PERFORMANCE OF AN AXIAL FLOW PUMP FOR LAKE DESTRATIFICATION[1]

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ABSTRACT

A propeller pump was operated for 120 days on a lake of 40 ha surface area in north-central Oklahoma in the summer of 1975 to accomplish artificial destratification. The pump created a downflow of well-oxygenated surface water by means of a 1.82 m diameter propeller located 1.8 m below the lake's surface. The pump produced a flow of 1.72 m³/sec, equivalent to 12.9% of total lake volume per day, at 17 rpm with a 1.0 h.p. electric motor. Four days of pumping eliminated thermal stratification, it raised the temperature of the hypolimnetic water 9.5 C, but increased surface temperature less than 1°C. Thereafter the entire water column remained isothermal (27-29°C) during the summer. Dissolved oxygen at 5 m increased from 0.2 to 4.3 mg/ after the first day of pumping; thereafter DO levels at 5 and 9 m depths were above levels observed in 1973 and 1974; in mid-July 100% of the lake's volume contained more than 5 mg/l DO. BOD levels averaged 2.3 mg/l before pumping but 1.2 mg/l after pumping began. Turbidity did not change substantially with pumping but vertically the variation at 1, 5 and 9 m depths was reduced.

INTRODUCTION

Most man-made and natural lakes in the southern third of the 48 contiguous states of the U.S. circulate freely from fall through spring, and stratify only in the summer when density differences do not allow ambient wind velocities to set the entire body of water in motion. In mid-summer the thermally stratified lake is characterized by two horizontal isodensity strata (epilimnion and hypolimnion) having significantly different physiochemical characteristics. These isodensity strata are separated by a zone of rapid change in density (thermocline) characterized by several narrow isodensity strata. Density differences prevent wind-induced eplimnetic currents from penetrating the hypolimnion. Biological respiration (BOD) and chemical reduction processes (COD) in the hypolimnion cause oxygen depletion, accumulation of hydrogen sulfide (H_2S), ammonia (NH_4), carbon dioxide (CO_2) reduced iron (Fe) and manganese (Mn) and orthophosphorus (PO_4P). Reduced iron, manganese and sulfides create a commonplace water quality problem of municipal water supply reservoirs (Symon 1971). Ammonia and hydrogen sulfide are toxic to fish, and the anoxic conditions are inimical to continuous occupancy by fish and cause a reduction in species diversity of the benthos (Toetz et al. 1972, Smith et al. 1975). The effects of summer stagnation affect downstream fisheries as well; chronic low penstock discharges of cold and anoxic water impoverish fish fauna in tailrace areas. Even where the normal discharge is epilimnetic, a sudden release of a large volume of anoxic water to augment stream flow has caused fish kills because of the low DO and toxic quantities of H_2S and NH_4 (Eley et al. 1967).

Because hypolimnetic water quality characteristics of stratified meso- and eutrophic lakes are undesirable for aquatic life and for municipal water uses, lake aeration either hypolimnetic or total, has been used for both *in situ* water quality management, and for improvement of reservoir discharges to meet effluent standards. Some beneficial effects of

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artificial destratification in impoundments include: (1) increase in total dissolved oxygen (DO), (2) reduction in pronounced diel pulses in pH and DO, (3) increase in the heat budget, (4) oxidation and precipitation of Fe and Mn, (5) decrease in NH_4, CO_2 and H_2S, (6) increase in bicarbonate alkalinity, (7) decrease in algal biomass, (8) colonization of the profundal zone by a greater diversity of macroinvertebrates, and (9) expanded vertical distribution of fish (Toetz et al. 1972, Smith et al. 1975).

Artificial aeration has been attempted most often by destratification rather than hypolimnetic aeration. The former by (1) releasing compressed air near the bottom (Riddick 1957, Meyer 1962, Ford 1963, Fast 1966 and 1968), and by (2) mechanical pumping of hypolimnetic water to the surface (Hooper et al. 1953, Irwin et al. 1966). Direct hypolimnetic aeration or oxygentation was accomplished without changing the temperature profile and is an attractive management tool for trout lakes and where water quality criteria includes a maximum limit temperature (Bernhardt 1967, Björk et al. 1972, Fast 1971 and Speece 1971).

