ARTIFICIALLY INDUCED CIRCULATION IN THERMALLY STRATIFIED LAKES

BY

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To Professors: Hasler

Weiss

Evans

This thesis having been approved in respect to form and mechanical execution is referred to you for judgment upon its substantial merit.

Dean

Approved as satisfying in substance the doctoral thesis requirement of the University of Wisconsin.

Major Professor

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PREFACE

The purpose of this paper is to describe some aspects of an artificial physical disturbance in the lake environment. It is with some misgiving that the words of Aldo Leopold are recalled (1949, p. 221):

> "Conservationists are notorious for their dissensions Superficially these seem to add up to mere confusion, but a more careful scrutiny reveals a single plane of cleavage common to many specialized fields. In each field one group (A) regards the land as soil, and its function as commodity-production; another group (B) regards the land as a biota, and its function as something broader. How much broader is admittedly in a state of doubt and confusion." He goes on to say, "In the wildlife field, a parallel cleavage exists. For group A the basic commodities are sport and meat; the yardsticks of production are ciphers of take in pheasants and trout. Artificial propagation is acceptable as a permanent as well as a temporary recourse - if unit costs permit. Group B feels the stirrings of an ecological conscience."

I feel that this work is unfortunately proximal to "A group." It can only be hoped that in some measure the results may serve to enlarge our understanding of the aquatic environment as it will aid in our exploitation of it.

The guidance of Professor Arthur D. Hasler is gratefully acknowledged. The counsel of Professor James R. Villemonte is also acknowledged.

Only those who have extracted limnological measurements from a frozen lake can appreciate the real contribution to this work made by Oscar Brynildson, Richard Parker, Raymond Stross, Waldo Johnson, James Gammon and John A. Miller. All of the work with the use of radio-isotopes in the field and laboratory was conducted by Eldon Zicker and M. C. Sparr. I wish to thank them both for permission to call upon their skill with the use of this material and also for their collaborative efforts in these experiments.

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The use of the lands and facilities of Mr. Ben S. McGiveran of Milwaukee, Wisconsin, Mr. Guido Rahr of Manitowoc, Wisconsin, and the University of Notre Dame Estate of Land O'Lakes, Wisconsin, is greatly appreciated.

And finally, I wish to thank my wife for her invaluable aid and incomparable patience.

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PART I

EXPERIMENTS WITH ICE-FREE LAKES

INTRODUCTION

The states in the vicinity of the Great Lakes, U.S.A., can truthfully boast that their inland lakes number in the thousands and that there are, in addition, an uncounted number of unnamed basins. This is quite true, but under close scrutiny, the reason why many basins remain unnamed, may be discerned. It is because in most instances these lakes present an exceedingly poor, if not hostile environment to the fishes. Consequently, for man's purpose in our present economy, they contribute little to the fishery of either the sport or commercial category. While they present a problem to the fish manager, they offer to the experimental limnologist a manageable unit for testing his theories on the dynamics of lakes as well as a unit for applying his findings to management.

One of the objectives of the investigators at the University of Wisconsin Hydrobiological Laboratory has been to study limnological problems by the experimental method (Hasler and Einsele, 1948) by modifying certain environmental factors in a small lake in order to appraise the effects.

Numerous researchers in the past have sought to modify the chemical environment of bog lakes in order to render them suitable and increase their carrying capacity for fish: Smith (1948), Ball (1950), Hasler *et al.* (1951), Johnson and Hasler (1954), Waters (1956) and Zicker *et al.* (1956).

Some of the approaches to the problem have met with limited success, but all of them have contributed to our knowledge of limnology.

In the course of investigations concerning the productivity of small brown-stained lakes in Upper Michigan and northern Wisconsin, it has been observed that great amounts of plant nutrients, for example, phosphorus, have accumulated in the profundal mud.[1] During the greater part of the year the nutrients are not available to the autotrophic forms in the euphotic zones and do not readily enter into the biological flow of energy within the basin. It has been shown that nutrient materials can pass upward through the thermocline in accordance with their respective concentrations (Hayes and Beckett, 1955). However, in certain lakes (Punchbowl and Blackbrook lakes of Hayes and Beckett, *op. cit.*) a state of equilibrium between chemicals in solution of the epilimnion and hypolimnion probably never occurs during the period of summer stratification. Consequently, excess concentrations of soluble nutrient materials do in fact accumulate in the hypolimnetic water as well as in the profundal mud.

[1]The actual phosphorus content of the muds is known to attain concentrations of 4,690 Kg/ha (Hasler, 1957).

Birge stated with regard to the overturn of lakes, that the vernal circulation period is generally less complete than the autumnal circulation even in larger lakes such as Mendota (Neess and Bunge, 1957, p. 52). This effect is more marked in the small lakes dealt with here. In the spring they fail to circulate for a sufficiently long time to resaturate the lower strata with oxygen; in fact, they often do not circulate at all. One of the chief reasons for this defection is the intense coloration of the water. The consequent rapid absorption of solar heat results in the formation of a very shallow thermocline (Berg and Petersen, 1956; Stross, 1958). The consequence of a limited vernal circulation is the drastic limitation of space imposed on all aerobic forms owing to a constriction of the living zone. This effect is particularly pronounced in a brown-stained lake because the usual allochthonous flow of organic materials from the watershed increases the demand for oxygen.

The data of Brynildson (1958) and Schmitz[1] show that certain lakes in Chippewa County, Wisconsin, usually do not circulate at all during the vernal period. Berg and Petersen (*op. cit.*) consider Lake Gribsø, which is in many ways similar to the lakes dealt with here, to be in

[1]Unpublished data, Department of Zoology, University of Wisconsin.

a transition stage approaching the "spring meromictic" type referred to by Åberg and Rodhe (1942).

The practical value of synthetically inducing a complete circulation of thermally stratified lakes appears to be quite clear - because it would enrich the surface waters with nutrients wrested from the hypolimnion and bottom soils. Moreover, it would renew the oxygen supply of the hypolimnion. Earlier suggestions and discussions of this approach have been made by Zigerli (1939), Thomas (1944), Grim (1952), Hooper *et al.* (1953) and others.

ARTIFICIAL CIRCULATION OF LAKES BY WATER PUMPING.

Attempts to circulate artificially by pumping water have previously been made by Grim (*op. cit.*). In their trials the water was transported through the thermocline in pipes. Hooper *et al.* (*op. cit.*), using a water pump to bring hypolimnetic water to the surface, did completely circulate a lake. They found that certain events of the autumnal overturn were simulated qualitatively: (a) an exchange of electrolytes between bottom-soil and water, (b) an introduction of oxygen into the lower strata, (c) a transport of dissolved and suspended substances of the hypolimnion into the zone of photosynthesis. They indicated that since no climatic seasonal changes had occurred during the course of their experiment, the biological change, primarily a phytoplankton and periphyton-increase, was due

directly or indirectly to the artificially induced circulation.

1. Cather Lake Experiments, 1952.

Cather Lake is a small kettle lake located in Chippewa County, Wisconsin (Fig. 1). Despite the fact that its long axis lies in approximately the same direction as the prevailing winds, it ordinarily does not circulate during the vernal period. The data of Brynildson (1958) for July 1 and May 3, show that such was the case in 1952.

Two exploratory experiments were initiated in order to test the possibilities of inducing water circulation by means of ordinary water pumps of low capacity.

In the first test the intake of the pump was located near shore in the epilimnion at less than one meter below the surface. The discharge was in the hypolimnion at the ten meter-depth. The rate of discharge of the pump was measured and the pumping of water from the epilimnion into the hypolimnion was begun. This treatment continued for 18 consecutive hours, during which 410 m^3 of water were displaced.

The pre-treatment and post-treatment physical and chemical data obtained are shown in Table I.[1]

[1]For descriptions of all methods and routine procedures employed in these investigations, consult the appendix below.

