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A new hypolimnetic aeration system is described. This system increased the hypolimnetic oxygen concentrations of Lake Waccabuc, New York, from 0.0 mg/l to over 4.0 mg/l, while at the same time preserving thermal stratification. These improvements and others created a suitable habitat for cold-water fish, but care must be exercised in the use of the system to avoid problems of nitrogen gas supersaturation.

Eutrophication of lakes and reservoirs frequently leads to nuisance algal growth, anaerobic hypolimnetic conditions, and a general deterioration of water quality. Artificial aeration is often used to reduce eutrophication or conditions associated with eutrophication [*Symons*, 1969; *Toetz et al.*, 1972]. The two principal categories of lake aeration are destratification and hypolimnetic aeration. Destratification involves the up-welling of hypolimnetic water to the surface where it mixes with epilimnetic and thermocline water. When destratification is accomplished, the lake will be isothermal, oxygen will be present at all depths, and other chemical conditions will be more uniform. A properly designed destratification system may greatly improve water quality, but an inadequate system may create greater problems [*American Water Works Association*, 1971; *Fast*, 1973a]. Hypolimnetic aeration, on the other hand, involves only the aeration of the hypolimnion without thermal destratification. Several hypolimnetic aeration systems have been designed [*Bernhardt*, 1967; *Speece*, 1971; *Fast*, 1971], but not one is yet in widespread use. Hypolimnetic aeration has certain advantages over destratification including the following. (1) Nutrients are not upwelled into the epilimnion where they may promote algal growth. (2) Cold, well-aerated water is produced by hypolimnetic oxygenation, whereas only warm, well-aerated water is produced by destratification. The former condition is preferable for most domestic and industrial water uses. (3) Hypolimnetic aeration may permit the establishment of a cold-water fishery such as trout or salmon. Destratification may preclude such a fishery, since the cold-water region is eliminated [*Fast and St. Amant*, 1971; *Fast*, 1973*b*].

LAKE WACCABUC

A new hypolimnetic aeration system called Limno, which was installed and operated in Lake Waccabuc, New York, during the summer of 1973, and some of the effects the system had on the lake are described in this paper.

Lake Waccabuc is a moderately eutrophic lake located 80 km north of New York City in upper Westchester County, New York. It measures 53 ha surface area, 4.053 X 10^6 m^3 total volume, 7.228 x 10^5 m^3 hypolimnetic volume, and 13 m maximum depth (Figure 1). Hypolimnetic oxygen is typically depleted by midsummer, and algal blooms are frequent during the summer months. Floating mats of blue green algae were not abundant, however, and rooted plants are sparse due to the reduced littoral

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area and high turbidity of the water.

Alkalinity and pH average 29mg $CaCO_3$/l and 7.2, respectively. More than 300 residences are located in the adjacent watershed. All are served by septic tank disposal systems. Significant amounts of nutrients undoubtedly enter the lake from these sources and from lawn fertilization. The soil in and around the lake is sandy with granitic outcropping, and sub-surface infiltration is presumably significant.

METHODS

Temperature and dissolved oxygen were measured at least weekly during the summer months and twice monthly during the remainder of the year from July 1972 through December 1973. Temperature was measured with a resistance thermometer. Oxygen was measured either by the Alsterberg modification of the Winkler method or by an electronic oxygen analyzer. Water samples for the Winkler procedure were collected in a PVC water sampler. Phenylarsene oxide (PAO) was substituted for thiosulfate, and thyodene was substituted for starch solution. Both the Weston and Stack and the Delta electronic oxygen analyzer were used but were calibrated by the Winkler method.

Water flow through the aerator was measured with a General Oceanics digital flowmeter. The flowmeter was positioned in the center of each of the outlet tubes, and flow was calculated for each aerator on the basis of the average flowmeter reading, cross-sectional area of the outlet tubes, and the manufacturer's calibration curve for the flowmeter.

Water samples for dissolved nitrogen gas analyses were collected by a scuba diver. The diver collected the samples in 300-ml stainless steel flasks with pressure tight valves on either end. The flasks were filled with water at the lake surface, and the valves were closed. The flask was then lowered to the collection depth, both valves were opened, and a water volume equivalent to 10 flask volumes was flushed through the flask. The water was flushed by attaching the suction line from a low-pressure water pump to one end of the flask. The valves were closed at the collection depth, and the flasks were stored under ice until the samples were analyzed. They were analyzed within 24 hours of collection by using the helium stripping gas chromatographic technique of Swinnerton [1962]. Nitrogen gas was stripped from 3 ml of each water sample by using helium stripping gas. Triplicates were run on each sample and the results were calibrated by assuming that the surface samples were at equilibrium saturation for nitrogen gas.

