Final Technical Completion Report of
OWRR Project A-028-Okla

LOW ENERGY MECHANICAL METHODS OF RESERVOIR DESTRATIFICATION

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Low Energy, Mechanical Methods of Reservoir Destratification Completion Report

INTRODUCTION

This project involved two phases of research. There is a separate report covering each part. The first phase consisted of developing a low head, high volume axial flow pump. The primary objective was to design, construct and evaluate this pump. This research was conducted by Dr. Jorge Quintero and Dr. James Garton. The second phase involved determining the effectiveness of this pump as the lake destratification device. The pump was modified and the effect of lake destratification on several water quality parameters was observed.

This research project produced two Ph.D dissertations and two technical papers. One of the papers has been published and the other has been presented at the national meeting of the ASAE and will be submitted for publication.

Theses titles:

Jorge E. Quintero, A Low Energy Lake Destratifier. Unpublished Ph.D dissertation, Agri. Engr. Dept., Oklahoma State University, May 1973.

James M. Steichen, The Effect of Lake Destratification on Water Quality Parameters. Unpublished Ph.D Dissertation, Agri. Engr. Dept., Oklahoma State University, July 1974.

Paper titles:

Quintero, Jorge E. and James E. Garton, A Low Energy Lake Destratifier. Transactions of the ASAE 16(5) pp. 973-978, 1973.

Steichen, James M., James E. Garton and Charles E. Rice, The Effect of Lake Destratification of Water Quality Parameters. Presented at 1974 summer meeting of ASAE, Paper No. 74-5008.

A LOW ENERGY LAKE DESTRATIFIER*

by

J. E. Quintero and J. E. Garton

INTRODUCTION

When water is stored in reservoirs it frequently stratifies during the summertime. The reservoir then has three zones, the epilimnion, the thermocline and the hypolimnion. Circulation is limited to the epilimnion and oxygen transferred across the water surface does not reach the hypolimnion. As a result the colder water at the bottom of the lake becomes depleted of oxygen. The release of the bottom waters for downstream users places an additional load on water treatment plants, and sometimes causes fish kills. The low water temperature may interrupt the reproduction and growth of fish in the river downstream.

Because of the problem created by stratification, many attempts have been made at destratifying lakes. The methods used have usually been:

1. Release of compressed air at the bottom, or within a lake, to induce a circulation of the water.
2. The release of pure oxygen in lakes.

This research was financed in part by the U.S. Department of the Interior as authorized under Public Law 88-379.
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3. U-tube aerators, take water from the hypolimnion, add oxygen, and return the water to the hypolimnion.
4. Mechanical pumping from the hypolimnion to the surface.

From an engineering standpoint, it would seem more logical to take the oxygen-rich water from near the surface and move it downward to displace the water in the hypolimnion. This would require a high rate of pumping using an entirely submerged pump. The design, construction and evaluation of such a pump was the purpose of this research. Figure 1 shows the design which was tested.

OBJECTIVES

1. To design, construct and test a pump that will pump large volumes of water with low input of energy.
2. To determine the relationships of the flow rate through the pump to r.p.m., diffuser outlet diameter and diffuser length.
3. To determine the relationship of the horsepower to r.p.m., as other variables are varied.
4. To calculate the expected head loss through the device, based on available coefficients and measured velocities.
5. To make estimates of pump efficiency from measured values of horsepower and flow rate, using calculated values of head.

LIMITATIONS OF THE STUDY

The study involved the development of equipment for moving large volumes of water with low power input and was not a study

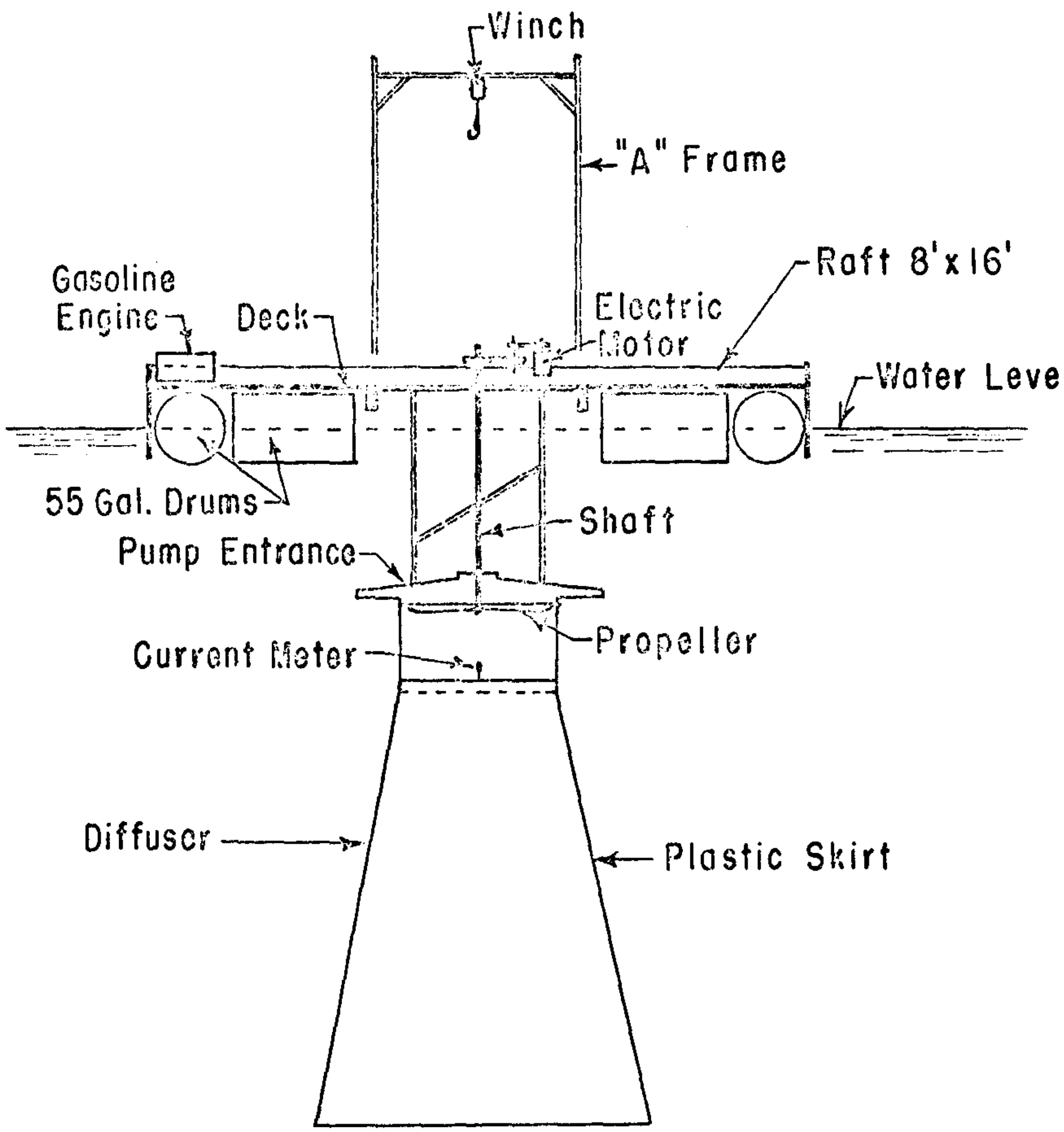

Figure 1. Assembly of Pump and Raft

of the effects of these flows on such stratification parameters as temperature, dissolved oxygen or biological effects.

Diffuser lengths were limited by lake depth to 24 feet or less. A maximum diffuser outlet diameter of eight feet was used. The diffuser was constructed of neoprene reinforced with nylon. The maximum propeller r.p.m. and flow rates were limited by the 1/2 horsepower electric motor used in the study.

REVIEW OF LITERATURE

Lake stratification is widespread, occurring at all latitudes in the United States (1) (figures 2 and 3).

Thermal stratification results in deterioration of water quality for both human and animal use, anaerobic and corrosive conditions, increased evaporation rates, reduced heat budgets and other undesirable properties within the lake (2).

Methods of Artificial Destratification

Reaeration of reservoirs has been primarily concerned with mixing by diffused air or pumping, with accompanying atmospheric reaeration at the water surface.

Two broad classifications of ways to create destratification are: a) mechanical pumping and b) use of compressed air or pure oxygen releases near the bottom of the impoundments.

Mechanical Pumping

Hooper (4) was one of the first researchers to study the pumping of cold water from the hypolimnion to the surface.

Symons (5) used a system in which he pumped hypolimnion water to the surface of a lake. He was able to pump 2880 GPM

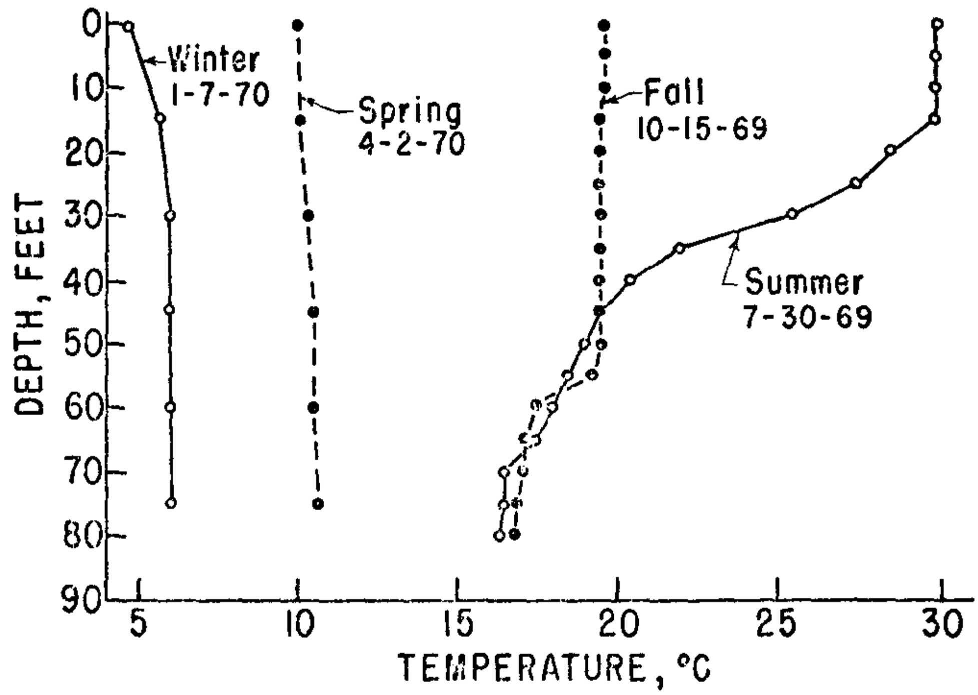

Figure 2. Temperatures for selected dates at one place at Lake Arbuckle, Oklahoma. (1)

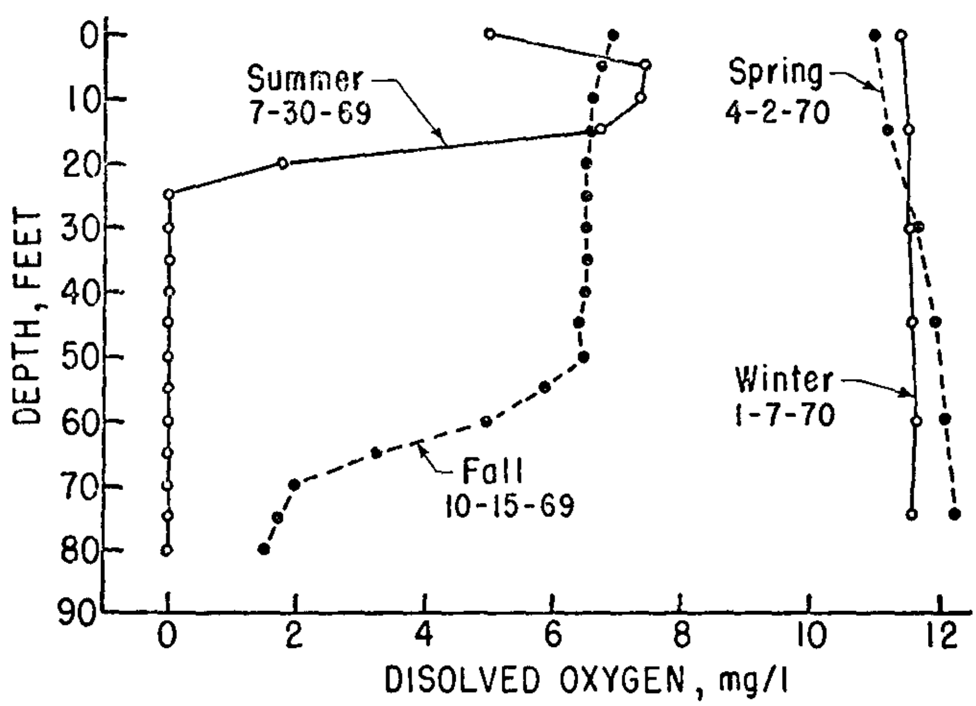

Figure 3. Dissolved oxygen for selected dates at Lake Arbuckle, Oklahoma. (1)

using a 12-inch mixed-flow pump with a power input of 12 hp.