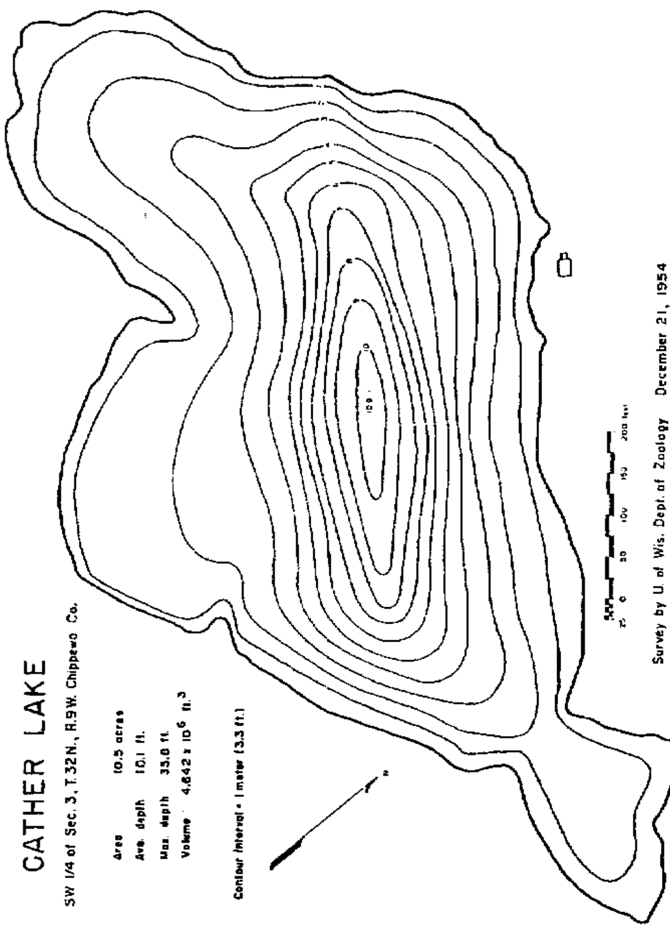

Fig. 1. Map of Cather Lake (Chippewa Co., Wisconsin)

Table I. Temperature and dissolved oxygen data for Cather L. before and after the pumping of epilimnetic water.*

Depth m	Pre-treatment 1400 CST 24 July		Post-treatment** 0900 CST 27 July	
	Temp. in °C.	DO in ppm	Temp. in °C.	DO in ppm
Surface	27.1	--	26.4	--
1.0	25.3	7.4	26.3	8.1
2.0	24.6	7.2	25.3	8.2
3.0	19.9	7.4	20.3	8.1
4.0	14.0	4.2	13.6	3.4
5.0	9.1	0.3	9.1	0.2
6.0	6.7	0.0	7.4	0.0
7.0	6.1	--	7.0	--
8.0	5.9	--	6.9	--
9.0	5.6	--	6.9	--
10.0	5.5	--	6.7	--

*Pumping started at 0840 CST 25 July 1952 and stopped at 1545 CST 26 July 1952.

**Ave. of 3 stations.

In the second test, the intake of the water pump was located in the hypolimnion at the 9 meter-depth. The discharge was simply spilled out onto the surface of a floating raft which was anchored over the deepest water on the lake. The pump unit was aboard the raft.

The pump's rate of discharge was measured and the displacement of the hypolimnetic water was begun. Approximately 1550 m^3 of water were pumped during the next 80 hours of operation.

A slight lowering of the isotherms was detected. (See Fig. 3.) The temperature and dissolved oxygen data are recorded in Table II.

Only 0.3% of the lake's volume was pumped in the first trial (25-26 July). Nevertheless, the effect of this amount of warm water forced into the cold hypolimnion was measurable. A vertical convection current was established above the pump outlet. This water was not directed in the manner employed by Grim (1952) but instead Archimedean forces created a thermally heterogeneous column of water of one to two m diameter over the discharging orifice. The temperature measurements were erratic in this column, indicating probable mixing of the less dense, warm water as it moved upward. The temperature of the hypolimnion was modified by approximately that amount which would be expected from the mixing of 410 m^3 of 26° C. water with the

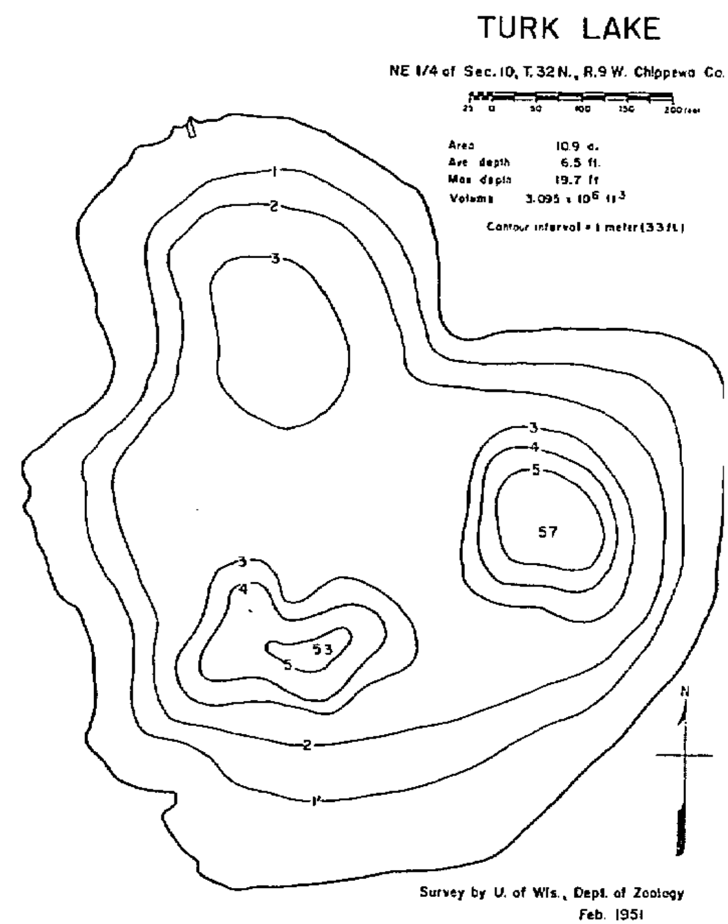

Fig. 2. Map of Turk Lake (Chippewa Co., Wisconsin)

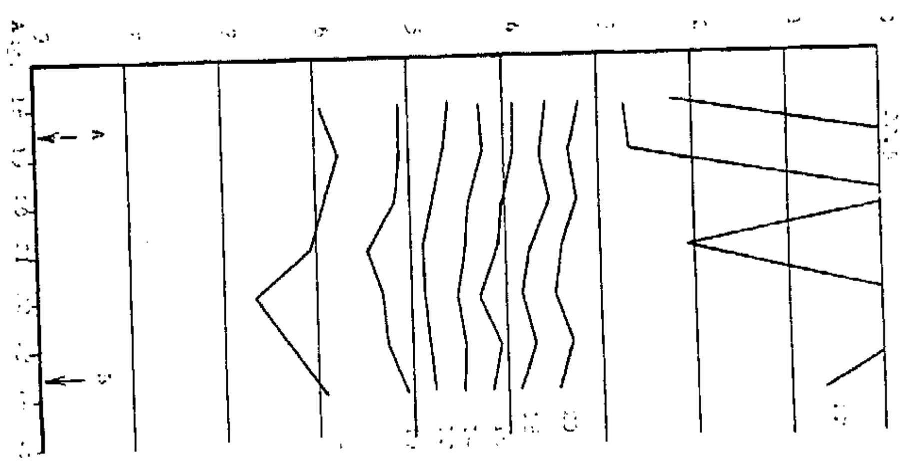

Fig. 3. The effect of pumping hypolimnetic water into the epilimnion, on thermal stratification, Cather L., 1952

Table II. Temperature and dissolved oxygen data for Cather L. before and after the pumping of hypolimnetic water.#

Depth meters	Pre-treatment##		Treatment##				Post-treatment##	
	0714 CST	18 Aug.	0752 CST	20 Aug.	0859 CST	22 Aug.	0858 CST	24 Aug.
	Temp. °C.	DO ppm	Temp. °C.	DO ppm	Temp. °C.	DO ppm	Temp. °C.	DO ppm
Surface	22.7	--	21.9	--	21.9	--	22.1	--
1	22.6	7.9	21.7	--	21.7	--	21.9	8.4
2	22.5	7.8	21.7	--	21.5	--	21.6	7.9
3	21.2	6.6	21.3	7.1	21.3	7.7	21.2	7.6
4	15.4	0.6	16.0	1.1	13.6	1.6	16.9	1.6
5	10.2	0.1	10.7	0.7	11.2	0.2	10.2	0.2
6	8.0	--	7.8	0.7	8.2	Tr	7.9	0.2
7	7.2	--	7.1	0.0	7.3	0.0	7.1	0.0
8	6.9	--	6.8	--	6.9	--	6.8	--
9	6.7	--	6.7	--	6.7	--	6.7	--
10	6.5	--	6.5	--	6.6	--	6.5	--

#Treatment started on 1032 CST 18 Aug. and stopped at 1215 CST 23 Aug. 1952.