In the past, insufficient effort was devoted to the efficiency (i.e., practicality) of the aerator apparatus. A number of systems have proven inadequate, because the pumping capacity was too small, breakdowns were frequent, and energy requirements were high (Smith et al. 1975). In 1972 Quintero and Garton (1973) built an axial flow (a pump in which most of the head produced by the propeller is from the pushing of the vanes), low head pump for lake destratification, which created a downflow of well-oxygenated surface water. The Quintero-Garton pump had a capacity of 0.67 m^3/sec powered by a 0.5 hp electric motor (373 watts). The apparatus consisted of an electric motor, a belt-drive reduction gear, a propeller, and an orifice shroud. It operated like a vent fan except that it moved liquid instead of air. The pump had a rounded subsurface entrance section made of sheet metal, a short cylindrical sheet metal throat, a 1.07 m diameter propeller (seven-bladed aluminum crop drying fan) and a non-rigid diffuser of nylon-reinforced neoprene to recover the velocity head (Figure 1).

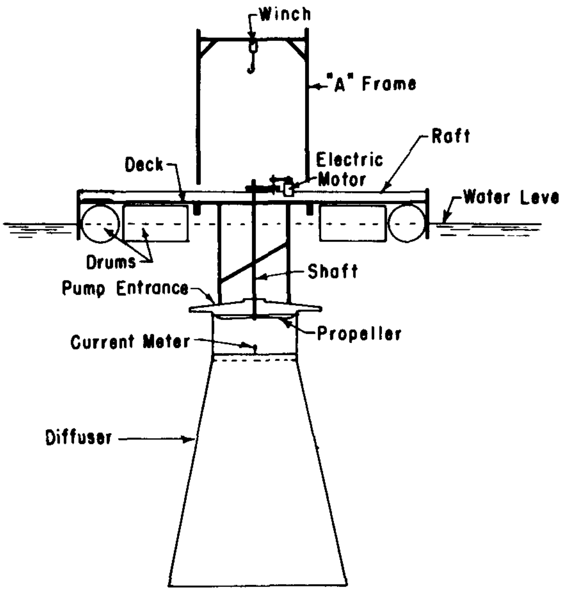

Figure 1. Schematic of the original Quintero and Garton (1973) axial flow pump. This pump had a diffuser skirt for recovery of exit velocity head to increase efficiency. Pump used in present study was similar but lacked diffuser (see Figure 2).

In 1973, Steichen (1974) made various modifications of the Quintero-Garton pump, and tested the pump with and without a rigid diffuser. A non-rigid diffuser was used in the original design (Quintero and Garton, 1973) as a mechanical means to recover exit velocity head, one of the major components of head loss. Steichen calculated that the diffuser increased flow by 32% at a given expenditure of energy. However, a massive diffuser increases construction costs and presents many difficulties in the installation, therefore, it will usually be more desirable to go without the diffuser and obtain an equivalent flow by increasing the fan speed. Steichen obtained a flow of 0.98 m^3/sec with a 4.88 m long sheet metal diffuser having a 2.13 m outlet diameter, then calculated a flow of 0.75 m^3/sec without the diffuser. The increase in flow with the sheet metal diffuser was equivalent to the flexible, fiber diffuser used by Quintero and Garton (1973). Steichen (1974) calculated the efficiencies of the Quintero-Garton pump to three types of air pumps and a mechanical pump. The diffused air pumps had efficiencies ranging from 0.03 to 1.5%, the mechanical pump 0.2% and the Quintero-Garton pump 4.6 to 6.0%.

The present report describes performance of a Quintero-Garton type of axial flow pump applied to Ham's Lake, Oklahoma in 1975. This pump had 2.2 times greater capacity than the pump used by Steichen. Vertical profiles of water temperature and density, DO, biological oxygen demand (BOD), pH, turbidity and suspended solids were measured to determine the effectiveness of the pump's operation on certain water quality parameters of a stratified lake.

DESCRIPTION OF STUDY AREA

Ham's Lake is located in Payne County, latitude 30°34′, longitude 58°36′, 9.6 km west of Stillwater, Oklahoma. The dam impounds Harrington Creek, a tributary of Stillwater Creek. The lake was constructed by Soil Conservation Service, U.S. Department of Agriculture, under Public Law 566, the upstream flood prevention program. It was completed in 1965 and first reached normal pool level in the spring of 1967. The surface area of the lake at the elevation of the principal spillway (287.1 m above sea level) is 40.0 ha. The morphometry of Ham's Lake is described in Table 1.

Although Ham's Lake is relatively shallow with an average depth of 2.9 m, it is thermally stratified from May through October (Steichen 1974). By midsummer of 1972 the epilimnion was about 4 m deep and was often supersaturated with DO. Most of the lake's basin was above the thermocline since average depth is only 2.9 m. There was rapid depletion of dissolved oxygen through the thermocline, and below 4 m the DO was often zero.