Enumeration of commercial manufacturers as well as the description of available equipment has been presented (3). Equipment available has been characterized by very high power input requirements. It is common to find commercially produced aerators that require inputs of 75 hp. (6).

<u>Compressed Air Releases or Pure Oxygen Releases</u>

Compressed air or gaseous oxygen have been used to increase the oxygen content of the water and also to create a vertical movement of water to induce hypolimnion circulation.

Use of compressed air in Eufala reservoir in eastern Oklahoma was successful (7).

Compressed air has been used to bring water from the bottom to the surface where a mechanical aerator produced the aeration (8).

Speece (9) describes the U-tube aeration system, in which air bubbles are injected into a water flow that follows a U configuration.

Systems have been devised to establish circulation and create destratification of large bodies of water. However, attention has not been directed toward reducing energy requirements.

TOTAL DYNAMIC HEAD

TDH, the dynamic head for a submerged pump represents the total head loss, which is the aggregate of: entrance loss, diffuser loss, and residual velocity head.

a) H_1 is the loss of head at the entrance, where the water enters the conduit from a comparatively large body of quiet water. The loss of head is a coefficient times the velocity head, or

$$H_1 = K_1 V_1^2/2g$$

Hamilton (10) presented K_1 values as a function of the ratio, radius of entrance rounding to pipe diameter.

b) H_2 is the loss of head due to friction and fluid turbulence in the expanding jet while going through the passage. Gibson (11) determined that the loss of head due to gradual enlargement is intimately related to the shape of such enlargement, so that

$$H_2 = K_2 (V_1 - V_2)^2/2g$$

K_2 is the coefficient dependent upon the cone angle and the area ratio. Figure 4, taken from Vennard (12) shows the relationship of K_2 for various angles and area ratios.

c) H_3 is the loss of velocity head at the exit, when the conduit discharges into a large body of quiet water. The exit loss is:

$$H_3 = K_3 V_2^2/2g$$

In this study K_3 was assumed to be unity.

Neglecting the friction loss in the short throat section the total loss of head through the passage is:

$$TDH = H_1 + H_2 + H_3$$

These losses represent the energy required for pumping.

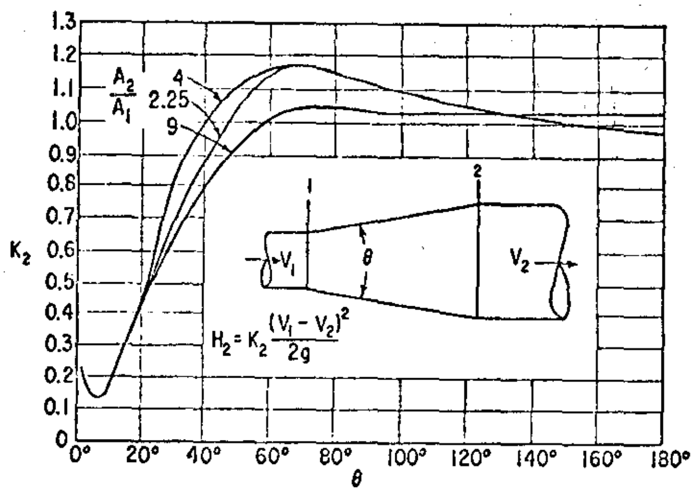

Figure 4. Loss coefficients K_2 for conical enlargements. (12)

EXPERIMENTAL EQUIPMENT

The test apparatus consisted of:

1. - Pump assembly

a) The axial flow type pump consisted of a propeller, a stationary casing and a diffuser, (figure 1).

The cast aluminum propeller had 7 blades with a 41-3/4 inch outside diameter, a blade length of 15 inches and a hub diameter of 11-3/4 inches. The pitch of the blades was 15 degrees at the tip and 30 degrees at the hub.

The pump body consisted of a piece of an air fan, with a bell-mouth type entrance, having a radius of curvature of 2-3/4 inches. A circular cylinder was added giving a total length of 29 inches and an internal diameter of 42 inches (figure 5). Straightening vanes at the entrance aided in suppressing vortices.

A plastic diffuser was installed under the pump. It was cone-shaped with maximum dimensions of:

Top diameter	3.5 Ft.
Bottom diameter (Outlet)	8.0 Ft.
Length	24.0 Ft.

The length and bottom diameter of the diffuser varied as shown in figure 6.

The diffuser material was nylon covered with neoprene.

b) Supporting structure.

The pump was held by a steel supporting structure with gimbals to allow the pump to remain vertical, figure 7.

2. - Platform structure

a) An 8 ft by 16 ft plywood raft floated on 10 fifty-five gallon barrels was used.

3. - Power source

a) An electric generator with 2.5 KVA capacity supplied the electricity.

b) A 1/2 Hp electric motor drove the propeller shaft.

c) A set of four pulleys using a jack shaft was installed. Nominal velocities of the propeller were 40, 56, 60 and 80 r.p.m. Positive drive belts were used to avoid slippage.

Prony brake tests were run to obtain the HP output versus the Kilowatts input to the motor of the shaft.

4. - Measuring devices

a) A laboratory "OTT" current meter with 50 mm diameter propeller was used to measure water velocity.

b) An ammeter, voltmeter and wattmeter were used to measure power input to the motor.

LOCATION OF THE EXPERIMENT

Lake Carl Blackwell located 10 miles west of Stillwater, Oklahoma was selected as the location for the experiments.

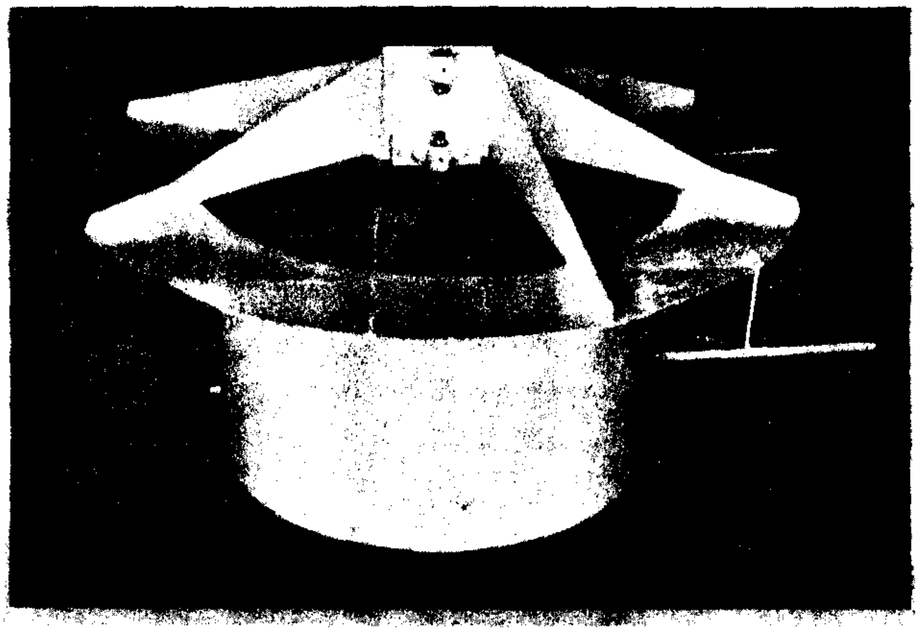

Figure 5. General view of casing

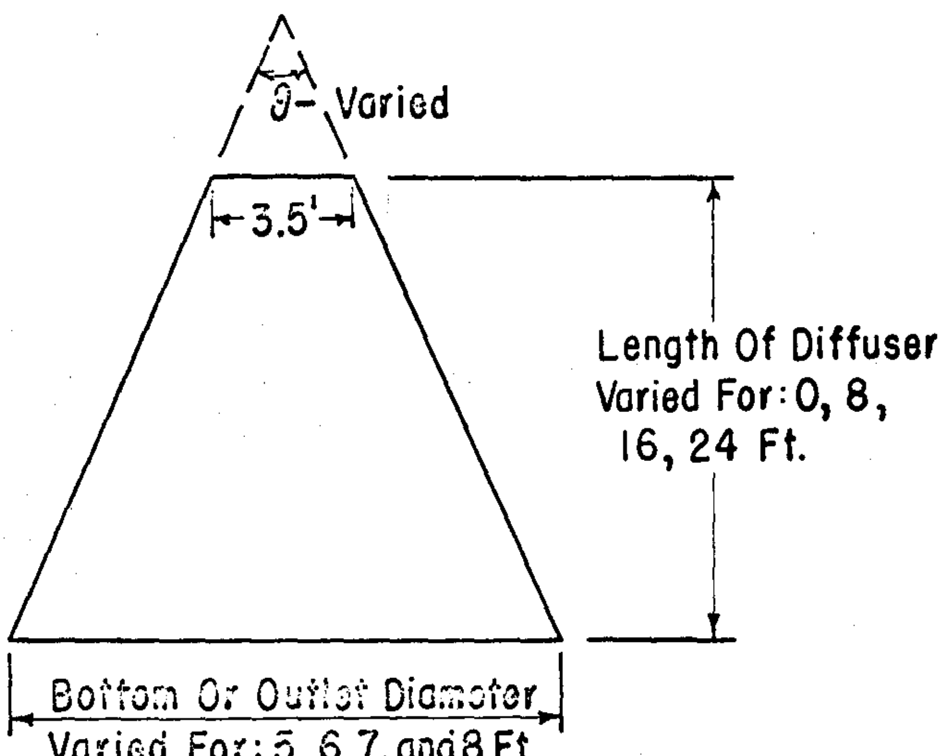

Figure 6. Arrangement of the diffuser

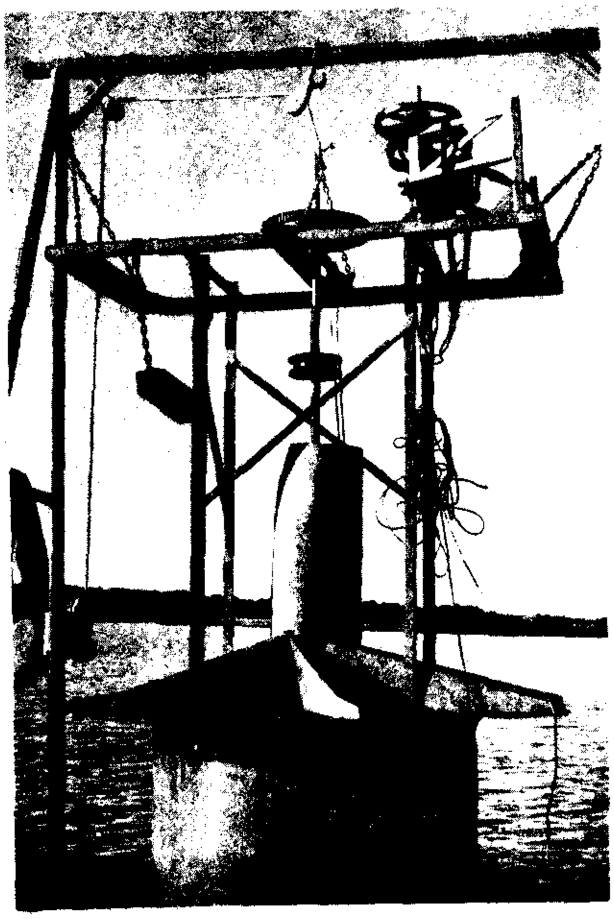

Figure 7. Supporting structure with gimbals

The depth during the tests was 9 meters. Depth was a limiting factor in establishing the length of the diffuser.