##Average of two stations.

known volume of the lake below five meters at an average temperature of 6.7° C. The actual average post-treatment temperature of the zone below the five meter-depth was 7.3° C. (from Table I). The calculated temperature expected was 7.1° C.

The changes in the oxygen concentrations are not interprotable. Changes of dissolved oxygen in the epilimnion naturally occur from day to day. It is perhaps significant in the light of later work, that a decrease in the oxygen concentration was measured at the 4 and 5 meter levels. While this change appears to be quite small (Table II), the oxygen-concentrations measured in the vicinity of the water discharge were 1.3 ppm and less than 0.1 ppm (trace) for the 4 and 5 meter-depths respectively. Later experiments demonstrate this effect more clearly.

In the second trial, about 1.2% of the lake's volume was displaced.

It is evident from these preliminary trials, that greater amounts of energy would be required in order to obtain significant effects.

2. Sawmill Pond Experiment, 1954.

Investigations of phosphorus-release from the soils of a lake were conducted by Dr. Eldon Zicker of the University of Wisconsin Zoology and Soils Departments during 1954. He planned to circulate artificially a very small lake after

enriching the hypolimnetic water with radiophosphorus. The hypolimnetic water was to be pumped in the manner of the Cather L. experiment (Aug. 1952). The marked phosphorus within the basin would be presumed to generally participate in the phosphorus cycle such as that demonstrated by Hutchinson and Bowen (1947).

My participation in this experiment was primarily to implement the actual circulation of the experimental lake and obtain what information was afforded. The measurement of tracer material, phosphorus analysis and a major portion of the limnological measurements were performed by Dr. Zicker. The material presented here represents only that which serves to illuminate the process of artificial circulation.

A miniature lake, Sawmill Pond (Fig. 4) was chosen for the experiment because it has characteristics typical of the brown-stained bog lakes of the area. It has a maximum depth of 7.1 m and a mean depth of 4.0 m. Its surface area is 1,250 m^2 and it contains 4,990 m^3 of water.

After the temperature and oxygen-conditions of the basin were measured, two units of diluted radiophosphorus were pumped through a hose into the hypolimnion on 2 October 1954. Two centrifugal water pumps were previously installed on the margin of the lake. The intake hoses were suspended so that their orifices were 6 meters below the

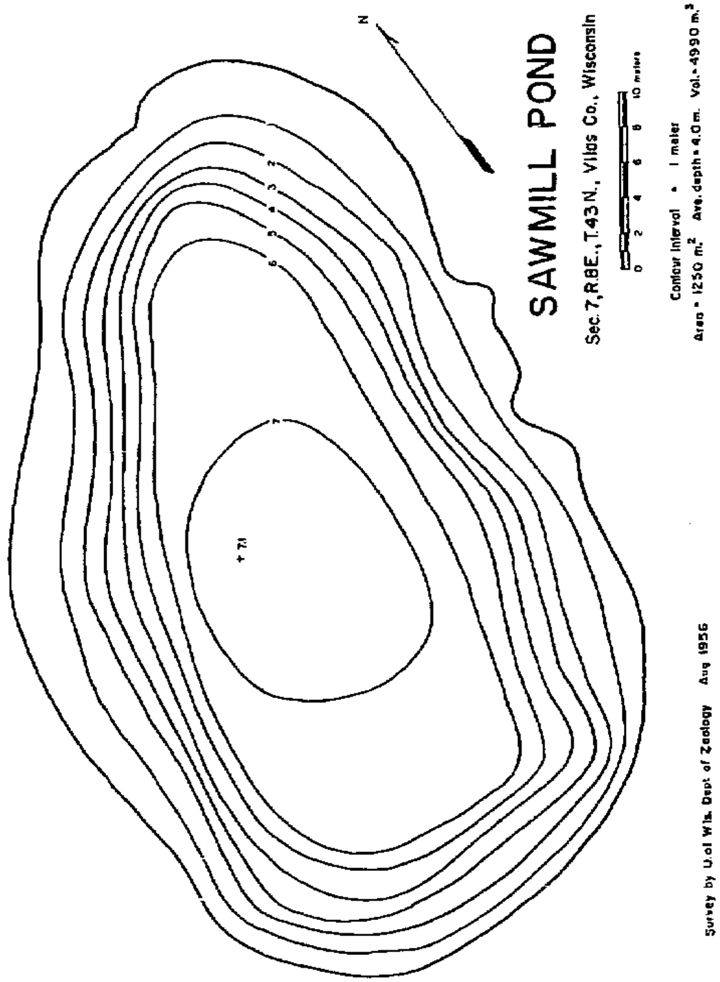

Fig. 4. Map of Sawmill Pond, Vilas Co., Wisconsin

surface. The discharge hoses were placed so that the water would flow onto the bog edge and then drain back into the pond.

The pumps used had a combined pumping capacity of about 14.1 m^3 per min., powered by eight horsepower each. Additional information regarding the pumping equipment employed is furnished in the appendix.

The pumps were turned on at noon, 3 October, 1954 and allowed to run continuously until noon of 7 October. During this time daily temperature and oxygen measurements were made. Quantities of water for later radiophosphorus determinations were collected at various depths.

The effect of pumping on the thermal stratification of the pond is shown in the diagrammatic representation of the installation in Fig. 5. A nearly homoiothermic condition prevailed above the level of the intake orifice after the first 24 hours of pumping. There was only a very slight increase in the absolute heat content of the pond during the period of circulation. The average temperature of the various strata obtained by planimetric integration of the temperature-depth curve, multiplied by the known volume of the respective strata gave 47.2 x 10^3 ton-calories of heat for the absolute heat-energy content on 7 October, and 47.0 x 10^3 ton-calories for the pre-treatment value on 2 October. It is perhaps significant that the mean daily air tempera-

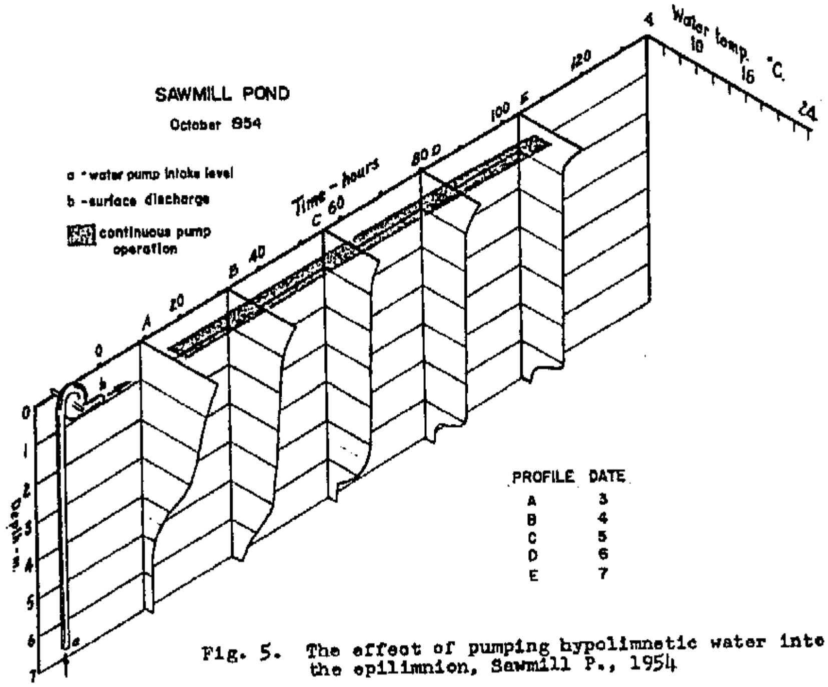

Fig. 5. The effect of pumping hypolimnetic water into the epilimnion, Sawmill P., 1954