AERATION SYSTEM DESCRIPTION

This hypolimnetic aeration system differs greatly from previously described hypolimnetic aeration systems [*Bernhardt*, 1967; *Speece*, 1971; *Fast*, 1971: *Toetz et al.*, 1972]. Unlike other hypolimnetic aeration systems, aeration occurs totally within the hypolimnion using compressed air and without upwelling water to the surface of the lake (Figure 2). This unique feature results in greater oxygen concentrations than those observed with other systems. The operation of the system is relatively independent of lake surface level fluctuations, and since the aerator is submerged, there is little evidence of its presence at the surface.

The main body of the aerator measures 4.6 m high and 8.5 m in diameter including the outlet tubes (Figures 2 and 3). It is constructed of glass fiber reinforced polyester plastic and is anchored within the hypolimnion of a lake. Compressed air from a shore-based compressor is released from a porous stone air diffuser suspended below the main body of the aerator. The rising air draws oxygen-depleted water into the inner cylinder of the aerator where aeration occurs. Oxygen and nitrogen gases diffuse into the water, while hydrogen sulfide, carbon dioxide, and other gases may diffuse out of the water and into the air bubbles. Upon reaching the top of the inner cylinder, most of the air separates from the water and collects in an air cavity within the aerator. These waste gases are vented to the surface through a small-diameter (7.5-cm) tube. The air cavity is an important design feature, since it helps maintain hydrostatic pressure on the water. The optimum cavity size is achieved by controlling the flow of waste gas through the vent tube. If the air cavity is too large, water will not flow through the inner cylinder, and if it is too small, water may be pumped to the surface with the waste gases. After, the air and water separate at the top of the inner cylinder, the water reverses its flow and flows downward between the inner cylinder and the outer walls of the aerator. This water flows out of the aerator through several outlet tubes. Earlier models had three outlet tubes, but the standard model now has six glass fiber tubes of 50 cm diameter. Any air remaining in the water collects at the top of the outlet tubes and is then vented to the surface inside a plastic skirt suspended from the surface float. If the main vent line becomes blocked, the aerator will tend to fill with air and rise. A safety valve (not shown) will then open and release the air within the aerator. This prevents the aerator from filling with air beyond a certain level and thus shooting to the surface.

The quantity of oxygen absorbed within the aerator is related to the oxygen concentration of the intake water, hydrostatic pressure, and volume of air injected. Multiple-aeration units can be operated from one air compressor. Each installation must be sized for a given lake on the basis of the size, depth, and oxygen demand of the ,lake and on the operating characteristics of the aerator. The Lake Waccabuc system consisted of two aerators located in the deepest depths of the lake (Figure 1). The aerators and anchor weights were installed by helicopter. Air was delivered to each aerator through 5.1-cm polyethylene plastic pipe from a shore-based compressor. The compressor delivered a total of 7.9 m3 air/ min (standard conditions) to the two aerators. Together the aerators discharged 30.3 m^3 water/min with an average oxygen concentration of 13 mg/l. If we assume that the inlet water averaged 5 mg/l of oxygen at equilibrium conditions within the hypolimnion, then 349 kg of oxygen was absorbed each day by the hypolimnion waters.

RESULTS

The thermocline of Lake Waccabuc during August 1972, a year before artificial aeration, extended between 4 and 7 m (Figure 4), and oxygen was absent below 8 m (Figure 5). The lake destratified naturally during the last week of October 1972, and an ice cover formed during December 1972. The ice cover was weak and transitory, and oxygen concentrations remained high all winter. The lake stratified thermally by the end of April 1973, and hypolimnetic oxygen was depleted by mid-June 1973.

We originally intended to install the aeration system and begin operation by mid-June 1973. However, equipment malfunctions delayed operation start-up until July 9, 1973. By that time the thermocline extended between 3 and 7.5 m, and oxygen was absent below 8 m. The hypolimnetic oxygen concentrations increased gradually after aeration began and averaged 3.5 mg/l by August 9, 1973. Hypolimnetic temperatures increased to only 8.5°C during this period, in comparison with 8.0°C during August 1972. Shortly thereafter, hypolimnetic oxygen concentrations plateaued at 4.0-4.5 mg/l and remained at that level until the lake destratified naturally during the last week of October. Hypolimnetic temperatures were only slightly increased during aeration. For example, during the first week of October 1972, hypolimnetic temperatures averaged 8.5°C compared with 9.0°C during the first week of October 1973 after 3 months of continuous aeration. A metalimnetic oxygen minimum of 0.2 mg/l persisted during the entire summer, an indication that the thermocline was not affected by the aeration process. Hydrogen sulfide was stripped by the aeration system. A rotten egg odor was especially prevalent near the vent pipe during the first few weeks of aeration. Thereafter it was undetectable even directly over the exhaust pipe.