In 1971-72 Ham's Lake was used for a caged catfish farming operation, which added large quantities of organic matter to the lake in the form of uneaten feed and catfish feces.

Table 1. Morphometry of Ham's Lake.

Area (Ao)	40.0	hectares
Volume	115.0	hectare-meters
Mean depth (Z)	2.9	meters
Maximum depth	10.0	meters
Maximum length	1,154.0	meters
Watershed area (drainage)	14.7	square kilometers
Shoreline length	10,975.0	meters
Mean pool elevation	287.1	meters, mean sea level
Lake area: watershed area	1.37	
Relative depth (Z_r)	1.4	$Z_r = \frac{88.6\,Z_m}{A_o}$
Shoreline Development (D_L)	5.0	$D_L = \frac{L}{2\sqrt{\pi A_o}}$
Relative depth Z/Z_m	0.29	

That enrichment apparently contributed to the demise of the enterprise when a catastrophic fish kill occurred in August 1972, killing about 150,000 channel catfish (about 0.5-1.0 kg each) at the end of a week of cloudy, cool weather. Steichen (1974) reports that during the sudden overturn, DO levels were nearly zero throughout the water column, and strong odors of hydrogen sulfide (H_2S) were present. Although the lake contained largemouth bass, bluegill, and channel catfish, only the caged fish died from the overturn.

PROCEDURES

The pump was supported from a raft with a 2 m^2 wooden deck provided with expanded foam flotation with a bouyancy of about 1730 kg; the raft was held in place by anchors connected to each corner. The propeller was 1.82 m diameter, heavy duty ventilating fan. Its performance in water was obtained by use of standard fan laws (Baumeister 1967). The propeller was located 1.8 m below the surface and surrounded by wire mesh to prevent entrainment of debris in the water current and to prevent swimmers from making direct contact with the propeller. The pump produced a calculated flow of 1.72 m^3/sec (14.86 ha-m per day), or 12.9% of the lake volume each day. The motor was 1750 RPM, 1 horsepower, single-phase 220 volt, A.C. with a right angle reduction gear. The electric supply was brought from shore by an underwater cable. A more detailed description of this model of the Quintero-Garton pump is given by Strecker (1976).

The pump and raft were assembled in the shop on campus, transported to the lake on a flatbed truck (Figure 2) and unloaded directly into the lake by backing into the water until the apparatus floated off. Water quality parameters were measured at 1, 3, 5, 7, and 9 m at each of six sampling stations (data for each contour is expressed as the mean of six observations at that depth). To simplify the graphical presentations, data are often shown for only the 1, 5 and 9 m depths. We used procedures in "Standard Methods" (Am. Public Health Ass. 1971) for determining the concentrations of chemical variables, however, volitile suspended solids were determined as described by Strecker (1976).

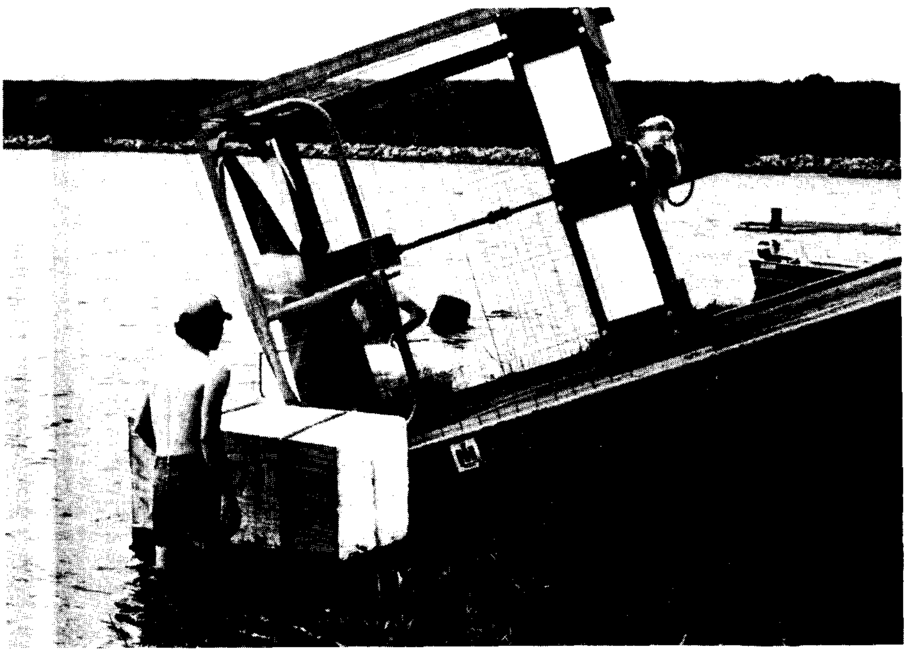

Figure 2. The 1975 model of the axial flow pump during unloading at Ham's Lake.