PROCEDURE

The experimental design was a complete factorial. The dependent variables were the velocity of the water at the throat and the power input required. The independent variables were propeller r.p.m., diffuser length and diffuser diameter.

The orders of the outlet diameters and the pulley sizes were radomized.

Experiments were run with the 24-ft. diffuser length first, then the 16-ft. length and finally the 8-ft. length. Observations of velocity, propeller r.p.m., and watts were made for every diffuser length, outlet diameter, and pulley size.

The lengths of diffuser used were: 0, 8, 16, 24, Ft.

The outlet diameters of diffuser used were: 5, 6, 7, 8, Ft.

The sizes of pulley (Number) used were: 20, 28, 30, 40.

PRESENTATION AND DISCUSSION OF RESULTS

Prediction Equations for Flow and Power

Equations 1 and 2 were obtained by multiple regression analysis of all the flow data obtained in this study. Data for the study is presented in Table I.

$$Q = -2.07 + 0.27\ N + 0.541\ Do + 0.0092\ L \qquad (1)$$

$R^2 = 0.96$

where

Q = Flow through the pump, cfs

N = Propeller shaft angular speed, rpm

Do = Outlet diameter of diffuser, ft

L = Length of diffuser, ft

R^2 = Squared value of the correlation coefficient

Flow through the pump was primarily a function of r.p.m. and was weakly related to skirt diameter and length. Interactions were not significant. Similarly, an equation was obtained for the power data of this study.

$$P_s = -0.024 + 0.00000120\ N^3 - 0.00113\ Do - 0.000476\ L \quad (2)$$

where

P_s = Propeller shaft power, HP

The power required was primarily a function of r.p.m. and was weakly related to skirt diameter and length. Interactions were not significant. The influence of the flexible diffuser was less than expected from the literature survey of rigid diffusers. Horsepower measurements of less than 0.1 horsepower on the 1/2 horsepower motor were probably more in error than measurements of horsepower greater than 0.1 horsepower.

Calculated Head Losses Through the Device

Losses due to entrance, H_1

From Hamilton's results (10), and the entrance dimensions used:

D - Diameter of entrance = 42 inches

R - Radius of curvature 2-3/4 inches

then

$$\frac{R}{D} = 0.065 \text{ and } K_1 = 0.10$$

thus

$$H_1 = \frac{0.10\ (V_1)^2}{2g}$$

<u>Losses due to enlargement, H_2</u>

From Vennard (12), values of K_2 were determined for the diffuser angles in the experiment figure 4 for use in the equation:

$$H_2 = K_2 \frac{(V_1 - V_2)^2}{2g}$$

<u>Losses due to exit velocity head, H_3</u>

In this study the K_3 was assumed to be unity, then:

$$H_3 = (1.0)\ \frac{V_2^{\ 2}}{2g}$$

<u>Total Head Losses, H_T</u>

The total head loss or total dynamic head, corresponds to the sumation of H_1, H_2 and H_3. The TDH affects the power requirements of the pump, and can be used to determine the efficiency of the pump.

Table I gives the total head loss. The maximum calculated value of total head loss was 0.05 foot.

Estimation of Pump Efficiency

Based on calculated values of head, pump efficiency was calculated using:

$$\text{Eff} = \frac{Q \times H_T}{3960 \times Hp} \qquad (3)$$

where

Q = Flow through the pump, gpm

H_T = Total hynamic head, ft

H_p = Power input, hp

Table I presents the efficiencies. The highest efficiency found was 45.8 percent. It is believed that low efficiencies were due to: a) propeller inefficiency, b) vane inefficiency and c) diffuser inefficiency. It is possible that efficiency can be improved by using a more efficient propeller which may resemble a ship's screw, and by construction of exit vanes to direct the exit flow. The use of a rigid diffuser may more efficiently recover the velocity head than the flexible diffuser used. As shown in figure 8, extrapolated values of efficiency versus specific speed give rather low values of efficiency for a propeller pump at high specific speeds. However, no references were found which listed values of specific speed as high as those prevailing in these tests.

ESTIMATION OF SPECIFIC SPEED

Conventional axial flow pumps have typical specific speeds of 7,500 to 14,000. Very low specific speeds are most often encountered in connection with small centrifugal pumps. For economic reasons it is necessary to select the specific speed always as high as possible, because for a given capacity and head, the dimensions of the pump will be the smaller the higher the specific speed (13).

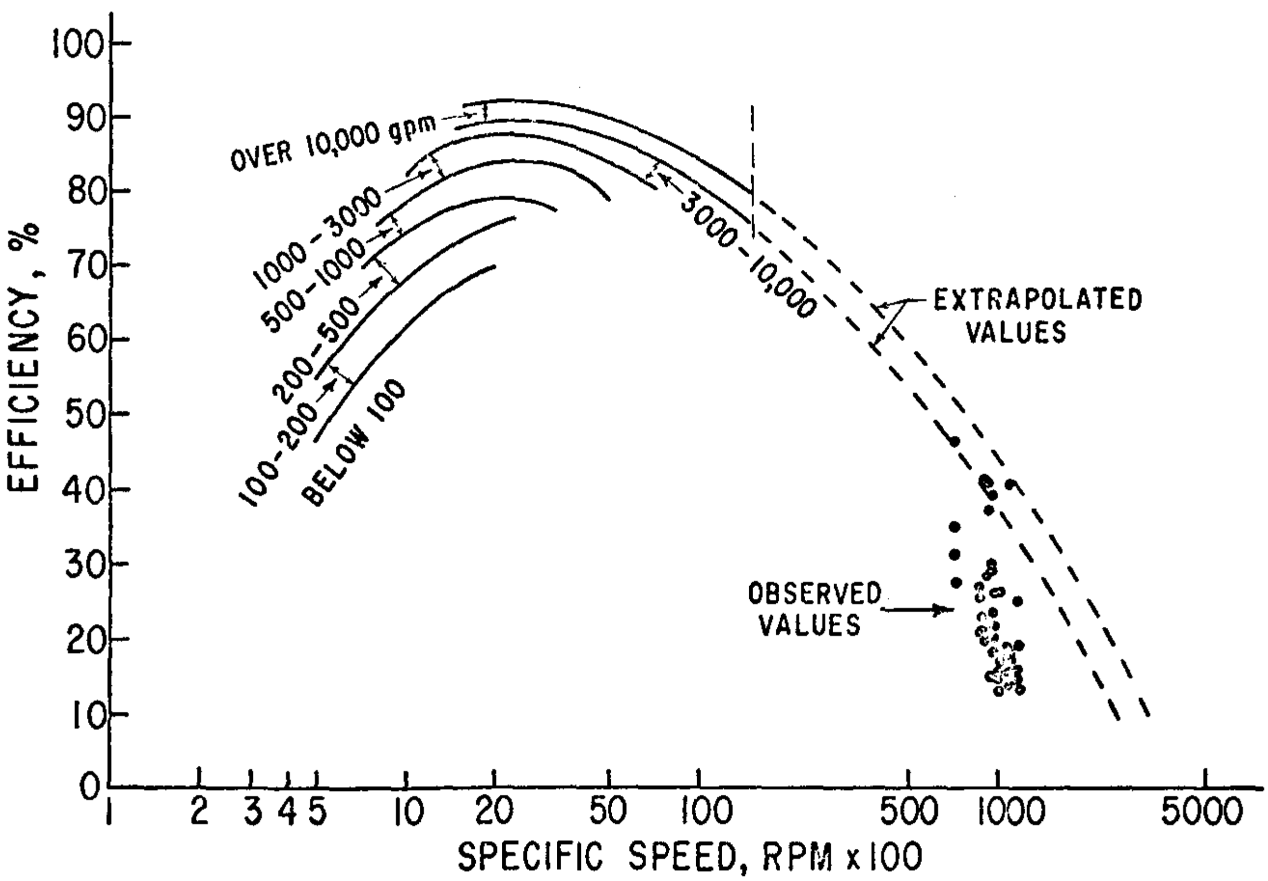

Figure 8. Approximate relation of specific speed and efficiencies of the pump. (13)

The specific speeds, as shown in figure 8, varies from 72,000 to 125,000 and were about 1 order of magnitude greater than those of a typical axial flow pump.

SUMMARY AND CONCLUSIONS

A lake destratifier was designed, built and tested to: 1) pump large flows of water with low inputs of energy, 2) establish the relationships among system variables, 3) calculate expected head loss through the device, based on available coefficients and measured velocities, and 4) make estimates of pump efficiency from measured values of horsepower and flow rate using calculated values of head.

Equations 1 and 2 were developed to describe the flow and power versus rpm, diameter and length for the range of variables studied.

The following conclusions are made based on the experimental results:

1. - The pump pumped large volumes of water with a low input of energy. A maximum flow of 10,703 gpm was obtained when using 0.498 horsepower. The maximum calculated value of TDH was 0.05 foot.

2. - The significant factor affecting the flow (Q) and Power (Ps) of the pump was the rotative velocity of the propeller shaft. The remaining factors had a minor influence. The interactions between combinations of the three design variables had little effect on flow and power input.

3. - The efficiencies of the pump were low. The highest efficiency found was 45.8 percent.
4. - Calculated values of specific speed varied from 72,000 to 125,000 as compared to values of 7,500 to 14,000 for typical axial flow pumps.
5. - The pump should be a practical means of pumping water from the top of a reservoir to the bottom with a low input of energy. This might be a means of destratifying reservoirs, of raising the oxygen content locally near domestic water releases, or of significantly raising the released water temperature for reservoirs with deep intakes to the release system.

   A 40-foot pump with a capacity of one million gallons per minute would probably require about 10 horsepower.

TABLE I

DIFFUSER LENGTH (FT)	OUTLET DIAMETER (FT)	PULLEY SIZE * NO.	MEASURED FLOW (CFS)	CALCULATED TOTAL HEAD LOSS (FT)	EFFICIENCY OF PUMP PERCENT	HORSEPOWER (HP)	CFS PER HP
8.00	5.00	20.	12.8	0.01121	40.9	0.040	320.9
8.00	5.00	28.	16.9	0.01940	22.6	0.165	102.3
8.00	5.00	30.	18.1	0.02231	20.9	0.220	82.3
8.00	5.00	40.	22.3	0.03386	17.6	0.488	45.7
8.00	6.00	20.	12.8	0.01023	37.2	0.040	319.7
8.00	6.00	28.	17.2	0.01857	20.4	0.178	96.8
8.00	6.00	30.	18.2	0.02079	19.6	0.220	82.9
8.00	6.00	40.	23.3	0.03387	18.0	0.498	46.7
8.00	7.00	20.	12.8	0.01173	38.7	0.044	290.7
8.00	7.00	28.	17.5	0.02203	26.1	0.168	104.3
8.00	7.00	30.	18.6	0.02482	25.0	0.210	88.6
8.00	7.00	40.	23.1	0.03818	20.9	0.480	48.1
8.00	8.00	20.	13.1	0.01535	45.9	0.050	262.9
8.00	8.00	28.	17.8	0.02820	34.6	0.165	108.0
8.00	8.00	30.	19.0	0.03204	31.4	0.220	86.3
8.00	8.00	40.	23.8	0.05023	27.7	0.490	48.5
16.00	5.00	20.	12.9	0.01087	29.0	0.055	235.2
16.00	5.00	28.	17.3	0.01947	20.2	0.190	91.1
16.00	5.00	30.	18.6	0.02238	20.5	0.230	80.7
16.00	5.00	40.	22.4	0.03248	15.3	0.540	41.4
16.00	6.00	20.	13.0	0.00882	26.0	0.050	259.6
16.00	6.00	28.	17.3	0.01567	16.7	0.185	93.6
16.00	6.00	30.	18.7	0.01821	16.8	0.230	81.1
16.00	6.00	40.	23.7	0.02928	15.3	0.515	45.9
16.00	7.00	20.	12.9	0.00892	26.1	0.050	257.7
16.00	7.00	28.	17.7	0.01682	18.3	0.185	95.6
16.00	7.00	30.	18.8	0.01909	18.2	0.225	83.8
16.00	7.00	40.	23.6	0.02983	15.7	0.510	46.2
16.00	8.00	20.	13.3	0.01042	41.4	0.038	349.2
16.00	8.00	28.	18.2	0.01955	23.1	0.175	103.9
16.00	8.00	30.	18.9	0.02124	20.8	0.220	86.1
16.00	8.00	40.	23.8	0.03366	18.3	0.498	47.9
24.00	5.00	20.	12.5	0.00980	30.8	0.045	276.7
24.00	5.00	28.	16.8	0.01788	18.2	0.188	89.5
24.00	5.00	30.	17.8	0.02007	18.5	0.220	81.0
24.00	5.00	40.	22.2	0.03114	15.2	0.518	42.8
24.00	6.00	20.	12.7	0.00796	28.7	0.040	317.3
24.00	6.00	28.	17.2	0.01463	15.9	0.180	95.6
24.00	6.00	30.	18.0	0.01597	14.8	0.220	81.7
24.00	6.00	40.	22.3	0.02458	12.3	0.505	44.2
24.00	7.00	20.	13.2	0.00835	25.0	0.050	263.7
24.00	7.00	28.	16.9	0.01380	14.8	0.180	94.1
24.00	7.00	30.	17.9	0.01544	14.0	0.225	79.7
24.00	7.00	40.	22.8	0.02501	12.8	0.507	45.0
24.00	8.00	20.	12.9	0.00843	41.3	0.030	431.1
24.00	8.00	28.	17.8	0.01588	19.1	0.168	105.7
24.00	8.00	30.	18.7	0.01754	18.1	0.205	91.0
24.00	8.00	40.	23.0	0.02662	13.8	0.505	45.5