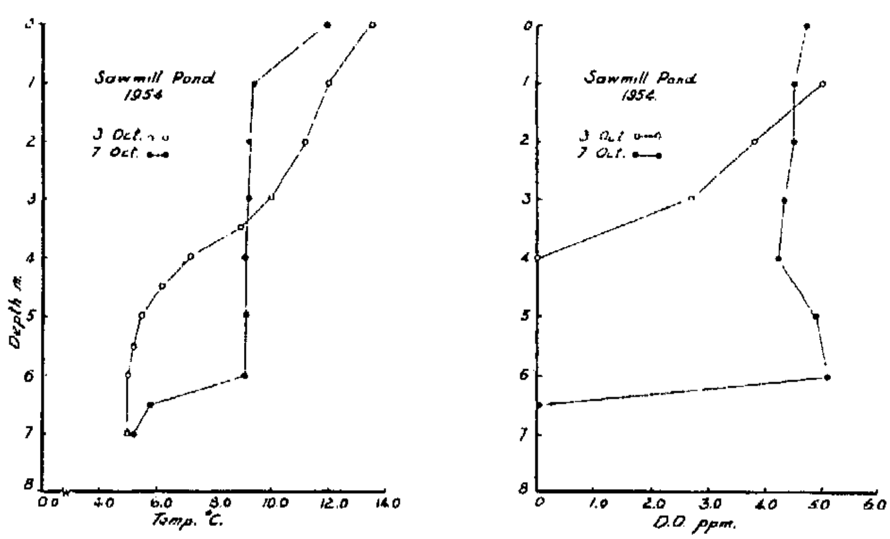

Fig. 6. Pre-treatment and post-treatment temperature and dissolved oxygen values in Sawmill Pond, 1954

ture during this period (U.S. Dept. Comm., 1954) fluctuated above and below the temperature of the homoiothermic water.

Unfortunately, dissolved oxygen measurements were made only before and after the treatment. Consequently, while it was determined that a considerable increase in the absolute quantity of this element occurred, the daily rate of apparent aeration was not determined. Figure 6 shows the pre-treatment and post-treatment values of dissolved oxygen and their distribution in the basin with relation to the prevailing water temperature. The average dissolved oxygen concentrations of the various strata, obtained by planimetric integration of the dissolved oxygen-depth curve and the known volume of the respective strata, gave a value of 14.2 kg. of oxygen and 21.6 kg. of oxygen for the absolute pre-treatment and post-treatment values.

The significance of this oxygen change, the associated induced circulation, and the stability of the basin will be dealt with in a discussion to follow.

With regard to this experiment, Hasler (1957) indicates that: (a) no contamination of the epilimnion occurred upon addition of P^{32} to the lake, (b) P^{32} was rapidly disseminated vertically throughout the basin, (c) the P^{32} was rapidly extracted from the water at all levels, (d) the rate of disappearance of P^{32} was greater in the euphotic zone.

Table III. Activity of water enriched with radioactive KH_2PO_4 in the hypolimnion of Sawmill P. (Hasler, 1957).

Date 1954 Oct.	Depth m	Counts/sec.	C/sec. minus background*	Corrected counts/sec.
3	0	0.54	0.00	0.00
	2	0.52	0.00	0.00
	4	0.51	0.00	0.00
	6	3.82	3.28	3.61
4	0	2.56	2.02	2.22
	2	1.55	1.01	1.64
	4	1.34	0.80	1.30
	6	1.59	1.05	1.97
5	0	1.57	1.03	2.46
	2	1.47	0.93	1.51
	4	1.22	0.68	0.75
	6	1.44	0.90	2.33
6	0	1.72	1.18	2.22
	2	1.70	1.16	2.18
	4	1.43	0.89	1.67
	6	1.50	0.96	1.80
7	0	--	--	--
	2	1.55	1.01	1.01
	4	1.20	0.66	0.66
	6	1.39	0.85	0.94
16	0	--	--	--
	2	0.94	0.40	0.54
	4	0.89	0.35	0.47
	6	1.03	0.49	0.66
24	0	--	--	--
	2	0.57	0.03	0.00
	4	0.47	0.00	0.00
	6	0.53	0.00	0.00

*Background reading determined to be 0.54 c/sec from vertical series of samples taken Oct. 2.

ARTIFICIALLY INDUCED CIRCULATION OF LAKES

BY COMPRESSED AIR

The results of the 1954 field experiments and the corroborative information from the laboratory suggested the continuation of a search for more effective methods of inducing artificial circulation. Preliminary laboratory experiments (Hasler, 1957) suggested that it would be possible to employ an "air lift" technique for the upward displacement of hypolimnetic nutrients. This technique would, it was thought, accomplish circulation in a considerably more efficient manner than by water-pumping by taking advantage of the turbulent force of bubbles of compressed air released along the lake bottom.

The experiments described below were undertaken to supplant the former water pumping procedure used in the field - the primary objective being the transport of nutrient material to the surface water (euphotic zone). At the inception of the trial, consideration was given to the fact that the "air lift" possibly would not destroy the thermocline, but rather would serve to transport water containing dissolved or suspended nutrient material upward. Thus, the thermocline would be disturbed, but it would remain intact. This would be considered to be most ideal since it was considered desirable to preserve the identity of the cold water zones.

The introduction of compressed air into natural waters is used extensively for many purposes. The chief objectives are to increase the oxygen-content of lakes or streams or to remove the ice from water surfaces. Wagner (1956) describes a number of applications using this technique, some of which were proposed as early as 1929 (Bach).

1. Sawmill Pond experiment, 1956.

Sawmill P. (Fig. 4) was chosen for the initial trial. Conditions of temperature and oxygen typically found in late summer are shown in Fig. 7.

A semi-rigid plastic pipe of 36.6m x 31.8mm (inside diameter) was suspended just over the bottom of Sawmill P. The underside of the pipe was previously perforated with 72 regularly spaced holes of 1.6 mm and 2.0 mm diameters. These sizes were so selected so as to produce an equitable distribution of air. In order to compensate for variations in hydrostatic pressure created by the slope of the littoral zone, 19 holes were subsequently closed. Fairly good distribution of air was obtained with an average line-pressure of 1.7 atmospheres. Since the pressure in the pipe was uniform across the length of the pipe, it was possible to calculate the rate at which the air was delivered: 351 l. of free air/min. at standard conditions (0° C., 1 atm.)

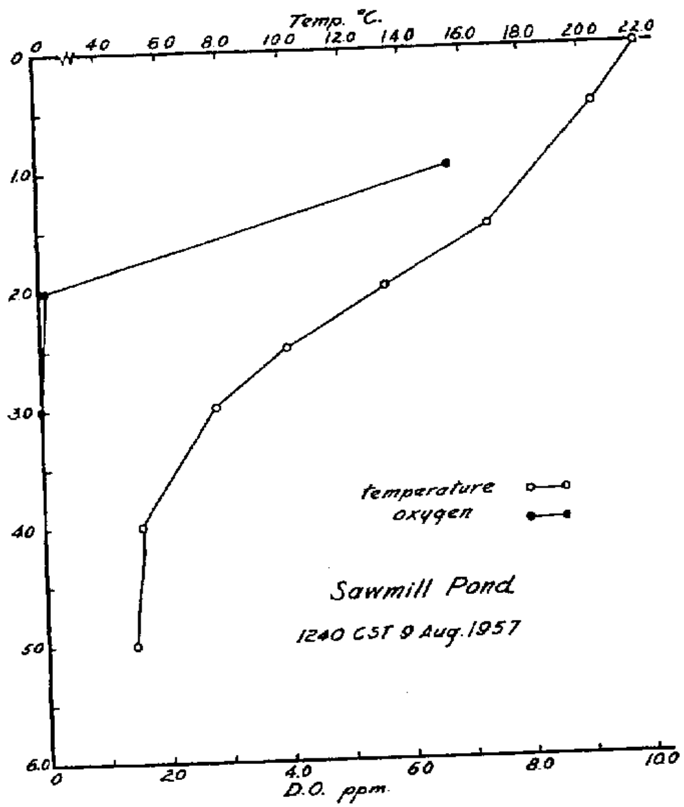

Fig. 7. Typical temperature and dissolved oxygen values for Sawmill Pond in August

were delivered to the lake with a piston-type gasoline driven air-compressor.