RESULTS

Temperature

Pumping began on the morning of 19 June. It was run continuously thereafter until 15 October (Figure 3). One day prior to pumping there was a 10.1°C temperature difference between 1 and 9 m depths, but after 4 days of pumping, the water temperature at 9 m had increased 9.5 C and the temperature difference between the surface and 9 m was only 1.2 C. Thereafter the entire water column was essentially isothermal through the period of pumping and remained between 27 and 29°C until early September.

Density profiles illustrate the pump's effectiveness in breaking the thermocline (Figure 4). The day before pumping started the thermocline was between the 4-7 m depths; after one day of pumping (20 June) the thermocline rose to the 2-3 m level; in 3 days the thermocline had risen to about 1.5 m, and by the fourth day (23 June) it had completely disappeared.

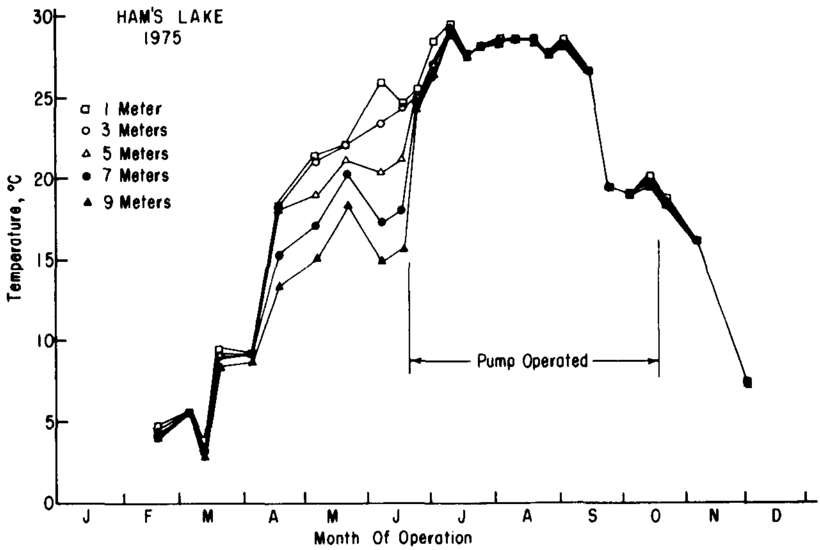

Figure 3. Variation in vertical temperatures at 1, 3, 5, 7 and 9 m depths in 1975. The pump was operated 19 June to 15 October.

Dissolved Oxygen (DO)

In the pre-stratification period of early spring, the concentration of DO was nearly homogeneous at all depths (Figure 5). By mid-May substantial oxygen depletion occurred at the 5, 7 and 9 m depths, and 24 hours before pumping began, the DO was 0.2 mg/l or less at 5, 7 and 9 m. After only 24 hours of pumping the DO increased from 0.2 to 4.3 mg/l at 5 m, and from 0.1 to 2.6 mg/l at 9 m. Dissolved oxygen at 3 m declined abruptly after pumping began. The temperature, BOD and pH (Figures 8 and 9) was orthograde after four days of pumping, but a chemocline in DO still existed: DO was 7.2 mg/l at the surface and 2.9 mg/l at 9 m. The DO chemocline disappeared on 14 July when DO level was 5.6 mg/l from the 1 to 9 m intervals. Although the pump accomplished thermal destratification in 4 days (19 to 23 June), it required 21 days more to eliminate a DO chemocline and establish orthograde DO concentrations.