* NOMINAL RPM OF PROPELLER ≐ 2 * PULLEY SIZE

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THE EFFECT OF LAKE DESTRATIFICATION ON WATER QUALITY PARAMETERS

by

J. M. Steichen, J. E. Garton and C. E. Rice

Since warm water is less dense than colder water, it is natural for the warmer water to be present at the surface of a reservoir. As a lake warms in the spring and summer, the surface water cannot mix throughout the lake by wind action because of the density difference. The lake then stratifies into three distinct layers. The surface strata (epilimnion) is warm and wind circulated. This layer is usually near saturation in dissolved oxygen. The middle strata or thermocline is a region of transition. There is a sharp temperature drop in this region. The thermocline acts as a diaphragm preventing surface induced mixing below that layer. Since the waters below the thermocline (hypolimnion) cannot be reoxygenated, they soon become void of oxygen by chemical reduction processes and biological respiration, forming a stagnant mass. Release of the hypolimnion waters for downstream users places an additional load on water treatment plants and may cause some fish kills.

Because of the problems associated with stratified lakes, many attempts have been made at destratification. There are two

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*Approved as Journal Manuscript No. J-2879 of the Oklahoma Agricultural Experiment Station.

basic systems used. They are mechanical pumping and the release of compressed air or oxygen near the bottom of the lake. Generally water is moved from the hypolimnion to the surface.

An axial flow pump was developed by Quintero and Garton (1973) capable of pumping 0.674 cubic meters per second from the surface to the hypolimnion with a power requirement of 373 watts. This study involved only the mechanical aspects of the pump's operation. No data were collected on the effect of operation on the lake's parameters such as temperature or dissolved oxygen.

Continued study of this device is reported in this research. The pump was modified including the design of a rigid diffuser to minimize the head loss. The effectiveness of the pump's operation on lake destratification was determined by observing various physical-chemical and biological parameters.

Objectives:

1. Determine the effect of the pump's operation on the water quality parameters of a stratified lake.

2. Optimize design for minimum head loss; construct and evaluate a rigid diffuser for the lake destratification pump.

3. Determine the relationships of shaft power, RPM and pump flow rate with and without the diffuser.

Limitations of Study:

The length of the diffuser was limited by the depth of the lake to 4.88 meters. The maximum propeller RPM and flow rates Q were limited by the 373 watt electric motor used in the study.

A limit was made on the number of physical and chemical parameters investigated. Alkalinity, dissolved oxygen concentration

(DO), temperature (t), pH, conductivity and turbidity were measured. The only measurements involving biological factors were the five day biochemical oxygen demand (BOD_5) and the identification and quantification of composite plankton samples. No attempt was made to study the effect of fish behavior or rate of growth.

Review of Literature:

Stratification is a natural phenomenon. In the case of a eutrophic lake stratification results in extreme consequences, the most notable of which is the loss of dissolved oxygen from the hypolimnion during the summer. When the natural fall "turnover" occurs, the DO of the lake usually drops sharply. Sometimes this "turnover" is enough to kill or stun fish. Artificial destratification keeps a lake mixed through the usual stratification season and therefore there is no fall "turnover".

By definition the primary effect of destratification is to break the layers of thermal stability allowing the entire water mass to mix. A column of water would be isothermal at all depths. At the same time other physical and chemical parameters would be brought to some mean value.

The more stable the stratification condition, the more energy that would be required to break it. The expenditure of energy necessary to upset an existing stratification or to bring it to a state where the whole water mass would have taken on the mean temperature by mixing is termed the stability of stratification. The idea of stability is important since it gives a value for the resistance that a given state of stratification is able to oppose the stirring effect of the wind and thus also a value for the degree to which the hypolimnion of the lake is shut off.

Since the center of gravity of a stratified body of water lies lower than that of an unstratified one (because denser layers are below) Ruttner (1963) defines stability as the work required to raise the center of gravity an amount corresponding to its displacement downward from its original position. This is equivalent to lifting the weight of the whole lake by a distance equal to the difference between the two centers of gravity.

A means of calculating the effectiveness of a destratification apparatus was suggested by Symons, et al (1970). Destratification efficiency (DE) is defined by the ratio:

$$DE = \frac{\text{Net change of stability from } t_1 \text{ to } t_2}{\text{Total energy input from } t_1 \text{ to } t_2} \times 100 \qquad (1)$$

In their studies destratification efficiency values of from 0.2% for mechanical pumping to 1.5% using a diffused air pump were reported.

The Quality Control in Reservoirs Committee of the American Water Works Association (1971) recommended artificial destratification to the water suppliers who are experiencing raw water quality deterioration in their reservoirs as a result of anaerobic conditions in the hypolimnion caused by thermal stratification. Barnett (1971) reported a definite decrease in chlorine demand during summer months after destratification.

King (1970) has suggested that the blue-green algae are more efficient at obtaining CO_2 from low concentrations than green algae, and that under circumstances when pH is high, as in eutrophic lakes, blue-green algae should predominate. Some species of blue-green algae have been identified as the source of taste and odor problems. Shapino (1973) investigated this hypothesis and found that by lowering pH and adding nutrients to bags of lake water dominated by blue-green algae, there was a shift to dominance of green algae. The addition of nutrients and CO_2 resulted also in a shift to green algae.

The mixing of a stratified lake is closely analogus chemically to adding CO_2 and nutrients. Symons, et al (1970) reported that when lake water dominated by blue-green algae is mixed, the blue-green algae decline and the green algae seem to become the dominant forms.

Experimental Equipment:

The axial flow type pump built by Quintero (1973) was modified and used in this project. The three major parts of the pump are: a propeller, a stationary casing and a diffuser (Figure 1). The modifications included changing the propeller and designing a rigid diffuser.

The nine-bladed propeller had an effective diameter of 1.06 meters. The chord angle of the blade varied from about 44° at the hub to about 20° at the tip. The hub was 0.292 meters in diameter. Quintero's propeller was the same diameter but had seven blades and the pitch varied from 10° to 20°. Both propellers had been originally designed for blowing air.

The design of the rigid metal diffuser was optimized for minimum head loss. The resulting diffuser had the following dimensions.

Inlet diameter - 1.07 meters

Outlet diameter - 2.13 meters

Length - 4.88 meters

The pump was floated on a 2.44 m by 4.88 m plywood raft floated by barrels. The pump was powered by a 373 watt electric motor. A more detailed description of the mechanical equipment used is given by Quintero and Garton (1973).

Location of the Experiment:

Ham's Lake (Figure 2), used for the tests, is a Soil Conservation Service flood detention reservoir located about five miles west of Stillwater, Oklahoma. The lake has a surface area of almost 40 hectares and a volume of 115 hectare-meters when at the principle spillway elevation of 287.0 meters above sea level. The pump was located near the deepest area of the lake, about 9.5 meters. Although it is a relatively shallow lake, it does exhibit thermal stratification. The temperature difference between the surface and the bottom is similar to deeper lakes in Oklahoma. In addition, oxygen stratification is very pronounced. During the summer the surface water is supersaturated while the dissolved oxygen goes to zero between three and four meters depth.

Methods and Procedure:

A major objective of this study was to determine the effect of the pump's operation on a stratified lake. Therefore, the lake was first allowed to stratify. The pump was then operated for one week without the diffuser attached to determine if the diffuser was necessary in order for the pump to destratify the lake. The pump was operated the rest of the season with the diffuser attached.

Eight stations were located by floating markers on the lake (Figure 2). Each day readings of dissolved oxygen (DO) and temp-