Measurements of transmission of light, temperature, dissolved oxygen and total phosphorus were made during the trial.

The air-treatment was begun at 1515 CST, 10 August and continued until 1940 CST of the same day. The treatment was repeated again and the thermal history was recorded as shown in Fig. 8.

The entire installation was moved to Tuesday L. on 13 August, and the treatment was begun on this lake at 0945 CST, 14 August and continued until 1430 CST, 16 August.

Temperature Changes in Sawmill P.

With the onset of pumping, the hypolimnetic water began to upwell through the epilimnetic water (see Fig. 9). Convection cells appeared in perpendicular relation to the length of the air-conductor. An almost complete homoiothermal condition was observed after four and one-half hours of treatment. This circulation may have occurred during the 4.2 hours of the initial pumping period. However, it was impossible to detect the exact time because of the interval between temperature measurements. The profile of the temperature of Sawmill P. before treatment and the subsequent changes owing to applications of compressed air are shown in Fig. 8.

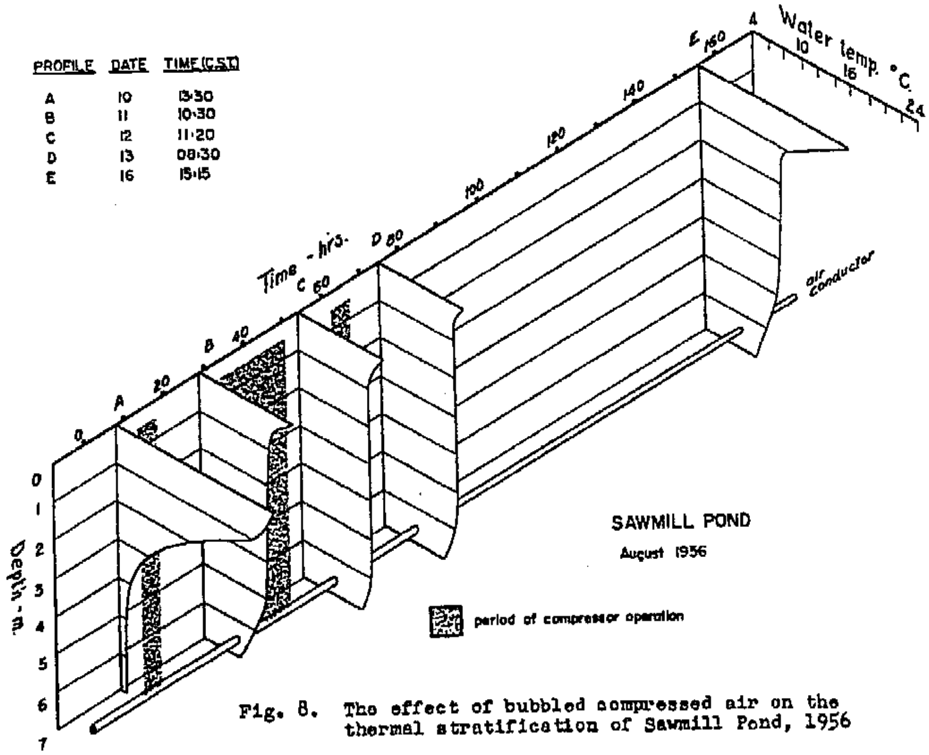

Fig. 8. The effect of bubbled compressed air on the thermal stratification of Sawmill Pond, 1956

Fig. 9. Surface agitation created by "air-lift" in Sawmill Pond, 1956

The distribution of heat-energy within the basin was radically altered and the absolute heat-content increased somewhat. For the period including 9-13 August the absolute heat-content increased by about 11.2%, or from 58.8×10^3 to 65.4×10^3 ton-calories. The increase of heat-content continued after the pumping ceased, and on August 16 the basin contained 72.6×10^3 ton-calories of heat-energy. The mean daily air temperature during this period was higher than the temperature of the surface water after the commencement of artificial circulation. These values are shown in Table IV.

Effect on the Content of Dissolved Oxygen

The effect of the induced circulation upon the total, dissolved oxygen-content was very extensive when compared with the effect upon the total heat-content. It can be seen in Table V that the dissolved oxygen-content of the basin was reduced from 11.4 kg. to 6.9 kg. after the initial treatment period. This rapid loss of oxygen was probably a reflection of the oxygen demand of the lower strata of water and associated humic materials. The rate of loss was 0.047 mg./cm^2/day for the 1.9 days after pre-treatment measurements were made. For this computation, the surface of the lake was considered as the basic area.

A rapid increase in dissolved oxygen was observed after the additional periods of treatment as shown in

Table IV. Temperatures, absolute heat-content and mean daily air temperatures for the Sawmill P. experiment, August 1956.

Date Aug.	Ton-cal. x 10^3	Mean water temp. °C.	Mean temp. of upper meter °C.	Mean daily air temp. °C.
9*	58.8	11.8	21.4	19.7
10*	60.4	12.0	22.6	20.3
11	58.3	11.7	13.2	19.4
12	62.4	12.5	13.3	18.4
13	65.4	13.1	13.6	20.2
14**	--	--	--	21.6
15**	--	--	--	21.4
16**	72.6	14.6	19.0	18.9

*Pre-treatment.

**Post-treatment.

Table V. The vertical distribution of dissolved oxygen in Sawmill P. during artificial circulation, August 1956.

Stratum m	Mean dissolved oxygen in ppm: 9 Aug. Pre-treatment	11 Aug.	12 Aug.	13 Aug.
0-1	7.8	1.8	5.6	4.4
1-2	3.6	1.6	5.1	4.3
2-3	0.6	1.4	4.8	4.2
3-4	0.0	1.4	4.9	4.1
4-5	0.0	1.3	5.0	4.1
5-6	0.0	0.8	5.2	4.1
6-7	0.0	--	5.4	4.0
Mean DO entire basin ppm	2.5	1.0	5.1	4.2
Absolute DO content	12.3 kg*	6.9 kg	25.7 kg	21.0 kg

*This value is obtained if it is assumed that the first meter of water was 95% saturated at 20.4° C. A more realistic saturation of 85% gives a value of 11.4 kg.

Fig. 8. The effect of the wind and general climatic conditions in augmenting this increase was considered negligible because of the small area of this lake, the protection afforded by the hilly nature of the terrain and the relatively stable condition of the weather during the experimental period.

Changes in the Distribution of Phosphorus

An analysis of the soluble phosphorus-distribution for this experiment (Sparr, 1958) suggests that it was transported into the upper strata of the lake during the course of artificial circulation. Tables VI and VII show pertinent portions of the data concerning this distribution. The range of values among samples taken at two horizontal stations before treatment seems so wide as to preclude satisfactory description of the actual events. However, it is noteworthy that the absolute content of the soluble phosphorus in the upper two meters was higher in every case than the mean of the pre-treatment values. It is also shown that the high concentration of soluble phosphorus in the 2-3 meter stratum was dissipated.

Effect on the Transmission of Light

Measurements of light were made before treatment at 1330 CST, 10 August and again at 1030 CST, 11 August after 4.2 hours of induced circulation. No change in the per-

Table VI. The distribution of soluble phosphorus expressed in grams per one meter stratum, for the artificial circulation experiment, Sawmill P., August 1956.