The percentage of lake volume containing more than 3, 4 and 5 mg/l DO describe the quantity of total lake volume suitable for fish habitation (Figure 6). In March and nearly all of April when the lake was isothermal, 100% of the lake volume contained more than 5

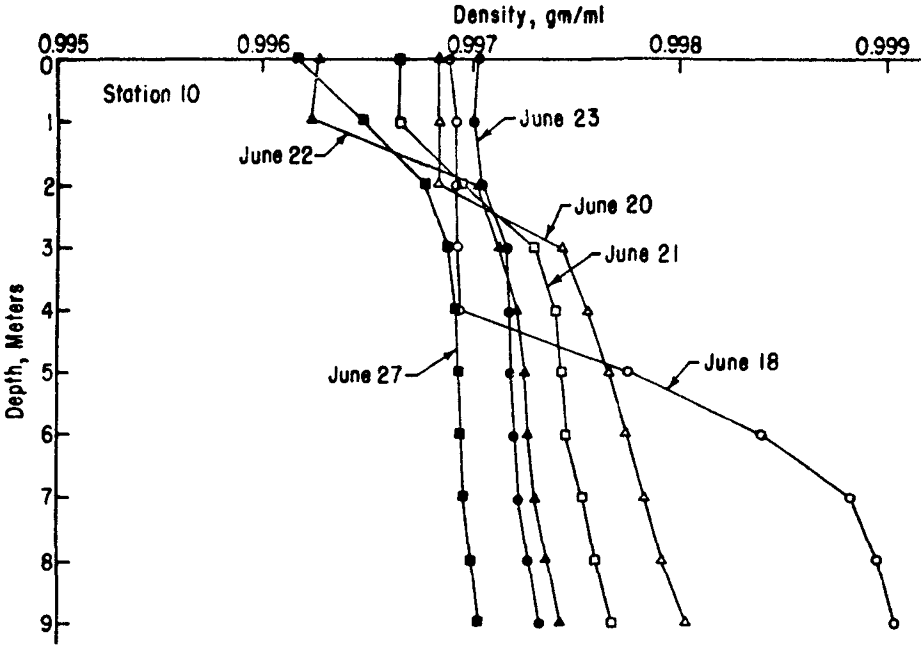

Figure 4. Density profiles in Ham's Lake during the first week of pumping; pumping began the morning of 19 June.

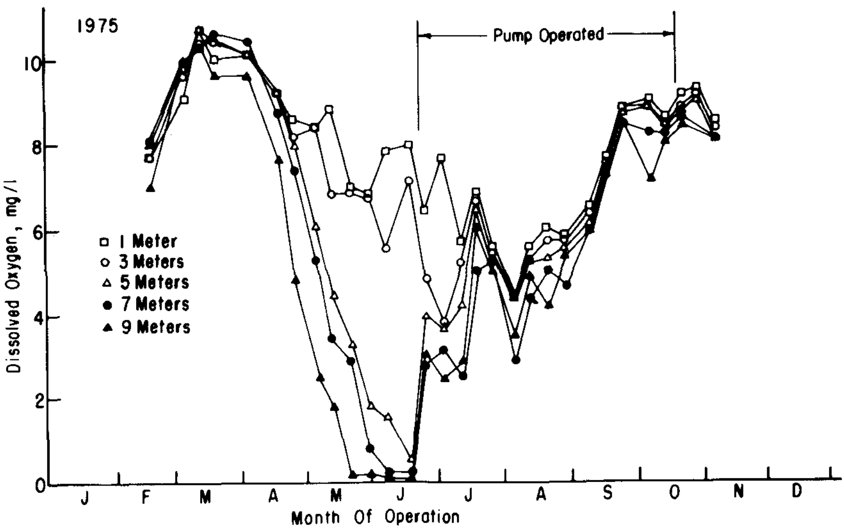

Figure 5. Variation in DO at Ham's Lake in 1975 at 1, 3, 5, 7 and 9 m depths.