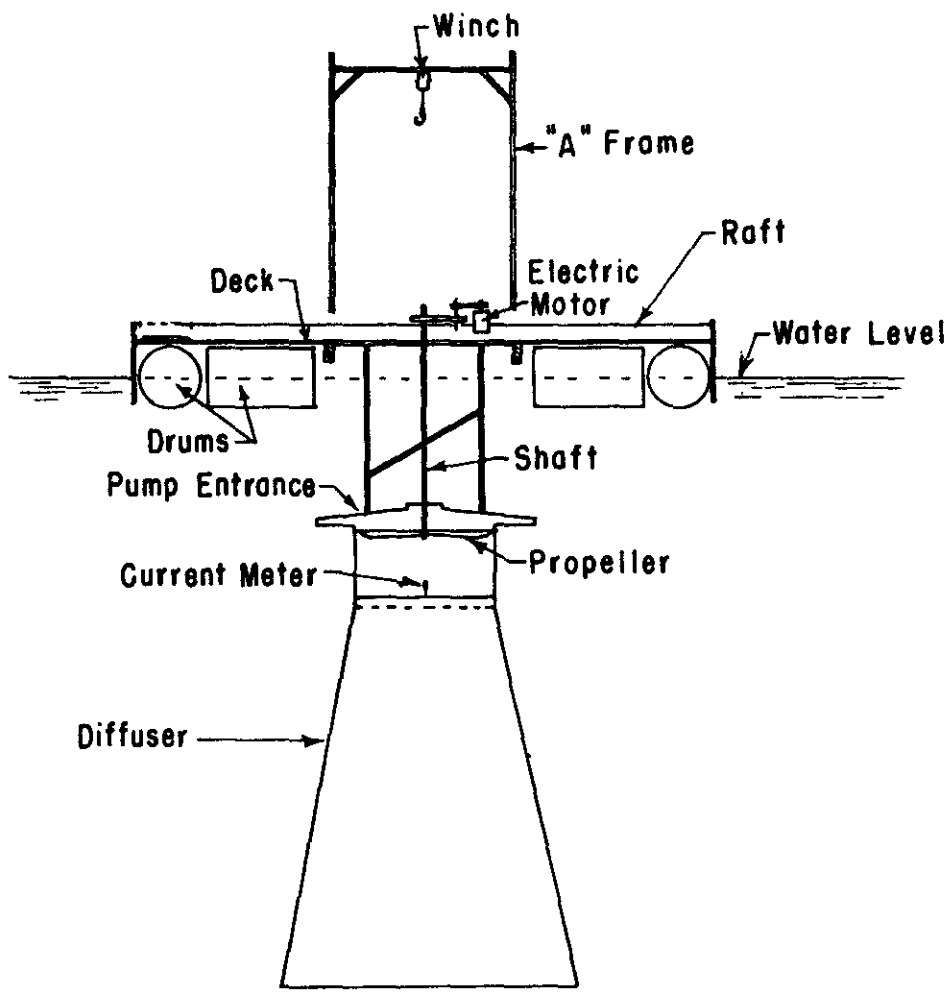

Figure 1. Assembly of Pump and Raft

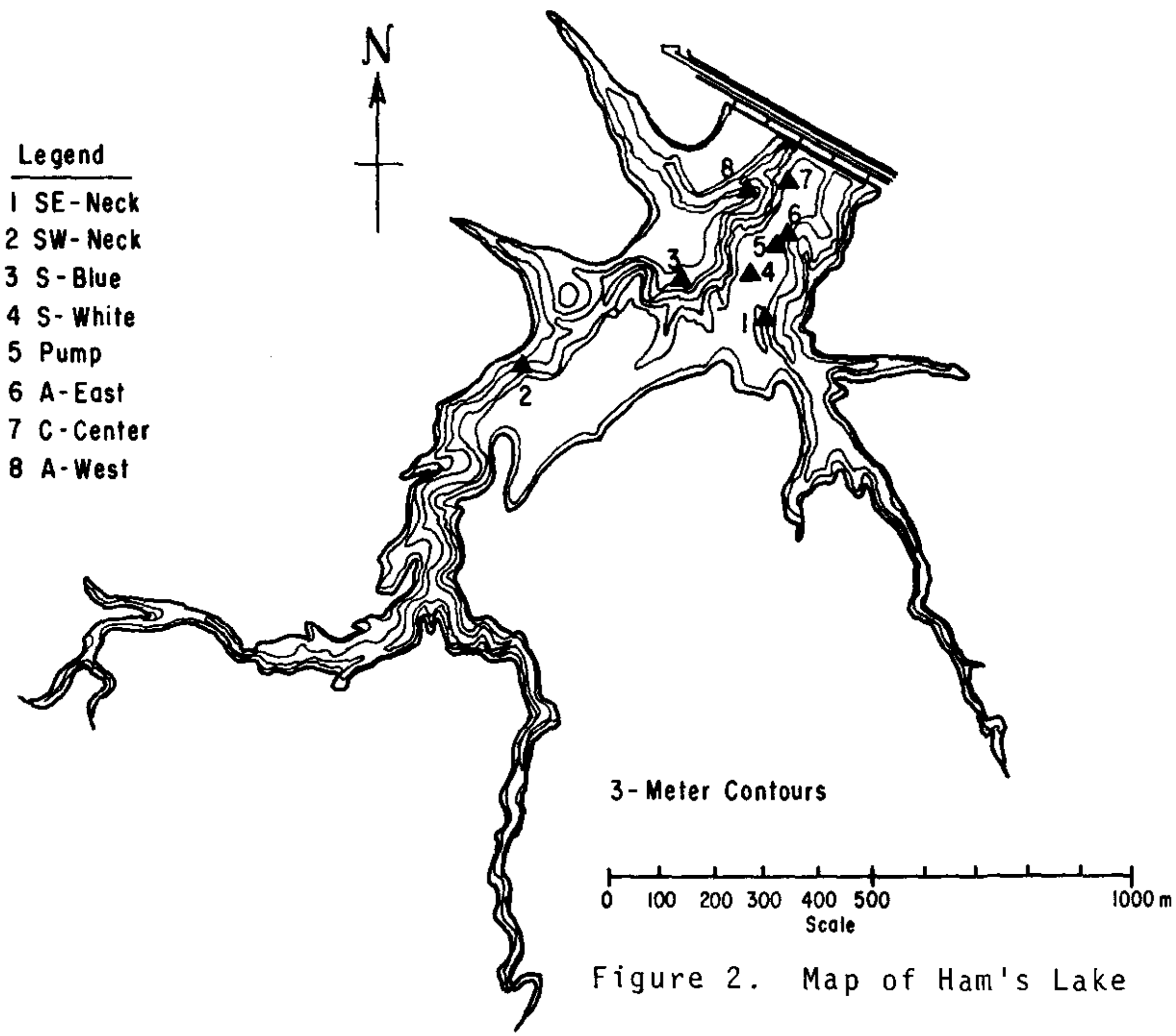

Figure 2. Map of Ham's Lake

erature were made at one meter depth increments at each station. These readings were always made in the morning beginning at 9:00 a.m. The electronic probe was used for these readings and checked regularly using a standard thermometer and the Winkler method for DO. Each day a surface sample was taken from near the platform to determine turbidity. This reading was made using a spectrophotometer and a calibration to Jackson turbidity units.

Water samples were taken using the Van Dorn water sampler. The samples were taken from the platform until June 20, after that date a station about 30 meters north of the platform was used. All water samples were taken from 1, 3, 5, 7 and 9 meters below the surface. Twice each week measurements of pH and conductivity were made using laboratory instruments. Using the same samples, total alkalinity and carbonate alkalinity were determined using the procedure from Standard Methods (1971). Once each week samples for determining the 5-day biochemical oxygen demand (BOD_5) were taken. The procedure from Standard Methods was followed.

Composite algae samples were taken twice each week and preserved using Lugol's solution. The composite sample was made by taking 125 ml samples from the surface and 1 and 2 meter depths at several stations and mixing them together. The identification and counting of the algae was done by an aquatic biologist.

The mechanical evaluation of the pump consisted of measuring the shaft horsepower, pump flow rate and propeller RPM with and without the diffuser. The propeller RPM was varied by changing pulleys on the motor shaft. Observations of average throat velocity, propeller RPM and watts were made for each condition.

Presentation and Analysis of Data:

The data gathered in this research project falls into three categories: physical-chemical, biological and mechanical analysis of the pump and diffuser.

Physical-Chemical:

Observation of physical-chemical parameters was used to determine the effectiveness of the pump's destratification capability. Changes in these parameters are easier to measure and analyze than the biological parameters.

Temperature and Dissolved Oxygen:

The temperature and DO are probably the most important parameters that affect a lake. During periods of stratification aerobic biota are excluded from the hypolimnion by anoxia.

Figure 3 illustrates the changes in the temperature profile at one station located about 30 meters from the pump. Other locations showed similar profiles. On July 14 before any pumping was begun, the surface water temperature was warmer than on June 29; however, in deeper layers the temperatures were nearly the same. On both dates strong temperature stratification was observed. On July 14 there was a 13.5°C temperature difference between the surface and the bottom. In the afternoon the temperature difference would be even greater since the surface often warmed to near 30°C.

The pump was operated 9-1/2 hours on July 14 and operated continuously after 9:00 p.m. on July 16. From July 16 to July 23 the pump operated without the diffuser. The diffuser was installed during the afternoon of July 23. The pump was then operated continuously until the last week of October.

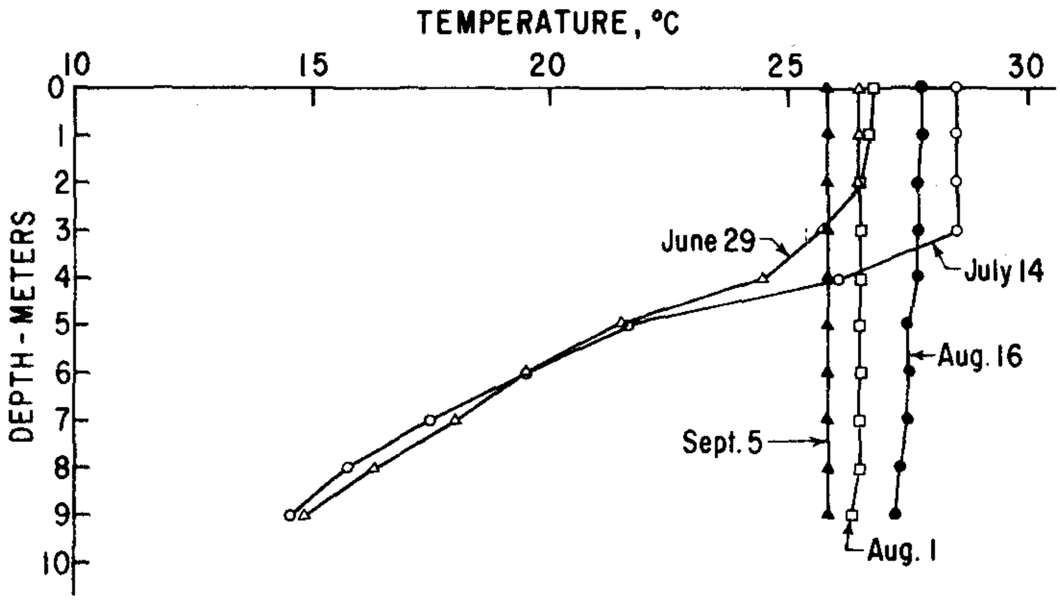

Figure 3. Typical Temperature Profiles

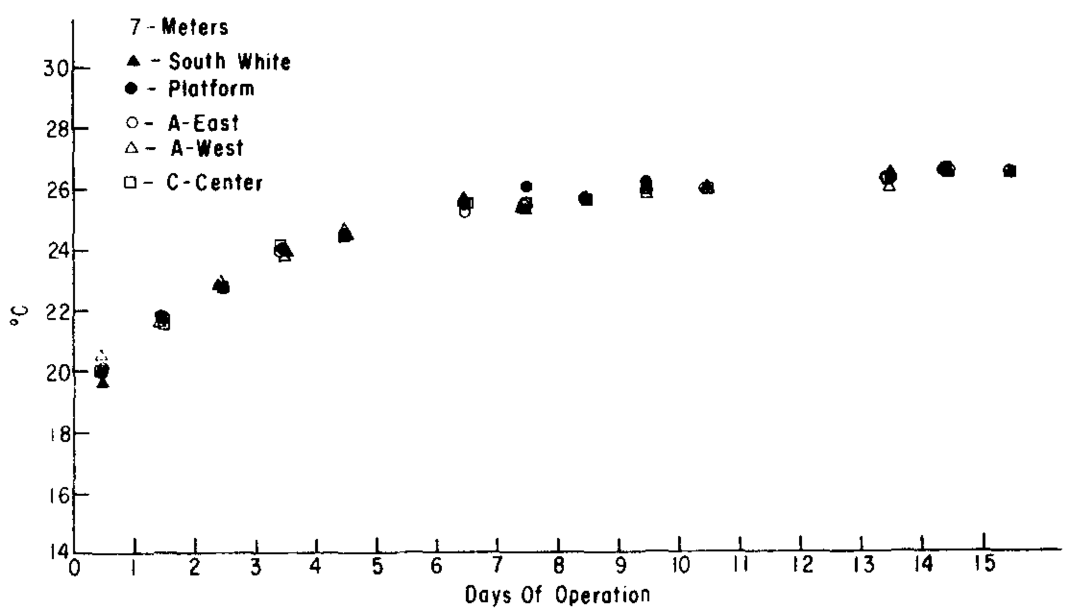

Figure 4. Plot of temperature versus time for Readings taken at the seven meter depth at various locations.

Operation of the pump without the diffuser for 9-1/2 hours on July 14 warmed the hypolimnion water about 1.5°C. Also DO was present at 4 and 5 meter depths away from the platform. At the platform DO was present at 6 meters. Before pumping, DO was absent at 4 meters everywhere in the lake. Since the pump had an effect on the hypolimnion even though a diffuser was not used, it was operated for 7 days without the diffuser. The lake warmed uniformly regardless of location. In other words, the temperature at a particular depth was the same whether it was near or far away from the pump platform. Figure 4 illustrates this fact with seven meter temperature readings taken at several locations. Other depths show similar results.

On August 1 the temperature profile was nearly constant at 26.5°C. After August 1 the temperature difference in the water column was less than 1°C. By August 16 the general temperature of the lake had increased about 1°C but the temperature profile was still nearly uniform. Fall cooling is evident by the decreased but still uniform temperature on September 5.

The warming of the lake from the start of pumping can be seen in Figure 5. First observation shows that the coldest water at 9 meters warmed at the fastest rate. For about the first three days this warming was at an exponential rate.