Hypolimnetic oxygen and temperature values were relatively homogenous during aeration. For example, 9-m oxygen concentrations on August 31, 1973, ranged from 3.1 mg/l at the station farthest from the aerator to 4.1 mg/l nearest the aerator (Figure 6). On this same date, 9-m temperature values ranged from 8.9° to 9.1°C, and the range of temperature values below 8 m, measured at 11 locations in the lake, ranged from 8.8° to l0.7°C.

Dissolved nitrogen gas on September 27, 1973, ranged from 15.7 mg/l at the surface to 29.9 mg/l at the bottom (Figure 7). The greatest increase occurred between 6 and 7 m, and values were relatively uniform above and below these depths. Hypolimnetic dissolved nitrogen was 150% saturated in relation to the surface pressures, but only about 85% saturated within the hypolimnion because of the greater hydrostatic pressures and the colder water temperatures.

Discussion

The hypolimnetic aeration system successfully aerated Lake Waccabuc without significantly a affecting thermal stratification of the lake. These results are particularly pertinent, since aeration did not begin until the hypolimnion was anaerobic. The lake was thermally stratified for 183 days during 1973, and the hypolimnion was at least partially anaerobic for 30 days before aeration began. These conditions constituted an added oxygen demand that had to be overcome during aeration. In the future, aeration should begin soon after thermal stratification develops and before hypolimnetic oxygen is depleted.

This system can also be used during the winter if low-oxygen conditions develop. This situation will probably not develop in Lake Waccabuc because of the usually mild winters. However, severe winter conditions such as prolonged ice and snow cover, can lead to anaerobic conditions throughout a lake and a winterkill situation. *Fast* (l973*c*) describes the successful winter aeration of a Michigan lake using another hypolimnetic aeration system.

Dissolved nitrogen gas was supersaturated in the hypolimnion in relation to surface conditions because of its absorption from the aerator. This could cause serious problems in some instances. We are concerned about two situations in which adverse effects could occur. First, fish or other organisms that migrate through large vertical distances might be subject to gas bubble formation within their tissue. This condition, known as the bends in man, could possibly develop if the organism equilibrated with the gas content of the deep water and rapidly migrated to the surface. If its ascent rate was great, if it remained in the shallow water, and if its internal dissolved gas concentration was great in relation to ambient conditions, gas bubbles could form in the tissue. These bubbles could kill or severely injure the organism. We did not observe any such problems in Lake Waccabuc. We stocked 2100 trout (1500 rainbow trout (*Salmo gairdneri*), 300 brown trout (*S. trutta*), and 300 brook trout (*Salvelinus fontinalis*)) directly into the hypolimnion during August 1973 and monitored their depth distribution with sonar. These measurements indicate that the trout remained mostly in the thermocline during their first month in the lake. Thereafter they distributed throughout the hypolimnion. We could not measure the vertical movements of these fish, but sonar traces indicate that they were present in shallower water as well. We observed only a few dead trout shortly alter they were stocked and none that had gas bubble symptoms. Apparently, the fish adjusted their behavior to accommodate any potential problem, if indeed a potential problem existed. If a fish experienced discomfort when it moved to shallower water, it might return quickly to deep water and thus avoid extensive bubble formation. Furthermore, trout may not remain long in shallow water because of the much warmer temperature. Although we did not observe any mortalities in Lake Waccabuc due to nitrogen gas supersaturation, mortalities could develop in much deeper lakes where supersaturation could greatly be elevated in relation to surface values and/or if aeration was continued for a longer period each year. For example, if the hypolimnion of Lake Waccabuc had reached equilibrium saturation values for nitrogen gas, it would have been more than 200% saturated in relation to surface values.

The second situation in which hypolimnion nitrogen gas supersaturation could be a problem is the withdrawal of hypolimnetic water for downstream releases. Many reservoirs are designed for such releases, especially if hydroelectric power is generated by the releases. In these cases, saturation values of 200% or more could easily occur in the tail waters if this system is used to aerate the reservoir. *Schneider* (1970) found that fish subjected to as little as 110-114% saturation may develop gas bubble disease.

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Figure 1. Bathymetric map of Lake Waccabuc showing compressor installation, aerator locations, and seven principal sampling sites.