Stratum	1200 CST, 9 Aug. Sta 1	Sta 2	Ave (pre-treatment)	1130 CST, 11 Aug. Sta 1	Sta 2	Ave	1200 CST, 12 Aug.	2030 CST, 12 Aug.	2030 CST, 12 Aug.	0800 CST, 13 Aug.
0-1	3.7	6.6	5.1	5.9	7.4	6.6	6.2	6.7	7.6	5.2
1-2	5.1	0.8	2.9	5.0	7.8	6.4	5.4	6.2	8.7	4.3
2-3	10.2	10.3	10.3	3.6	4.7	4.1	6.0	2.8	3.6	3.7
3-4	2.7	3.5	3.1	4.8	3.2	4.0	5.4	3.3	3.8	1.1
4-5	4.5	4.0	4.3	3.1	3.3	3.2	5.4	2.4	2.1	3.1
5-6	--	2.4	--	4.2	4.5	4.4	3.2	3.1	2.3	4.0
Total		27.6		26.6	30.9	31.6	24.5	24.5	28.1	21.4

Table VII. The concentration of mean total phosphorus in micrograms per liter in the euphotic and aphotic zones, Sawmill P., August 1956 (Hasler, 1957).

Date Aug.		2.0-5.5 meters (aphotic zone)	Upper 2 meters (euphotic zone)
9	pre-treatment	21.9	15.8
10	after initiation of treatment	19.4	19.3
11		17.1	17.1
12	1200 CST	20.5	21.0
12	1800 CST	13.7	41.0
12	2030 CST	18.9	20.4

centage of surface radiation transmitted at any depth was observed.

2. Tuesday L. experiment, 1956.

An attempt to confirm the concept of artificially induced circulation was conducted in nearby Tuesday Lake (Sec. 36, R42W, T45N, Gogebic Co., Mich.). This lake has a maximum depth of 17 m and an estimated mean depth of 8-9 m. It has an area of about 3 ha and contains approximately 25 x 10^4 m^3 of water. The dimensions presented for this lake were based upon a brief preliminary examination since no hydrographic map was available.

The effect of the air-treatment on Tuesday L. was similar to that observed in Sawmill P. The surface water was cooled from 24.8° C. to 13.0° C. and the lake became essentially homoiothermal at 11.0° C. between the 0.5 m and the 9 m depths after a maximum of 19 hours of treatment. When the end of the air conductor was lowered to the 14 m level, homoiothermal conditions were extended to that depth, after an additional five hours of treatment.

The concentrations of oxygen decreased in the region that originally constituted the epilimnion, from 7 ppm to 1 ppm after the first 19 hours. This initial loss of oxygen was also observed in Sawmill P. during the artificial circulation of that lake (10-13 Aug. 1956).

No other measurements were made on Tuesday L.

3. Tub L. experiment, 1957.

The thermal stratification in the Sawmill P. experiment of 1956 was completely destroyed within four hours after initiation of the treatment. It was obviously impossible to ascertain whether or not the air-lift technique could have transported soluble or other forms of nutrient material through an "intact" thermocline.

The preservation of a thermocline is considered desirable under certain conditions: (a) in instances where the thermal and chemical stratification is such that rapid circulation would rapidly deplete the oxygen level or introduce anaerobic decomposition products into the living zone of fish or other aerobic forms, (b) where the introduction of sufficient amounts of air to disrupt the thermocline might prove to be impractical. An experiment to test the effect of reduced amounts of turbulence was conducted in Tub L. in 1957.

Tub Lake (NW 1/4 of Sec. 11, T32N, R9W, Chippewa Co., Wis.) is a small, nearly cup-shaped kettle lake. It is partly surrounded by bog margins and its water is characteristically deeply stained. No hydrographic map is available for this lake, but fairly accurate dimensions were obtained in the process of installing an air conductor under its surface. The lake is elliptical with semiaxes of about 53 m and 43 m. Its area is roughly 7200 m^2. Its mean depth is approximately 3.0 m and its volume is 2.16×10^4 m^3. The maximum depth is 7.7 m.

Prior to 21 September 1957, a semi-rigid plastic air-line was suspended in Tub Lake in the same manner as described above for the pipe in Sawmill P. Ten holes of 0.82 mm diameter were drilled in the pipe (2.54 cm inside diameter). Difficulties encountered in the suspension of the pipe over the bottom caused the holes to be suspended irregularly at the following levels: 2.8, 3.2, 3.5, 3.6, 4.0, 4.3, 4.6, 5.0, 5.2, and 6.0 m.

On 21 September pre-treatment measurements of temperature, dissolved oxygen, total and soluble phosphorus, pH and light were made. Three hundred millicuries of radiophosphorus were added to the hypolimnion at about the 5.5 meter level. Subsequent sampling of the isotope and the related work of this experiment is treated by Sparr (1958).

At 1930 CST, 22 Sept., a gasoline-driven air compressor was connected to one end of the air pipe. A pressure of 1.05 kg./cm^2 (gauge) or 2.02 atmospheres (absolute) was maintained in the pipe during the next twelve days. The size of the air conductor was large enough to eliminate significant losses of pressure in the line; consequently, the pipe for purposes of computation was considered as a

plenum chamber for the small volume of air flow delivered. Calculations based upon the head of pressure in the pipe and the corresponding hydrostatic pressure for the orifices used (see Crane, 1942) indicate that 84.7 liters of free air (0.0° C. and 760 mm pressure) were delivered to the lake each minute.

On 3 October the pipe was opened so that the air was released, in effect, through a 25.4 mm orifice and was lowered to a depth of seven meters near the center of the basin. The full delivery of the compressor was used and an estimated 700-800 liters of air per minute (std. condition) was pumped during the next 12 hour period.

The temperature of nearby Cather Lake was measured on 26 September and 5 October for use as a reference with regard to the local climatic effect upon the thermal conditions in an untreated basin.

The results of the above trial are summarized in Table VIII. There occurred a steady descent of the thermocline. For purposes of this paper it has been considered most convenient to use the upper boundary of the thermocline defined as: the intersection of the tangent to the depth-temperature curve whose slope is equal to unity when plotted on x and y ordinates in °C. and meters, respectively. This generally used, arbitrary definition serves very well to demonstrate the movement of the thermocline in temperate

Table VIII. Miscellaneous data for circulation experiment on Tub-Cather lakes (21 Sept.-5 Oct. 1957).

	Lake	Depth UBT m	Ave. L. temp. °C	Tot. heat t-C x 10^3	Ave. DO ppm	Tot. DO kg	Air discharge below UBT l/min.	Hours pumping (total)	Tot.* air vol m3
Sept. 21	Tub	3.2	14.3	308	5.2	112	--	0	0
23	"	3.5	14.0	301	5.2	112	68	21.4	106
24	"	3.7	14.2	305	5.3	114	51	36.4	175
25	"	4.3	14.3	308	5.2	112	42	54.9	264
Oct. 4	"	4.7	13.8	296	6.1	132	25	230	1100
5	"	6.7	14.3	307	6.5	140	750	242	1680**
Sept. 26	Cather	5.4	15.1	1970					
Oct. 5	"	5.8	14.5	1890					

*Rate = 4.8 m^3/hr.

**Rate = approx. 45 m^3/hr.

lakes of this type. In almost every case considered here the so-called "knee" of the temperature-depth curve at the upper boundary of this layer was very sharp and more easily determined than, for example, the inflection point of the temperature-depth curve.[1] Minor "knees" in the temperature curve created by surface radiation or artificial turbulence in the epilimnion are ignored. It should be noted in this connection that in the lakes under observation, the chemical stratification is usually so sharp that little confusion can occur in the interpretation of the upper thermocline boundary (henceforth referred to as UBT in this paper).

By 4 October the UBT had descended to the 4.7 meter level, a change which exceeded the natural descent of the corresponding boundary in Cather L.

The absolute dissolved oxygen-content increased at a relatively low rate. No apparent increases of dissolved oxygen were found below the thermocline at any time.