The changes in the DO regime are even more pronounced. Figure 6 shows the DO profiles for the same station as the temperature profiles. On June 29 the surface DO was 8.0 mg/l and DO was zero below 5 meters. By July 13 the surface condition was similar but the DO dropped from 7.2 mg/l at 3 meters to 0 at 4 meters. Readings of DO taken at sunset ranged as high as 10 to 11 mg/l at the

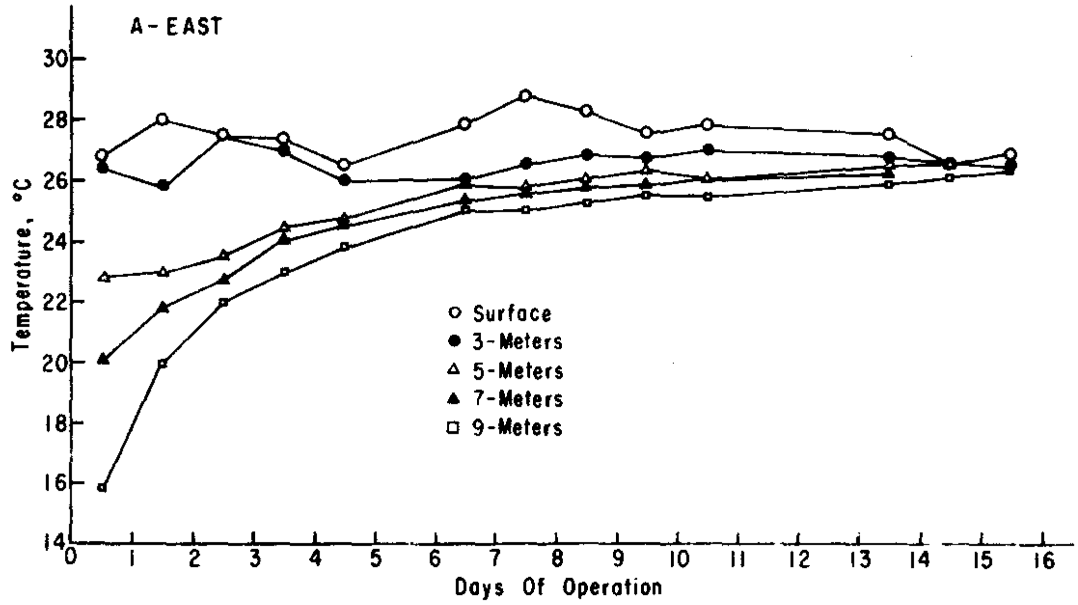

Figure 5. Plot of Temperature Versus Time At Station A-East.

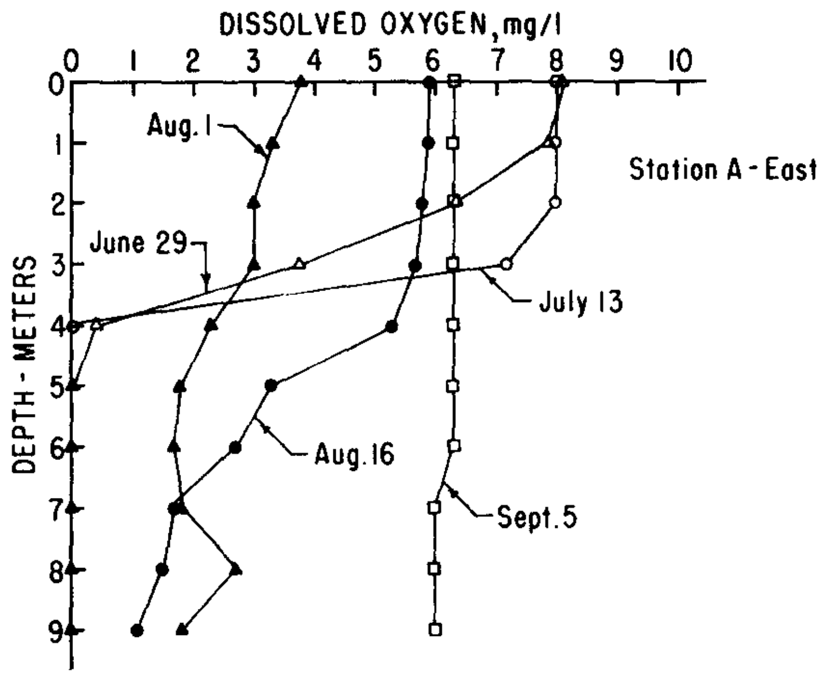

Figure 6. Typical Dissolved Oxygen Profiles.

surface. This highly supersaturated condition was due to the high rate of photosynthesis occurring. On August 1, the first day that the temperature profile was entirely uniform the DO profile ranged from 3.8 mg/l at the surface to 1.1 mg/l at the bottom. This was a significant reduction in the surface DO. The cause was probably the mixing of the surface water with the high BOD water from the hypolimnion. Even more significant was the presence of DO at all depths. A general increase in DO had occurred by August 16. The DO concentration was relatively uniform although not saturated on September 5. More time was required to raise DO to a uniform level at all depths than was necessary to make the lake isothermal. This was probably due to the high organic load that was present in Ham's Lake.

Figure 7 illustrates how the DO varied with depth after pumping began. Oxygen could be found at the lower depths at the pump earlier than at other locations.

The changes in the weighted average temperature and DO and the stability index are graphed in Figure 8. The broken line on July 13 indicates the last day that no pumping occurred. The solid line on July 16 indicates that day on which continuous pumping commenced.

The average temperature was observed to increase both before and after mixing. The lake did not begin to cool until late August. Although the surface temperature cooled some after mixing, the average temperature increased to a higher temperature than if the lake had not been mixed. The heat budget of the lake was increased. The reason is that the hypolimnion water had been warmed considerably.

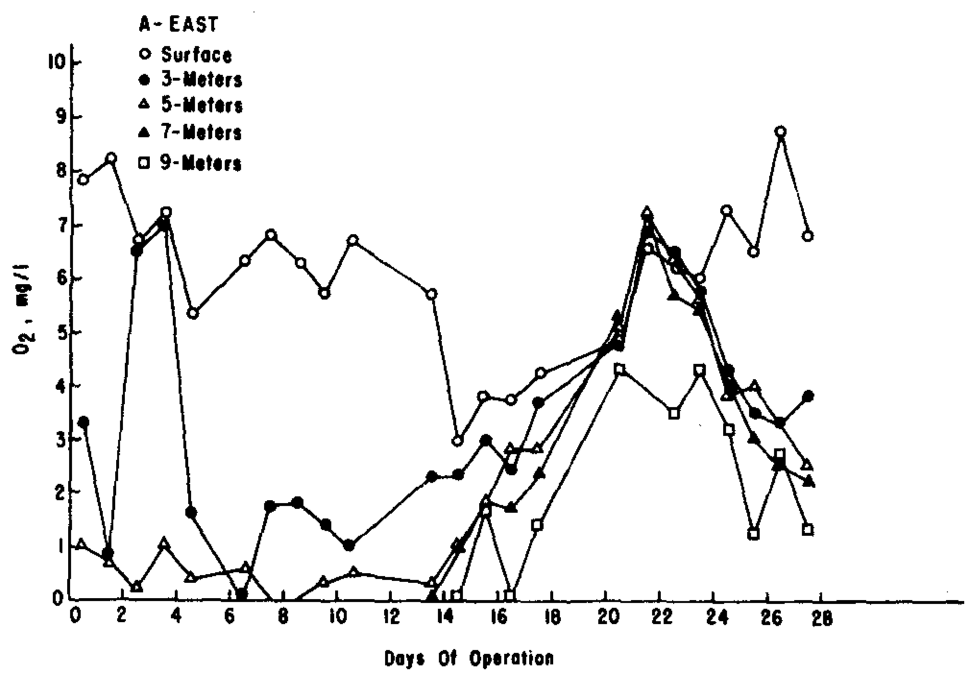

Figure 7. Plot of Dissolved Oxygen Versus Time at Station A-East.

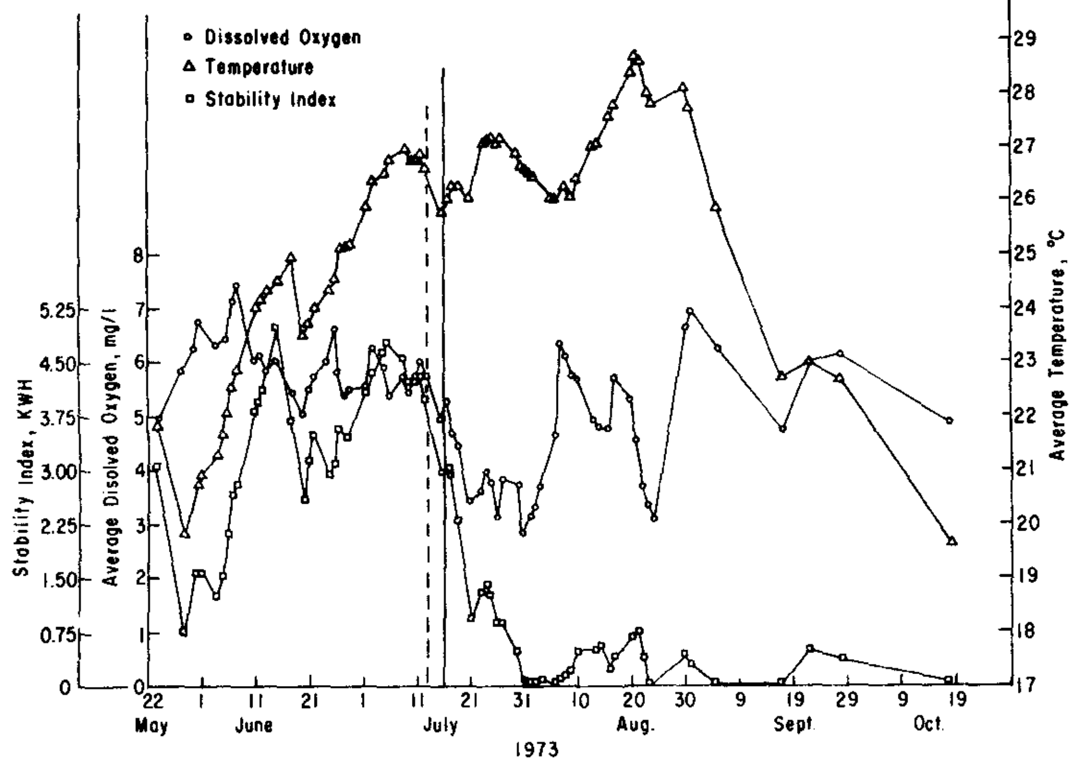

Figure 8. Plots of Average Dissolved Oxygen, Average Temperature and Stability Index Versus Time.

The average DO generally varied between 5.0 and 6.5 mg/l before mixing. Unfortunately almost all of this was at the surface. When mixing began the average DO began to drop until it reached a low of 2.85 mg/l on July 31. This drop was probably due to the oxidation of the high BOD water brought up from the bottom. At no time was the surface DO near zero nor was a fish kill observed. The average DO built back to its level before mixing, but DO was mixed throughout the water column.

The stability index is a measure of the resistance to mixing of a stratified lake. The stability index generally tended to increase during the warming period in June and early July. Variations in the index occurred from day to day generally caused by the wind. On a still day the top meter of water warmed up more than it did on a windy day when the top 2 or 3 meters were usually well mexed. After pumping began the stability index dropped sharply. By August 1 the stability index was 0.033 KWH compared with 3.95 KWH on July 13 before mixing began. After August 1 the index increased on some days, usually because of the calm winds. Readings taken at dawn usually showed a nearly constant temperature, indicating that the index dropped nearly to zero at night.

pH, CO_2 and Alkalinity:

The plots of the pH profiles for June 25 and July 13 on Figure 9 are typical of the enriched lake. A lake rich in nutrients is capable of supporting a large crop of plankton. In the surface layers of the lake exposed to sunlight, algae, carbon dioxide and water combine by photosynthesis to produce oxygen and sugar. Little photosynthesis occurs in the hypolimnion since light cannot penetrate to that depth. Respiration still occurs there releasing CO_2. Since the hypolimnion cannot mix, the CO_2 is trapped. Carbon dioxide dissociates in water to form carbonic acid. This reaction results in a pH decrease as the CO_2 concentration increases. At about pH 8.3, the phenopthalein end point, no CO_2 remains dissolved in water. Figure 10 shows that before mixing, CO_2 disappeared from the surface and increased in the hypolimnion. This was accompanied by a pH generally above 8.5 at the surface. When CO_2 disappears photosynthetic algae use bicarbonate as a carbon source.

The immediate effect of mixing was the reduction of pH in the surface water and the increase of pH near the bottom. This was accompanied by the return of free CO_2 to the surface and reduction of CO_2 near the bottom. By August 1 the pH was nearly uniform at about 7.7. Twice the pH did rise above 8.5, the result of a bloom, but it fell back below 8.0 afterward.

For a month before mixing, carbonate alkalinity was present at 1 meter and sometimes at 3 meters. As stratification became more intense total alkalinity in the hypolimnion increased. Pumping lowered the total alkalinity in the hypolimnion in a few days. A general decrease in the total alkalinity throughout the water column developed in the long run. Carbonate alkalinity was reduced to zero by July 30. Only on two occasions afterwards was carbonate alkalinity present and then only for a short time.