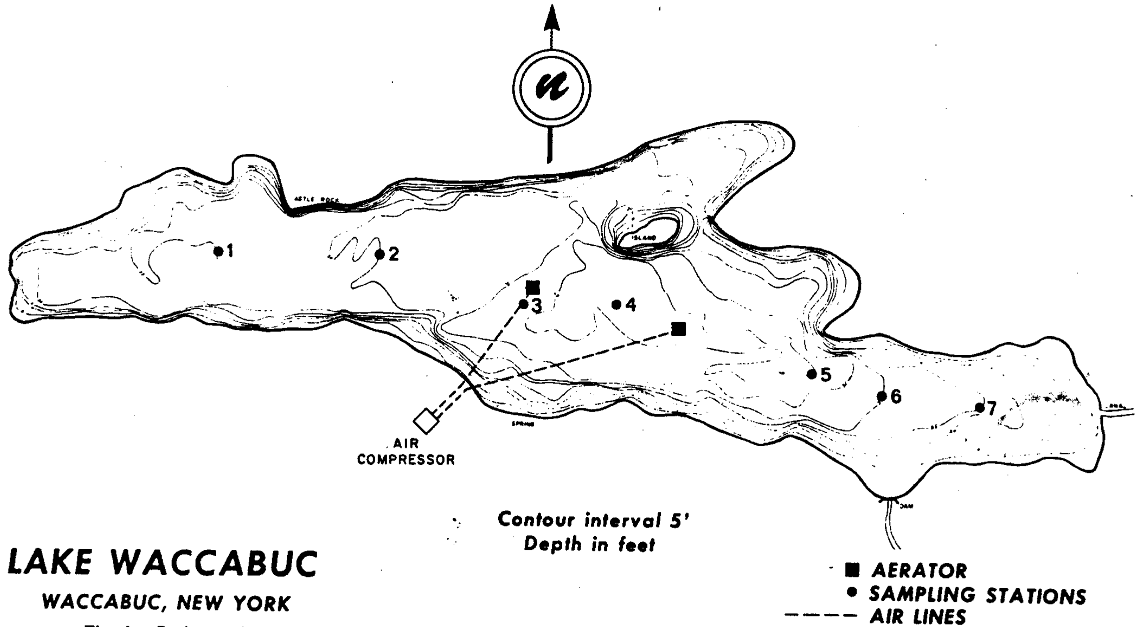

Figure 2. Exposed view of aerator in operation. Compressed air is Supplied by a shore-based compressor.

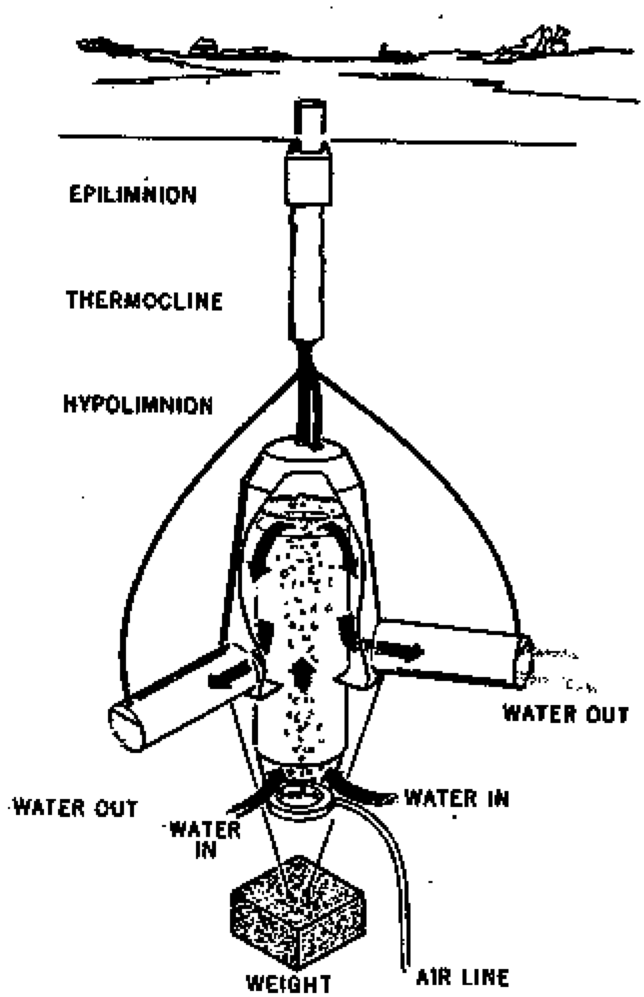

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Figure 3. Aerator being assembles before installation into Lake Waccabuc