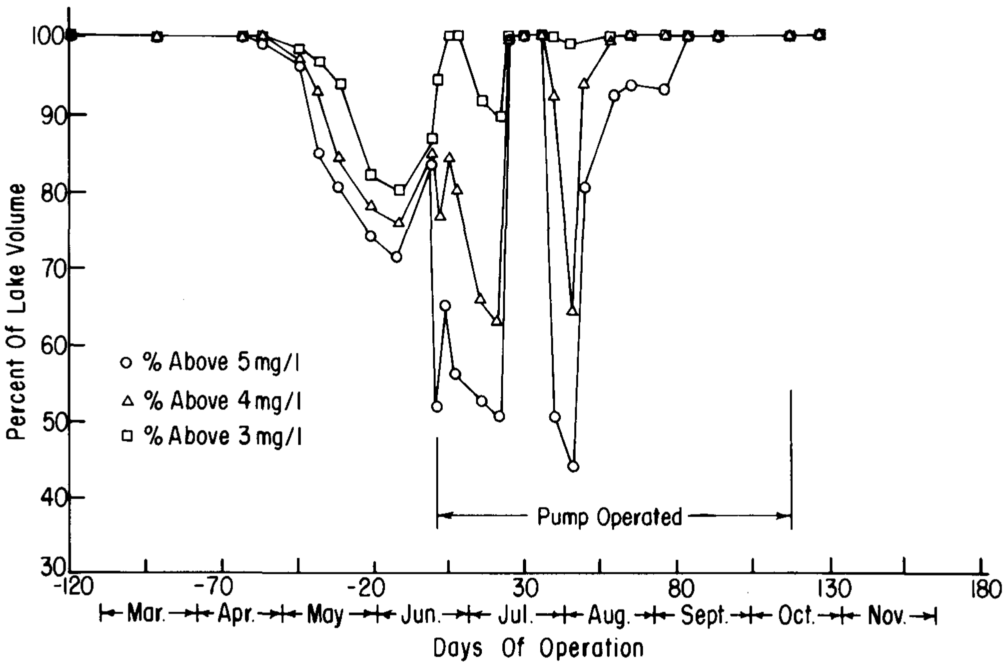

Figure 6. Variation in distribution of the 3, 4, and 5 mg/l DO isopleths as percent of total lake volume.

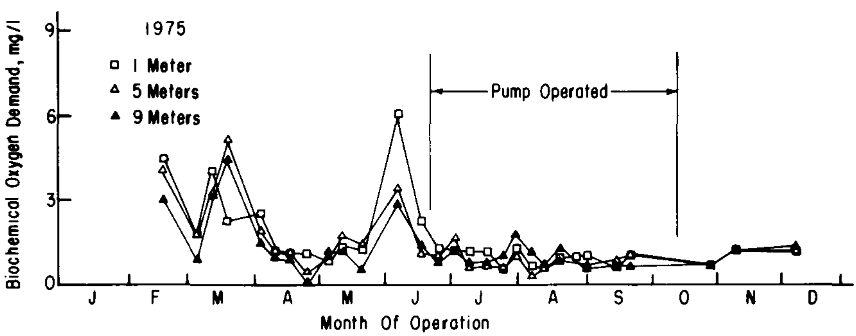

Figure 7. Variation in Bod in Ham's Lake at 1, 5 and 9 m depths.

mg/l DO. By early May, the increase in ambient temperatures, density gradients, and heightened metabolic processes caused a quantitative decrease in percentage of lake volume with more than 5 mg/l DO. On 9 June, 10 days prior to starting the pump, 20% of the lake contained less than 3 mg/l DO, but pumping definitely perturbated the lake, at first greatly reducing the quantity of water with more than 5 mg/l but increasing the quantity of water with more than 3 mg/l DO to 100% (Figure 6). In mid-July, when DO was nearly orthograde, 100% of the lake volume contained more than 5 mg/l DO. In early August, temperature differences were less than 1°C, but substantial DO stratification occurred, however, there was still 3 mg/l in all but 6.6% of the lake's volume at that time.

Biological Oxygen Demand (BOD)

The seasonal BOD curve was bimodal, the first peak occurred in mid-March when values were 2.2 mg/l at 1 m and 4.5 mg/l at 9 m, and the second peak occurred in early June when the BOD was 6.2 mg/l at 1 m and 2.7 mg/l at 9 m (Figure 7). Biological oxygen demand averaged 2.3 mg/l at 9 m from late February through 18 June (prior to pumping). By contrast, after the pumping began, the BOD was never more than 1.5 mg/l at any depth and the average was 1.2 mg/l.

pH

Considerable variation of pH was observed at the 1, 5 and 9 m intervals before pumping began (Figure 8). A typical vernal algae bloom in late April elevated the pH to 8.5 at that time. Thereafter the surface pH declined precipitously to only 6.6 by mid-May. On 18 June, the pH ranged from 8.4 at the surface to 7.7 at the bottom. After four days of pumping the pH was 7.7 from 1 to 9 m depth contours. Thereafter the pH at all levels increased somewhat and a sharp increase in early July coincided with a conspicuous, but short-lived algae bloom. After the algae bloom subsided, pH remained nearly orthograde, total variation was between 7.9 and 8.3.