Sparr (1958, p. 51) reported that radiophosphorus was brought through the thermocline during this period, without destruction of that layer (see Table IX).

[1]Hutchinson (1957, p. 428) selected the point of inflection as the definition of the thermocline. For general use it is certainly the more desirable.

Table IX. Concentrations of radiophosphorus in Tub L. as affected by agitation with compressed air (modified after Sparr, 1958, p. 49).

Depth m	Concentration of P^{32} at station M in disintegrations/sec./1					
	Sept. 22*	23	24	25	Oct. 4	5
2.0	0.3	7.1	2.4	1.0	2.2	0.0
3.5	0.0	6.5	2.2	0.8	1.9	1.5
5.5	6.6	27.1	24.2	12.9	2.0	1.4
UBT (m)**	3.2	3.5	3.7	4.3	4.7	6.7

*Application of radiophosphorus made on 21 Sept. 1957. Bubbling began after sampling on 22 Sept. 1957

**Relative level of the UBT or upper boundary of the thermocline = -------

CONCLUSIONS

The results of these six trials of artificial circulation during periods of open-water, while not directly comparable because of changes in the technique employed, do offer some interesting contrasts with regard to their effect.

1. Phosphorus

The upward transport of phosphorus by artificial circulation, as observed in the Sawmill P. 1954, 1956, and Tub 1957 trials, was accomplished. Quantitatively, the net increase in the euphotic zone was small, although the true contribution of phosphorus to this zone may be masked by the dynamic characteristics of this element. The rapid losses of the tracer element, as shown in Table III, confirm this.

The radiophosphorus can be forced upward through the thermocline without disruption of this layer as was shown in Tub Lake, Table IX, by very small amounts of bubbled air (77.4 l/min. in Tub, 1957). The displacement of phosphorus, however, is accompanied by a corresponding downward displacement of the thermocline.

The general effect of circulation on the phosphorus distribution was similar to that reported by Hooper et al. (1953). The major difference is the ease with which this effect was realized using air turbulence instead of water-pumping procedures. The comparison between these two methods can best be visualized by an examination of the amount of work expended.

2. Temperature

From the temperature measurements of the 3 trials described above (1954, 1956 and 1957) and from the results of Hooper _et al._ in 1953, it appears that the mean temperature of the lake, as a result of artificial circulation, changes very little, e.g., + 0.2° C. in Sawmill P. (1954), + 1.1° C. in Sawmill P. (1956), 0.0° C. in Tub L. (1957), and - 0.3° C. in West Lost L. (Hooper _et al._, _op. cit._). Since there is no information available regarding the amount of insolation, or of the air temperatures (other than mean daily temperatures from nearby stations), or the actual flow of surface water during the periods of circulation, an interpretation of the minor gains or losses of total heat is impossible.

For some purposes the change in the distribution of heat is more pertinent when compared to the resulting concentrations of oxygen. Table X shows that, in every case, the zone that is considered to be indefinitely habitable for trout or the "living zone"[1], was greater

[1]Bryniildson (1958, p. 91) considers the "living zone" for trout as that stratum of water in which the oxygen tension is at least 3 ppm.

Table X. Effect of artificial circulation on the volume of the habitable stratum for zooplankton and trout.*

Lake	Year	Zone	% Change
West Lost	1952	trout	210 increase
		zooplankton	20 "
Sawmill	1954	trout	89 "
		zooplankton	48 "
Sawmill	1956	trout	1300 "
		zooplankton	170 "
Tub	1957	trout	31 "
		zooplankton	29 "

*Lower oxygen limit for trout = 3 ppm (Bryniildson, 1958, p. 92).
Lower oxygen limit for zooplankton = 0.3 ppm (Johnson and Hasler, 1954).

in volume after the treatment period than before. Black (1953) found 22.4° C. as the upper limit in which this species can survive for 24 hours (acclimation temperature 11° C.). This suggests that in every case considered here, the upper temperature limits were not exceeded.

Two of the lakes treated in this study are known to contain warm-water fish. Inspections of the littoral areas did not reveal any losses that could be ascribed to temperature shock.

3. Work required to induce circulation

The actual work applied to the lakes in the above trials can be crudely estimated by considering the amount of horsepower required to induce a given degree of change in the lake in a segment of time. The work in this case is the horsepower-rating of the equipment employed x the hours of operation (hp-hrs). This unit of work is used to compare the effectiveness of the water-pumping procedure with the "air-lift" technique. It is not assumed that the work applied to the water in these two processes is proportional to the work expended through the machinery. It means only, that for a given effect, a certain quantity of work was actually done by the equipment. For comparing the effects of various degrees of "air-lift" treatment, it is felt that the work done by the expanding bubbles was probably close to the real amount of work applied to

the water. Therefore, the theoretical work-input[1] is used for comparing effects. The theoretical work is that amount of work done in the expansion of the bubble, as it rose from the point of discharge to the surface of the lake. The question as to whether this expansion is an adiabatic, polytropic or isothermal process is open, pending further investigation. For the calculations employed in this report the compression is considered to be isothermal. If later calculations or experimentation indicate that the expansion of the rising bubble is polytropic or adiabatic, then the work expended would be correspondingly higher by some amount less than 30% (see O'Neil, 1939).

The maximum expenditure of work required to circulate Sawmill Pond with air-turbulence, in 1956, was 3.37×10^3 m-t or 12.5 hp-hrs. The circulation of the same basin in 1954 when water pumps were used (see Fig. 5) required nearly ten times this amount of work. Moreover, the stability[2] prior to mixing as calculated by the method of Schmidt (1915) and Eckel (1950), in the 1956 trial was at least

[1] All references to horsepower (hp) or horsepower-hours (hp-hrs) refer to power or work at the rated power of the equipment expressed in the metric system. All references to theoretical horsepower (ihp) or theoretical horsepower hours (ihp-hrs) refer to the computed theoretical power or work expressed in metric system.

[2] Stability (S) is defined as the theoretical amount of work required to oppose the gravitational forces and render a thermally stratified lake homoiothermal.

four times as great as the stability of the basin in 1954. (S = 5.60 t-m on 10 Aug. 1956, and S = 1.32 t-m on 3 Oct. 1954.)

Perhaps the efficiencies are more readily compared by noting the increase in volume of the epilimnion for each unit of work expended in the various trials. In each case only the amount of work required to lower the upper boundary of the thermocline (as defined previously) to its lowest point is considered.

Assuming that the water-pump employed by Hooper et al. (op. cit.) required 14 hp, the overall effect of their experiment amounted to an increase of 6.1 m^3 in the volume of the epilimnion for each horsepower-hour of work expended. In the 1954 Sawmill P. trial (with a water-pump) the epilimnion increased in volume by just 3.9 m^3 for each hp-hr. When bubbled, compressed air was used in this lake in 1956, the epilimnion increased 86.9 m^3 per hp-hr.

The volume increase in the 1957 Tub Lake experiment amounted to 25.8 m^3 per hp-hr, but this value was low owing to the irregular placement of the discharge-holes with relation to depth. Actually, by the time the upper boundary of the thermocline descended to the 4.7 m level, only three holes were discharging below the UBT. The volume/work ratio for the 3.2 to 4.3 meter UBT levels was 115 m^3 per hp-hr.

It was noted that this ratio decreased as the UBT approached the level of the intake of the pump where water-

pumps were used, or the level of the discharge when air-turbulence was used (see Table XI).

It can be concluded that far less work is required to mix stratified basins with the "air-lift" technique than with the water pump technique.

The Sawmill P. trial of Aug. 1956 and the Tub L. trial of Sept. 1957 afforded information with regard to the relative amounts of work needed for air-induced circulation. Since the volume of flow from the pipe was known, the work expended above the pipe by the rising bubbles could be computed from the following relationship: $w = p_1 v_1 \log_e \frac{p_1}{p_2}$,

where w = work, p_1 = the hydrostatic pressure at the average depth of the discharging air, v_1 = the volume of the discharged air at the prevailing water temperature and pressure, p_2 = atmospheric pressure.