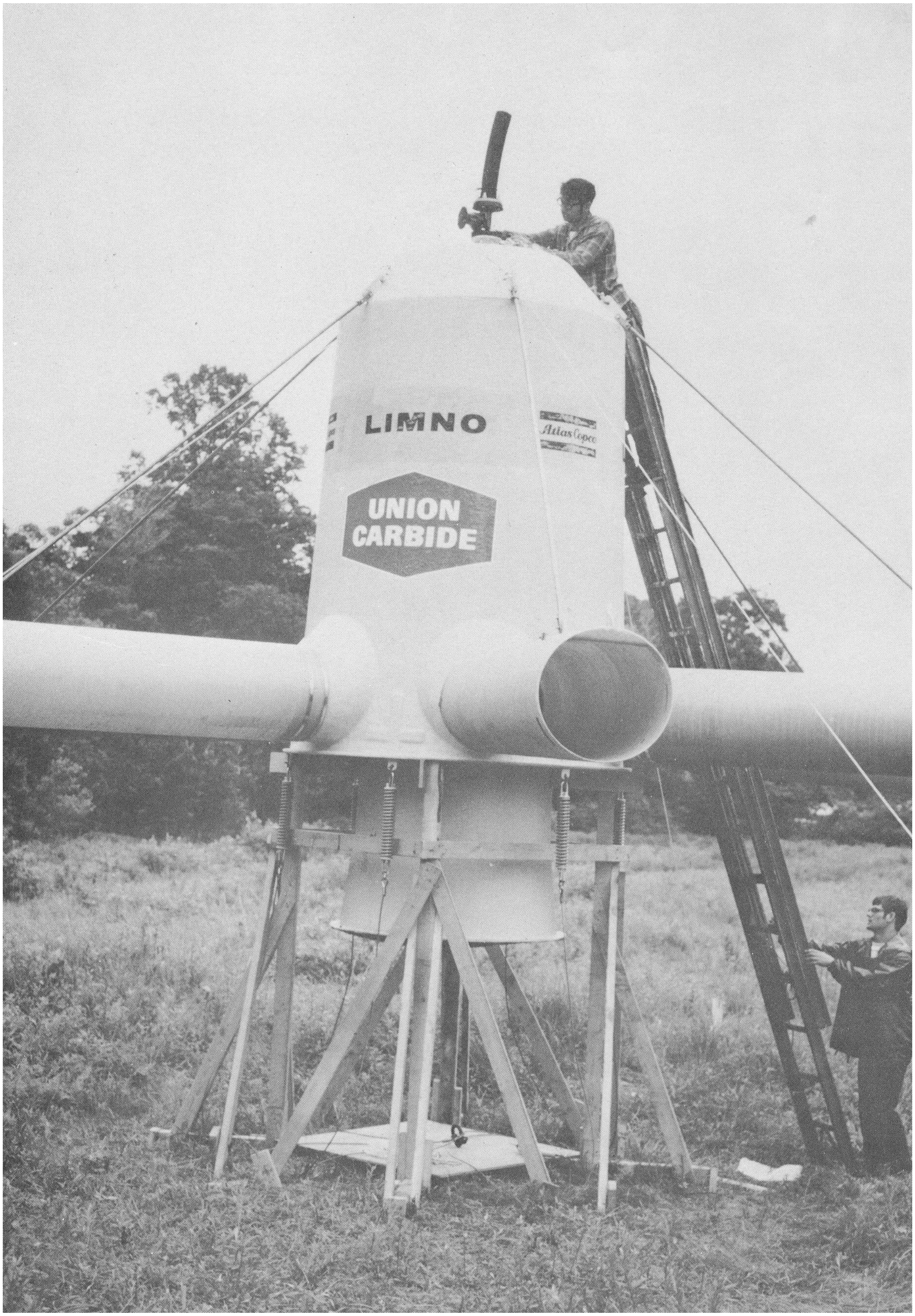

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Figure 4. Lake Waccabuc isotherms in degrees centigrade during 1972 and 1973. The measurements were made at station 4 (Figure 1). Hypolimnetic aeration began July 9, 1973.