BOD_5

The most striking feature of the BOD_5 profiles in Figure 11 was the increase in BOD_5 in the hypolimnion during stratification

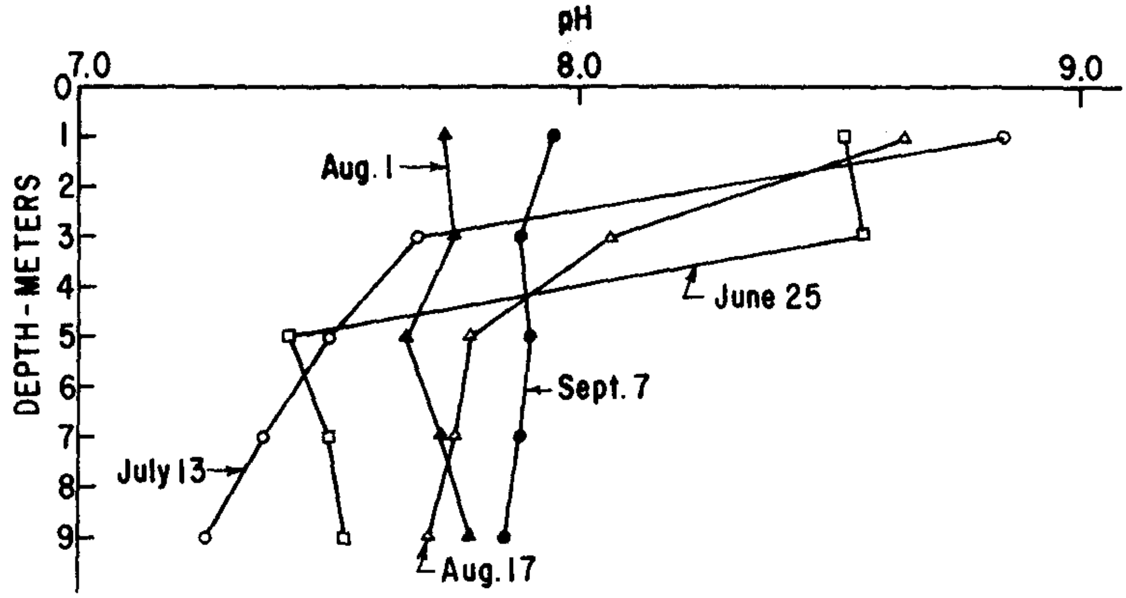

Figure 9. Typical pH Profiles.

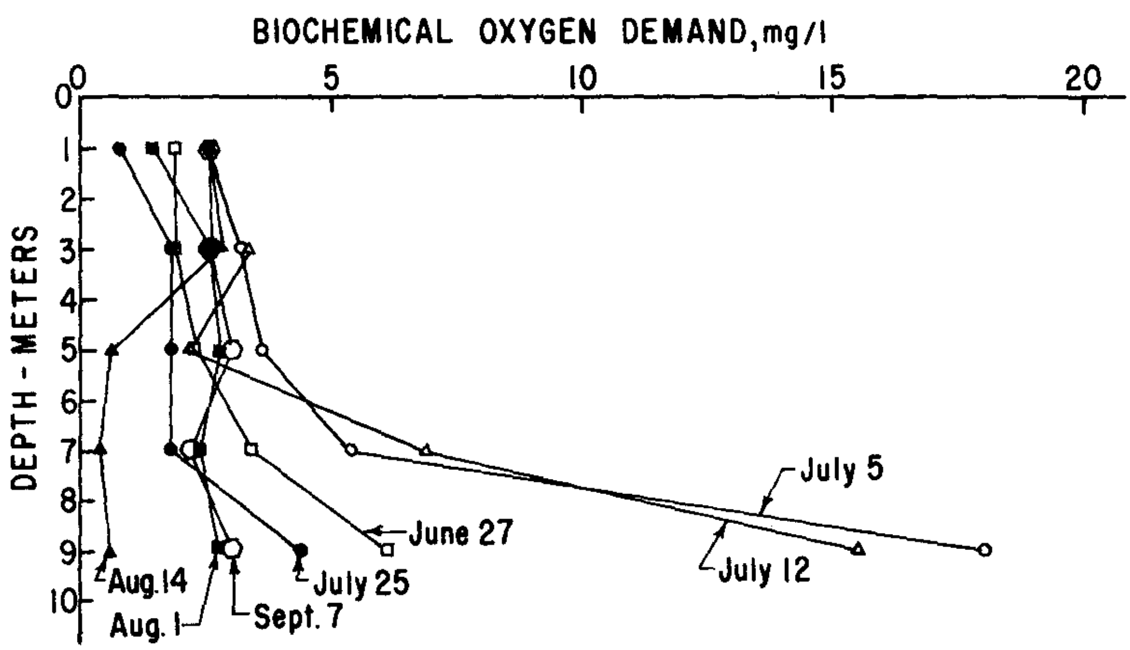

Figure 11. Typical Biochemical Oxygen Demand Profiles.

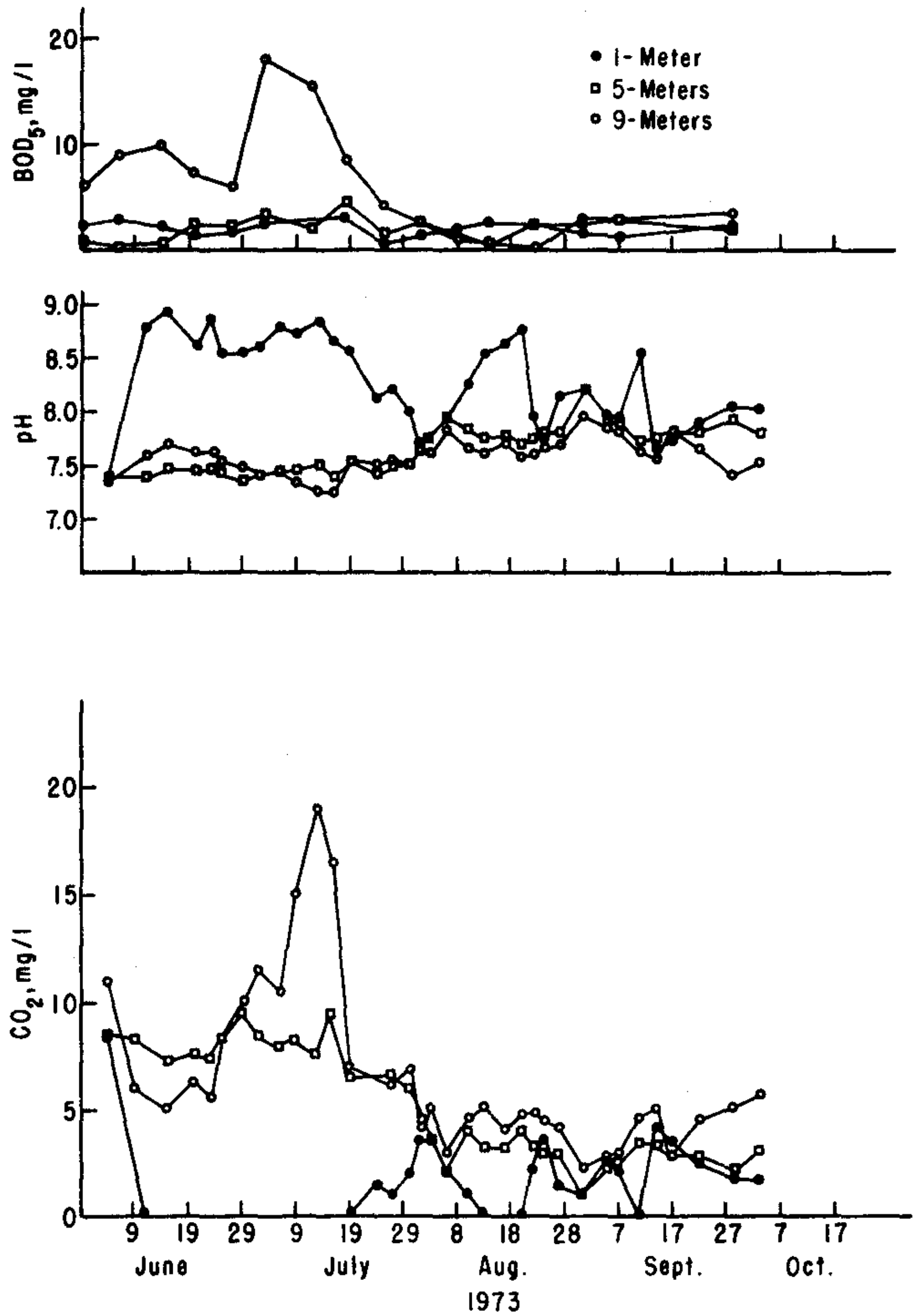

Figure 10. Plots of BOD_5, pH and CO_2 Versus Time.

and the rapid decrease after mixing. Figure 10 shows that relationship among BOD_5, pH and CO_2. The sharp increase in BOD_5 at 9 meters before mixing was accompanied by an increase in CO_2 and a slight decrease in pH. Mixing allowed the organic material near the bottom of the lake to oxidize since oxygen was then available. The CO_2 stored in the hypolimnion and the CO_2 produced by the oxidation of organic matter resulted in a more uniform distribution of CO_2 throughout the water column. The availability of CO_2 also resulted in the reduction of pH in the surface water.

Specific Conductance:

Specific conductance is a measure of a water's capacity to conduct an electric current. This property is related to the total concentration of the ionized substances in a water and the temperature at which the measurement is made (Standard Methods, 1971). Specific conductance followed a pattern similar to other physical chemical parameters. Figure 12 illustrates how specific conductance was stratified before mixing was begun on July 16. By July 24 the stratification was less sharp and on August 3 conductance was uniform top to bottom.

Biological:

Collection of biological data was limited to collection of plankton samples. No analysis of fish behavior or production was made. The identification and counting of the plankton samples was done by a biologist.

For initial analysis the plankton was divided into four groups: green algae (Chlorophyta), blue-green algae (Cyanophyta), flagellates

(Euglenophyta and Pyrrhophyta) and diatoms (Chrysophyta). Numbers of these groups graphed versus time are given in Figure 13. The numerical scale is logrithmic.

Early in June flagellates, especially Euglena, predominated. Blue-greens hit a small peak June 29 and then dropped until July 6. Their numbers began building before pumping began and peaked July 19 with bloom proportions. The blue-greens dropped sharply and did not build back until a month later. Flagellates again hit a brief peak near the end of July. On August 6 all types of plankton except diatoms had very low counts. Diatoms began a quick growth rate and maintained high numbers for about a month and a half. Cyclotella was the most common diatom but Melosira became more important late in the season. Blue-greens built up to bloom proportions again in late August, and remained high through September.

The expected shift in predominance from blue-green to green algae apparently did not occur. Comparison of the counts observed showed that blue-green algae were more numerous. Some of this may be misleading since some of the green algae forms had cell volumes larger than the blue-greens, and could still have a similar biomass even with smaller numbers (Prescott, 1951). There were changes in the types of blue-green algae present (Figure 14). Before mixing Anabaena and Microcystis (Anacystis) dominated. At the onset of mixing Dactylococcopsis appeared and became the dominant blue-green. Sometimes it was present in numbers as high as 1,130,000 per liter. Frequently both Microcystis and Anabaena are mentioned as being "nuisance" algae.