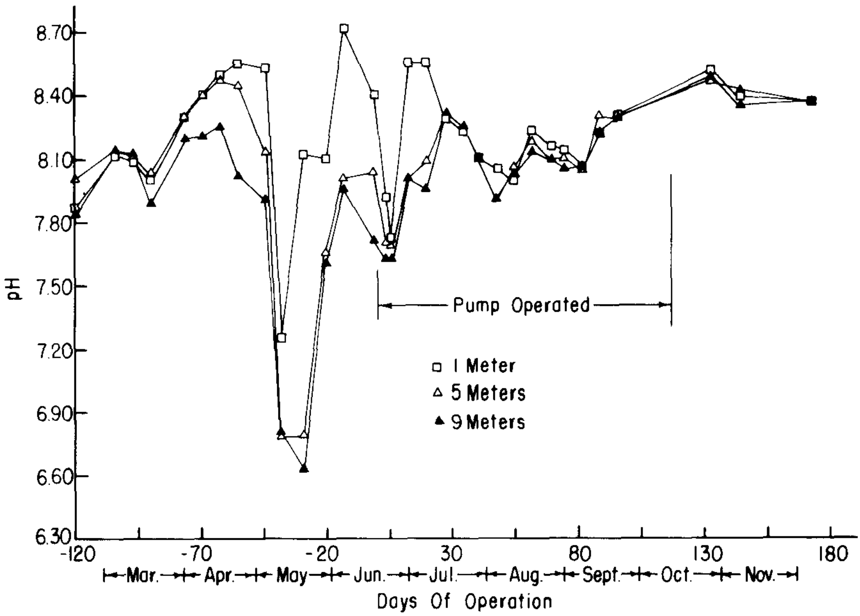

Figure 8. Variation in pH at 1, 5 and 9 m depths in Ham's Lake in 1975.

Turbidity

Turbidity measurements at 1 m declined abruptly after pumping began (Figure 9), and after one week of pumping, turbidity at 9 m decreased by almost half of the prepumping level, although it increased slightly at the 5 m depth. Turbidity at 1, 5 and 9 m varied substantially in the first 85 days after pumping began, even so, the variation was less than before pumping began. Turbidity measurements at 1, 5 and 9 m were nearly indistinguishable from mid-September to the end of pumping. Turbidity measurements were less than 15 JTU in the 85-100 day post-pumping interval.

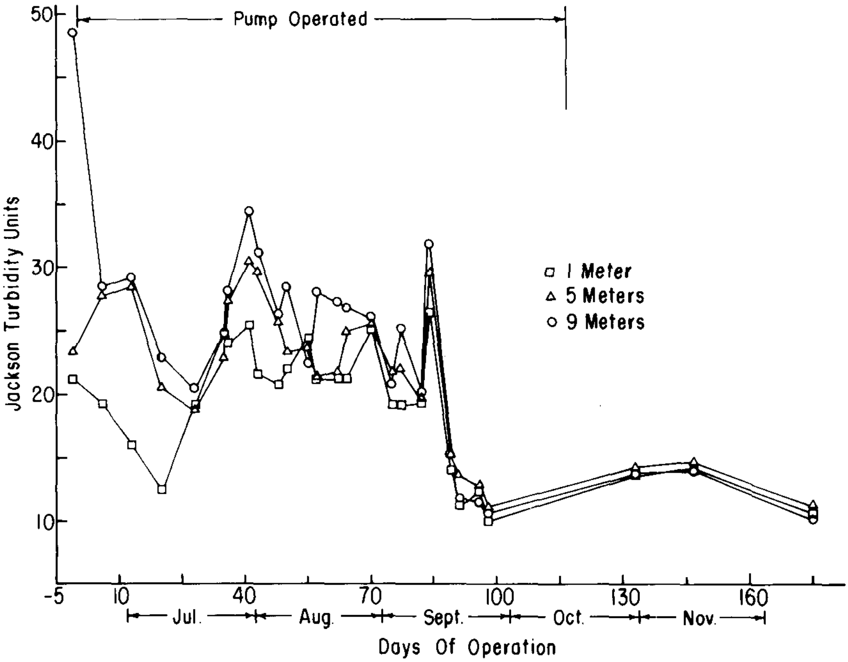

Figure 9. Variation in turbidity at 1, 5 and 9 m in Ham's Lake in 1975.

DISCUSSION

The experiment in the summer of 1975 using an axial downflow pump (1.72 m^3/sec capacity) of the Quintero-Garton design (1973), thermally destratified Ham's Lake, a 40 ha (1950 ha-m) man-made lake, in only four days compared with 15 days in 1973 using a pump with 0.76 m^3/sec flow (Steichen 1974).