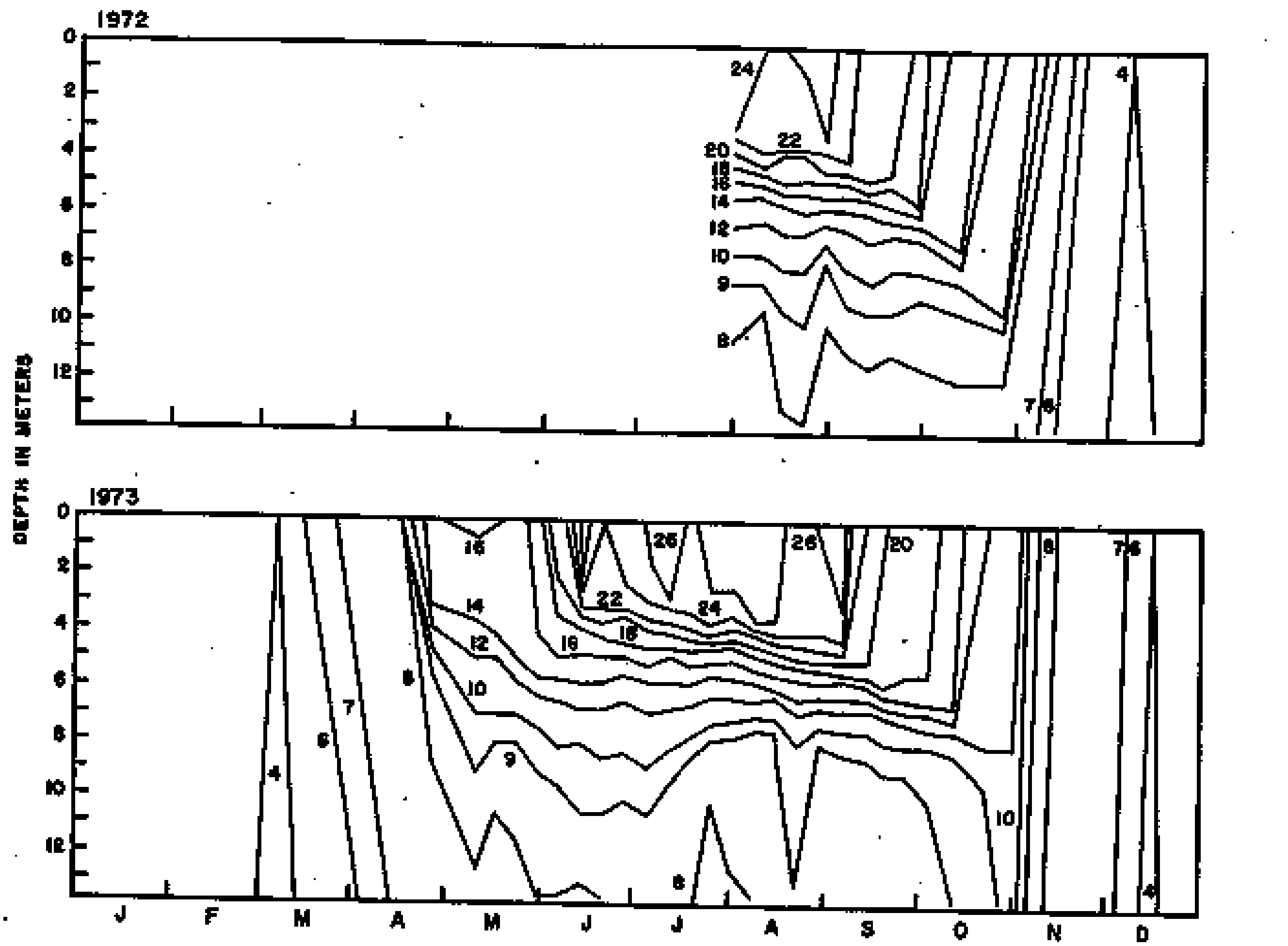

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Figure 5. Lake Waccabuc oxygen isopleths in milligrams per liter during 1972 and 1973. The measurements were made at station 4 (Figure 1). Hypolimnetic aeration began July 9, 1973. Zones with less than 1.0 mg/l of oxygen are shaded.