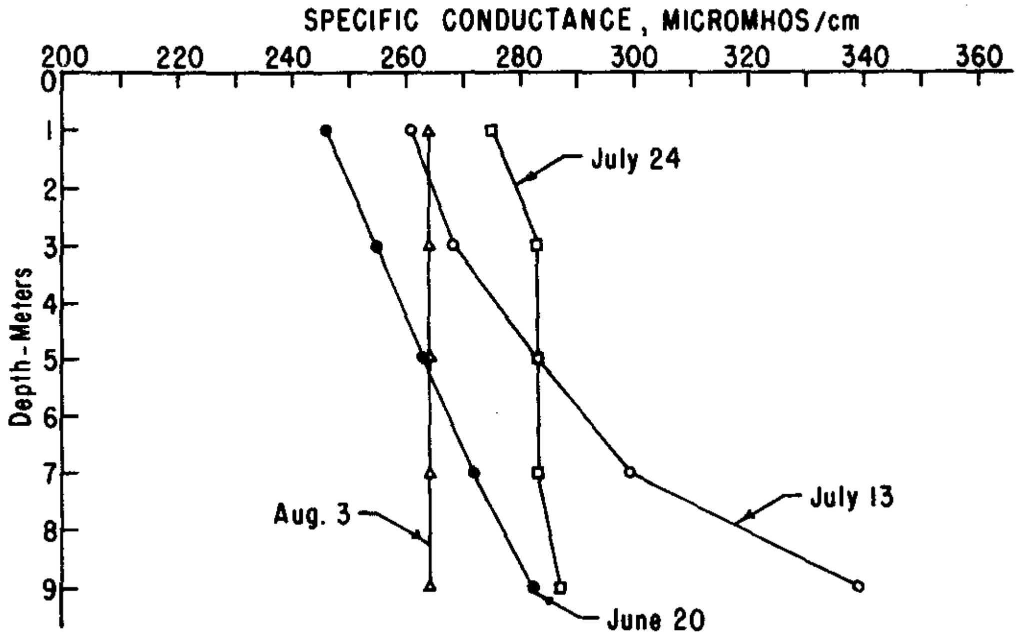

Figure 12. Specific Conductance Profiles

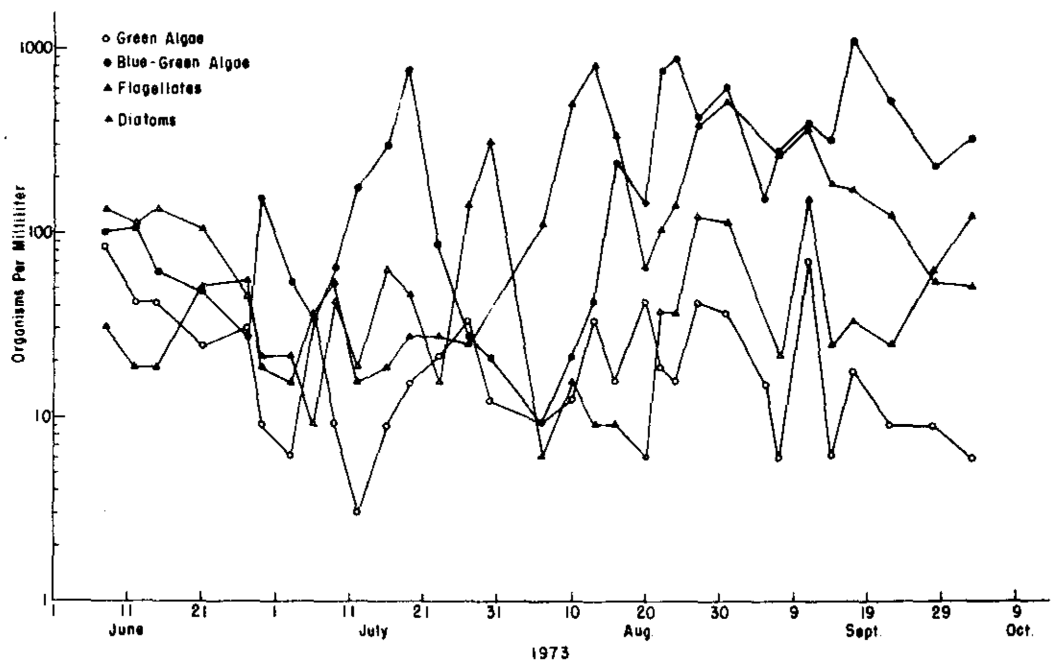

Figure 13. Plot of Plankton Counts Versus Time.

After mixing both of these algae were reduced in number and sometimes disappeared. Dactylococcopsis has not been identified as being as troublesome as Anabaena or Microcystis.

Analysis of Pump

Pump Operation:

Originally it had been thought that the diffuser was necessary not only to reduce head loss but also as a conduit to move the pumped surface water to the hypolimnion. The power and flow rate measurements were first taken without the diffuser. Before installing the diffuser, the pump operated during hydraulic testing for 9-1/2 hours on July 14. Even though the exit of the pump was only 1.8 meters below the water surface, apparently the pumped water had enough energy to penetrate the thermocline located between 3 and 4 meters depth. That night when the pump was shut off the hypolimnion water temperature had risen about 1°C. Earlier observations showed that the hypolimnion temperature did not change prior to pumping.

The pump was continuously operated without the diffuser from 9:00 p.m. July 16 until 1:30 p.m. July 23. Using the 18-tooth pulley with timing belt, the rotation was 37 RPM, the flow rate 0.666 cubic meters per second and the power 261 watts. The rigid metal diffuser was installed during the afternoon of July 23. The 18-tooth pulley was still used but the flow rate increased to 0.773 cubic meters per second and the power decreased to 194 watts. On August 2 a V-belt drive system was installed which rotated the propeller at about 44 RPM. The V-belt drive was used during ordinary operation because of the increased life of the

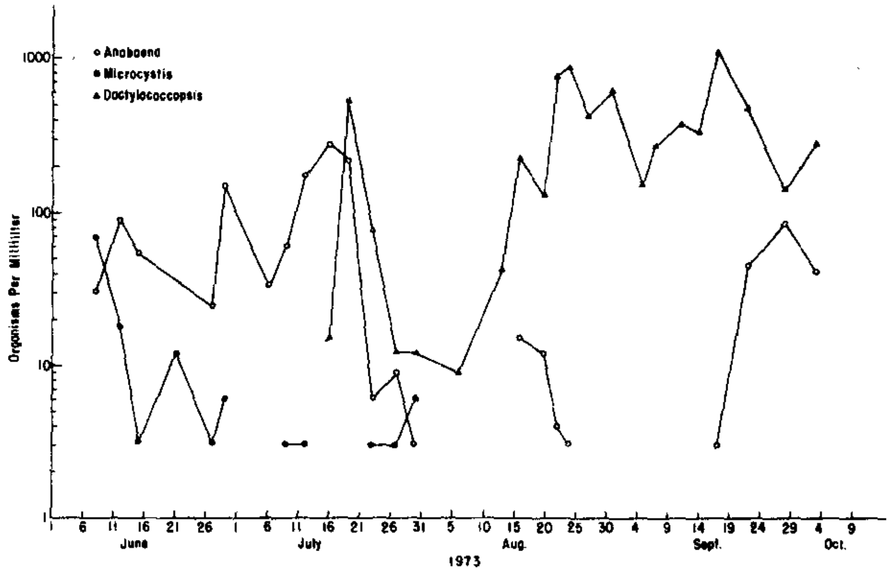

Figure 14. Plot of Predominant Blue-Green Algae Counts Versus Time.

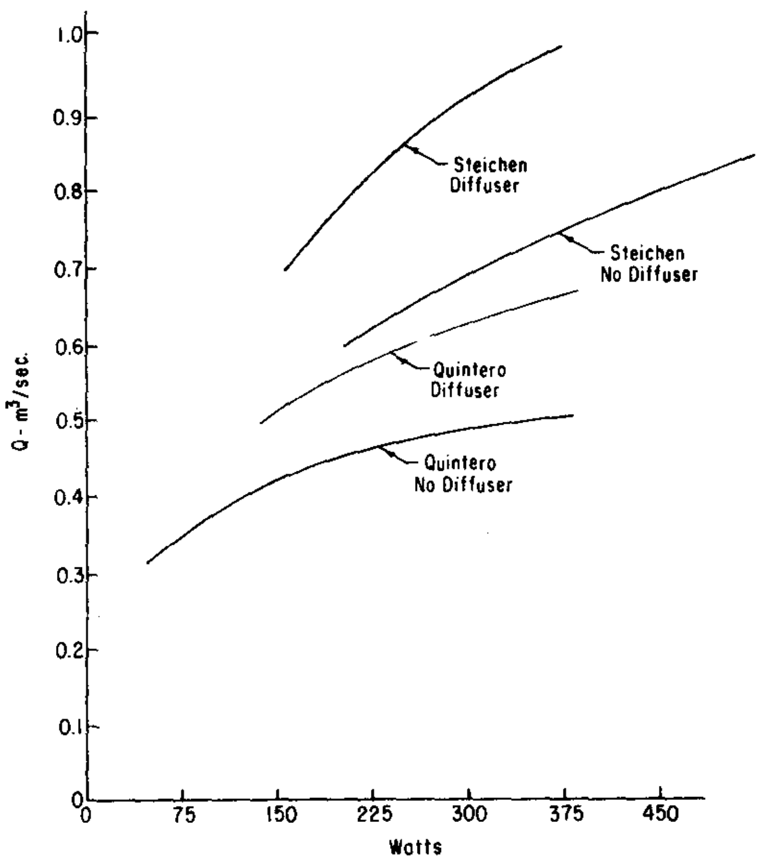

Figure 15. Flow Rate Versus Horsepower Curves for Pump.

belts. The timing belts were used earlier to obtain a given speed ratio and were used in calculating the power output.

Analysis of Pump Design:

Comparison of the power and flow rate characteristics for the pump are shown in Figure 15. Data for the Quintero pump are for conditions with and without a flexible fabric diffuser (1973). The diffuser dimensions used are 4.88 meters long with an entrance of 1.07 meters diameter and an exit of 2.13 meters diameter. The rigid metal diffuser had the same dimensions. The Quintero data were obtained using a propeller blade with less pitch but faster rotation.

At 373 watts compare the flow rates for the four conditions in Figure 15. Using the Quintero data there is a 32% increase in flow due to the diffuser. The same 32% increase was found using the Steichen data thesis reference (1974). However, comparing the two conditions both with and without the diffuser, there is a 49% increase in flow using Steichen's propeller. This would indicate that there was little improvement in efficiency due to the rigid metal diffuser compared with the plastic fabric diffuser used by Quintero. The improvement can apparently be explained by using the different propeller blade.

Effectiveness of Pump:

The best way to measure the effectiveness of a destratification device is to measure the destratification efficiency defined in Equation 1. The pump operated without the diffuser for 170 hours and used 44.4 KWH of energy. During this time the stability index dropped from 3.95 KWH to 1.30 KWH. The destratification efficiency was equal to 6.0%.

By extending the period of analysis to August 1, when the lake was fully destratified, another efficiency can be calculated. The pump was operated for a total of 377 hours and used 84.5 KWH. The stability index on August 1 was 0.033 KWH. The destratification efficiency was 4.6%.

Table I compares destratification efficiency for several other devices. This pump was found to be a very efficient destratification device in comparison. Several days were required to totally mix the lake. This can be an advantage since a nearly instantaneous overturn is not usually desired. This device would also be useful as a stratification prevention device, if operation is begun before the lake stratifies.

TABLE I

COMPARISON OF VARIOUS DESTRATIFICATION EFFICIENCIES

Lake	Dates of Mixing	Method	Volume Ha-M	Surface Area Ha	Max Depth M	Destratification Efficiency %
Ham's	7/16 - 7/23/73	Mechanical Pump	115	40	9	6.0
	7/16 - 8/ 1/73					4.6
Roberts	23 hours	Diffused Air	121	28	9	0.14
	74 hours					0.04
	144 hours					0.03
Boltz	8/ 6 - 9/10/65	Mechanical Pump	358	39	19	0.2
	6/ 2 - 6/ 7/66	Diffused Air				1.5
Falmouth	6/10 - 6/15/66	Diffused Air	567	91	13	0.9

CONCLUSIONS

1. Within two weeks the pump completely destratified the lake thermally.
2. A longer period of time was necessary to destratify DO than was necessary for thermal destratification.
3. Although there were some changes in algae species predominating in the lake, there was no real shift from blue-green to green algae predominance.
4. The pump was capable of destratifying the lake without the diffuser attached. The destratification efficiency during this period of 7 days was 6.0%.
5. Fifteen days of operation were required to lower the stability to nearly zero. The destratification efficiency for this period was 4.6%. Destratification of all physical-chemical parameters monitored was observed.
6. No significant improvement in diffuser efficiency was found in comparing the rigid metal diffuser with the flexible fabric diffuser.
7. Use of the propeller with a pitch varying from 44° at the hub to 20° at the tip resulted in as much as 49% more flow at the same power as a propeller with pitch varying from 10° to 20°.

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