In 1975, mixing did not lower surface water temperature but warmed the bottom water about 10°C, thereby increasing the total heat content. The larger capacity pump used in 1975 also maintained a smaller temperature difference between 1 and 9 m depths. Destratification was achieved by a warming of the hypolimnion which implies a substantial increase in the heat budget of the lake. An increase in heat budget has been reported using other lake aeration procedures (Fast 1968, 1971; Haynes 1971). The downflow pump described here eliminated cool (less than 21°C) hypolimnetic water. This procedure would eliminate habitat for two-story trout fisheries (Kirkland and Bowling 1966, Wilkins et al. 1967). To preserve lake habitat for cold water fishes, a hypolimneter aerator system is needed (Bernhardt 1967, Fast et al. 1975).

In 1975, DO concentrations at 9 m were increased from 0.2, or less, to 2.6 mg/l in one day of pumping but it took 21 days after thermal destratification to obtain an orthograde DO profile. Using 2 mg/l as the criteria limiting fish depth distribution (Gebhart and Summerfelt 1976), available fish habitat in Ham's Lake was expanded to the whole lake within the first day.

The BOD at 1, 5 and 9 m intervals was quickly reduced and made vertically homogeneous after pumping began: average BOD was reduced from 2.3 mg/l in pre-pumping interval to 1.2 mg/l in the pumping interval. By inference, we believe the warming and addition of DO from the surface increased aerobic metabolic processes favoring bacterial decomposition. Lacking wind action, respiration may cause some oxygen depletion even in the absence of thermal stratification, but in the prairie states, ambient wind velocity is usually sufficient to mix a destratified lake.

Seasonal variation in turbidity at 1, 3 and 5 m was substantial, but pumping appeared to reduce its vertical variation. Turbidity was not increased by pumping, and in late summer the water was exceptionally clear (<15 JTU). The expected turbulence produced by the pump was not apparent; conversely the pump appeared to minimize fluctuations which would likely occur from seasonal algae blooms.

Algal nutrients are often solubilized from lake sediments and return to the euphotic zone during fall turnover contributing to autumnal plankton blooms. Since phosphorus (P) in lake sediments is mainly bound as organic-P, Al-P, Fe-P, Ca-P, or P-absorbed to particles (Anderson 1975), the contribution of orthophosphate from lake sediments depends on the actual composition of the sediments, their degree of oxidation and the pH. Mixing and prevention of stratification ought to effect nutrient cycling by changing temperature, redox potential and pH. Under anoxic conditions complete mineralization is inhibited, but under aerobic conditions, a large proportion of orthophosphate is precipitated before entering synthesis (Anderson 1975). Orthophosphate bound to Fe and Al is solubilized at low pH, but the pH at 9 m was always above 7.5 during pumping, and toward the end of the summer, the pH at 9 m increased to 8.1-8.3. Aeration of the near bottom sediment should reduce solubilization of the orthophosphate and facilitate development of an oxidized mud-water interface. This would effectively isolate historical accumulations of phosphorus.

We observed, as have many others, lower pH values during pumping. Shapiro (1973) found that a lowering of the pH can cause a shift from blue-green to green algae, and King (1970) suggested that the mechanism of blue-green algae dominance is related to their greater efficiency in obtaining CO_2 at a higher pH. Other investigators have found that aeration and mixing reduced algal populations (Malueg et al. 1971, cited by Toetz et al. 1972) and caused a shift from blue-green to green algae (Symons et al. 1970).

Many water-utility managers practice artificial destratification for water quality control in municipal water-supply reservoirs to overcome the classical problems of water quality degredation associated with anaerobic conditions in the reservoir hypolimnion of the stratified lake (Symons 1971). These problems include taste and odor, reduced iron, manganese and hydrogen sulfide and algae. The downflow pump used in the present study should improve water quality and eliminate most of the classical problems for municipal water supply. At the same time, improvement in the depth distribution of dissolved oxygen will increase fish depth distribution and probably result in the improvement of the diversity of macrobenthos populations important as fish food (Garton et al., 1976).

The authors believe that a pump of this design with a capacity of about 2.0 m^3/sec could destratify lakes up to 100 ha with a volume of about 100-125 ha-m.

The authors caution of the potential for immediate DO depletion if a large volume of anoxia water is mixed too rapidly with a narrow stratum of epilimnetic water. Leach and Harlin (1970) accomplished destratification of Lake Roberts, New Mexico in three days by an air bubble system, but the lake went anoxic from surface to bottom causing a nearly complete fish kill. To avoid a fish kill, a downflow pump should be operated prior to normal onset of stratification, or, if dealing with a stratified lake, mixing must be slower, and the thermocline lowered gradually. Whenever attempting to destratify a lake, it is obviously expedient to closely monitor DO profiles.

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