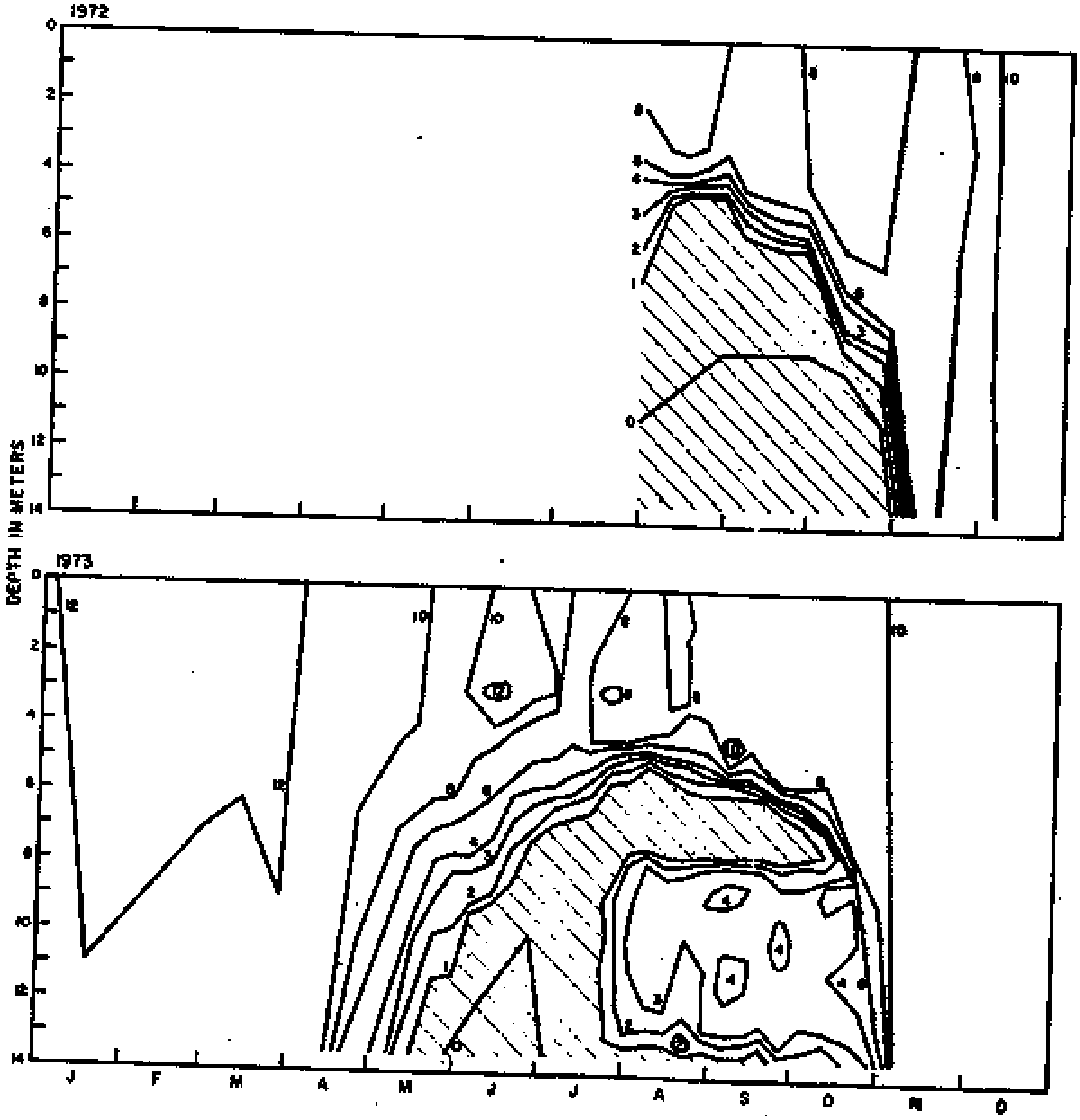

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Figure 6. Lake Waccabuc dissolved oxygen and temperature with depth profiles at seven transverse locations on August 31, 1973. The transverse bottom depth profile is also shown. The sampling station locations are shown in Figure 1.

