficient at moving water than bubbly flow (Andeen 1974), and oxygen transfer from the large bubble is minimal.

Analysis	Method	Reference No. **
NH_3-N	Distillation	2
NO_3-N	Modified brucine	3
Org-N	Kjeldahl digestion	2
Tot-P	Nitric-Perchloric acid digestion, phospho-molybdate, stannous ion reductant	4
Dis-P*	Phospho-molybdate, stannous ion reductant	1
Ca	Atomic absorption spectrophotometry	3
Mg	Atomic absorption spectrophotometry	3
Cl	Hg $(NO_3)_3$ titration	3
Tot-Fe	Ortho-phenanthroline	1
Tot-Mn	Atomic absorption spectrophotometry	1
Alkalinity	Acid titration	1
pH	Potentiometric	1
DO	Winkler, polarographic probe	1
BOD_5	Polarographic probe	1
COD	Acid dichromate	1

*Dis-P analysis is conducted on nonfiltered samples.

**Numbers correspond to the following references:

1. American Public Health Association (1965).
2. Brown, Skougstad & Fishman (1970).
3. Environmental Protection Agency (1971).
4. Katz and Proctor (1947).

APPENDIX 3: METHODS OF BIOLOGICAL ANALYSES

Water samples from 0, 1, and 2 m were collected using a nonmetallic Kemmerer water sampler. The water from the 3 depths was mixed together to give an integrated sample and Lugol's solution (10 g iodide, 20 g potassium iodide, 20 ml acetic acid, and 200 ml water) was added as a preservative. The preserved algae were filtered with a membrame filter (0.45 μ pore size). The volume of water filtered, usually between 50 and 200 ml, was dependent upon the biomass in suspension. The membrane filters were dried and cleared for algae enumeration at 400 or 1000 X. Identification of organisms was made from preserved nonfiltered samples using Hustedt (1930), Smith (1933), Prescott (1951), and Patrick and Reimer (1966) as references.

Volume estimates were made for all the major species identified by approximating the geometric shape of the species with a solid geometrical formula. Cell volume was converted to biomass by assuming a density of 1 mg/mm^3 for all species.

APPENDIX 4: METRIC–ENGLISH CONVERSIONS

ft	x	0.308	=	m	x	3.3	=	ft
yd	x	0.9	=	m	x	1.1	=	yd
mi	x	1.6	=	km	x	0.6	=	mi
acres	x	0.405	=	ha	x	2.47	=	acres
ft^2	x	0.09	=	m^2	x	10.89	=	ft^2
in^2	x	6.5	=	cm^2	x	0.16	=	in^2
lbs	x	0.454	=	kg	x	2.205	=	lbs
oz	x	28	=	gm	x	0.035	=	oz
ppm	x	1	=	mg/l	x	1	=	ppm
acre-ft	x	1233.5	=	m^3	x	0.0008	=	acre-ft
ft^3	x	0.03	=	m^3	x	35	=	ft^3
cfs	x	30	=	1/sec	x	0.035	=	cfs

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