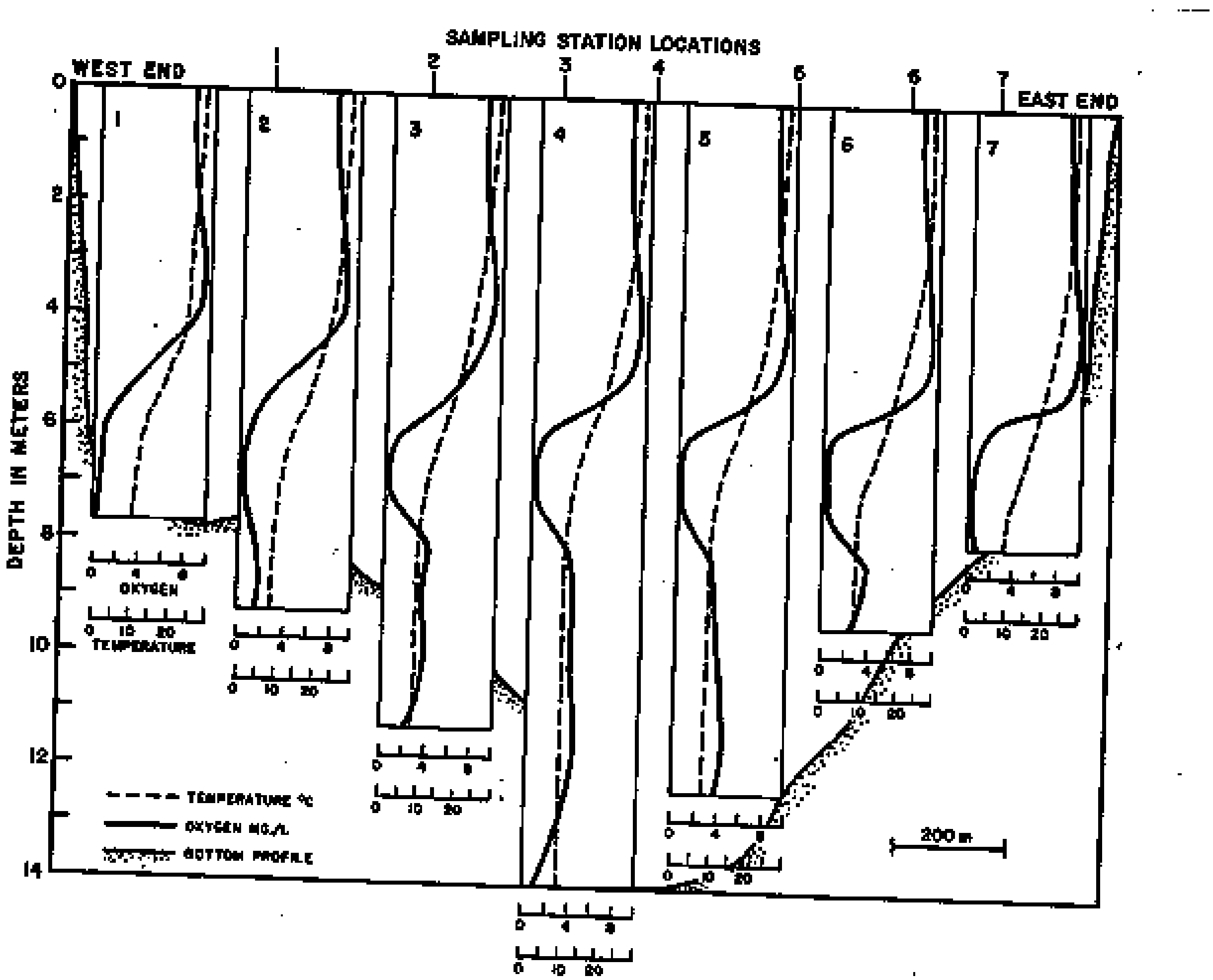

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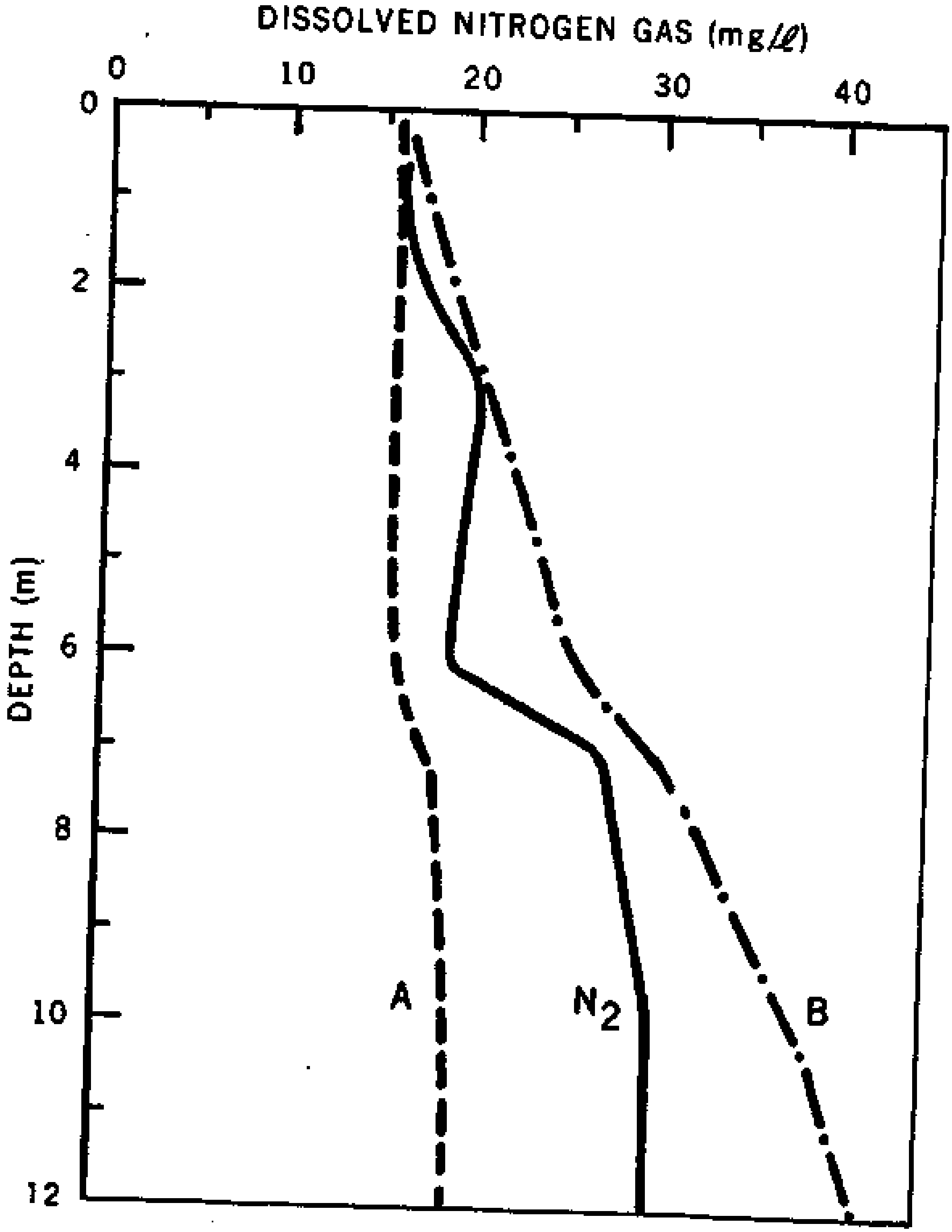
Figure 7. Lake Waccabuc dissolved nitrogen gas (N_2) with depth profile at station 4 (Figure 1) on September 27, 1973, after 80 days of continuous hypolimnetic aeration. Curve A represents 100% nitrogen saturation values adjusted for temperature values only at each depth, and curve B represents100% nitrogen saturation values adjusted for both temperature and pressure at each depth.



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