For each m^3 of increase of the epilimnion, a calculated amount of work was expended on each m^3 of the lake above the discharge point. For Sawmill P. this calculated amount of work is 18.4×10^2 gm-cm, and for Tub L. it is 8.17×10^2 gm-cm. The value for Sawmill P. is probably high since the lake was completely homoiothermal above the discharge-pipe when the temperatures were measured.

The work performed by the expanding bubbles far exceeded the amount of work theoretically required to render the lake homoiothermal, i.e., the initial stability of

Table XI. Work requirements for the lowering of the thermocline in Sawmill P.

Yr.	Method	UBT* depth-change	Volume change (m^3)	Hp-hrs used	Epilimnetic vol. incr. per hp-hr (m^3)
54	water-pump	2m to 5m	2115	315	6.7
54	water-pump	5m to 6m	502	360	1.4
56	air-lift	0m to 5.3m	4460	11.9	375
56	air-lift	5.3m to 6m	241	44.8	5.4

*UBT = upper boundary of the thermocline.

Sawmill P. in Aug. 1956 was equal to 5.60 t-m, while the amount of work done by the expanding bubbles during the initial circulation was equal to 350 t-m. The amount of air required to do the work indicated above, was within reasonable limits for small experimental basins, e.g., Tub L.[1] in which the HBT was lowered 1.5 m in 38.5 hours with about 100 l of air/min (20° C., 1 atm).

4. Oxygen

In every test of artificial circulation, whether using water pumps or the "air-lift" technique, the absolute quantity of dissolved oxygen was higher at the termination of the treatment. There were, however, rapid losses of oxygen observed when the circulation proceeded at a rapid rate. In the Sawmill P. trial (1956), in which complete circulation was effected in 4.2 hours, reductions of oxygen tensions by dilution alone were expected to reduce the average tension to about 2.5 ppm. The actual average oxygen tension observed was 1.4 ppm. Presumably the difference represents the sum of the positive values for oxygen derived from: aeration owing to bubbling and surface agitation, photosynthesis, and the negative values for the oxygen demand within the basin. (The relative areal oxygen deficit during the time of the circulation was 0.047 mg of

[1]Tub Lake has 7200 m^2 of surface area and contains 2.16 x 10^4 m^3 of water.

O_2/cm^2/day.) The slower rate of circulation induced in Tub L. (1957) was accompanied by no comparable oxygen decreases. Evidently the rate of aeration exceeded the rate of oxygen-loss.

The overall increase in absolute oxygen-content of Sawmill P. as indicated in Table V, required an application of approximately 7.7 hp-hrs of work for each apparent kg of oxygen added. The maximum efficiency during this trial amounted to 2.4 hp-hrs of work for each kg of oxygen added. In the Tub L. trial in which air was applied at a slower rate, 11.6 hp-hrs of work were required per kg of apparent oxygen added. By comparison, the aeration procedures employed by Wiley _et al_. (as cited by Wagner, _op. cit._) on the Flambeau River (Wisconsin) added 1 kg of oxygen for each 1.1 hp-hr of work expended.

By contrast, the water pumping techniques used in this study in 1954, required 123 hp-hrs of work for each kg of oxygen added. For this series of circulation trials it can be concluded that the use of "air-lift" was more effective than water pumping for aerating natural water.

In an aeration process the ratio of the oxygen introduced to the resulting increase of oxygen is often used to compare treatments (Wagner, _op. cit._). Wagner cites the following values for various artificial aeration processes used on natural waters: 1.3% (Mercier), 2-8% (Pista equipment), 3.3-8.8% (Wiley _et al_.). This ratio is not an

expression of the amount of oxygen absorbed by the water from the air delivered. It is rather, an expression comparing the observed increase (owing to additions of oxygen from all sources) with the amount of air delivered. For Sawmill P., 1956, this "absorption" was 9.5%. For Tub L. (1957) the value was 5.5%. The very favorable conditions for oxygen absorption in the first instance, (low water temperatures and a high degree of under-saturation of oxygen) contributed to the high value of absorption.

Many of the problems encountered in these trials point to the need for future investigation. Much information is available from the field of engineering regarding air-turbulence and aeration. Additional knowledge of the general effect of artificial circulation on lakes would facilitate more effective utilization of this information.

PART II

EXPERIMENTS WITH ICE-COVERED LAKES

INTRODUCTION

The problem to which the following experiments have been chiefly addressed is that of alleviation of the winterkill of fish. Briefly stated, winterkill is the suffocation of fish in ice-covered lakes. Greenbank (1945) has dealt at length with both the limnology of the ice-covered lake and the limnological factors relating to the winterkill problem. Detailed references to the literature will be made only as required in order to illustrate or substantiate the material in this paper.

Essentially the oxygen-budget of an ice-covered lake is governed by two biological forces in opposition: on the positive side, is the photosynthetic activity of the phytoplankton; on the negative side, are the respiratory demands of the bacteria, both aerobic and anaerobic. It is believed that all other oxygen demanders play relatively minor roles and that no other sources of oxygen (including the higher plants) within the lake basin itself serve to materially augment the oxygen supply.

All inflowing water is understood to originate from without the basin, from whatever its source. It is readily seen why the small northern brown-stained lakes described

earlier are vulnerable to winterkill. They are, in many cases, seepage lakes, receiving little water during the winter months. Hence, during the winter, their source of oxygen is largely internal. This internal supply is limited by the amount of radiation transmitted through the ice. Since their volume is usually small and their heat-content correspondingly small, they become ice-covered earlier than larger lakes. In the northern latitudes of Wisconsin and Michigan such lakes are usually covered with snow shortly after the ice forms. Even a thin covering of snow drastically reduces the amount of light transmitted through the ice. For example, Birge reports that 2.6 cm and 5.8 cm of snow were sufficient to reduce the incident surface light to 5% and 1%, respectively (Neess and Bunge, 1957). (The amount of reduction varies depending on the consistency of the snow.)

Bacteria, acting as oxygen demanders, are accountable for the depletion of dissolved oxygen observed shortly after the ice-cover forms. An external factor which magnifies their role is the usual large quantity of allochthonous humic materials supplied them from the surrounding watershed.

The resultant of these two biological forces is determined by the magnitude of each during the period of ice cover. Where conditions are such that little, if any, replenishment of the initial oxygen supply is afforded, the result is more predictable. It appears to depend on the morphometry of the lake and its general position in the productivity scale. Where replenishment does occur from one source or another, e.g., late winter thaws or surface runoff, the ultimate results, in terms of the oxygen content, are highly erratic and unpredictable.

The approaches to the problem of alleviating winterkill divide into two general categories: (1) to decrease the oxygen demand, (2) to increase the oxygen supply. Many attempts at solution of the problem are listed by Greenbank (op. cit.). The first approach would include such activities as: the diversion of effluents which contain pollutants or any material which would exert an oxygen demand upon the water and, the removal from the basin of some portion of the organic material which creates the excessive demands. The second approach is to supply additional amounts of oxygen. (Greenbank chose to follow this second alternative.)

A brief summary of the main types of possibilities for winterkill alleviation are listed below:

a. Opening of holes in the ice cover.
b. Raising of the water level.
c. Diversion of flowing water from either surface or well into the lake basin.
d. Artificial aeration by means of compressed air.
e. Removal of snow-cover.

All of these have been considered by Greenbank. He found some of these possibilities to be without theoretical or practical soundness. Greenbank felt that the only reasonable possibility was removal of snow-cover. (This view was shared by Hubbs and Eschmeyer in 1938.) He suggested that this could be accomplished by pumping water from beneath the ice onto the lake surface, thus reducing the snow-cover to slush. The suggestion was accompanied by the recommendation that any attempt to augment the oxygen resources of a lake be of a preventive rather than remedial nature. It was from this suggestion that my first attempts to alleviate winterkill were given impetus.

Later accounts of work both in Europe: Schaeperclaus (1947), Puke (1950), Wagner (1956), Mercier (1954), Scheer (1948); and the United States: Hemphill (1954), suggested that perhaps Greenbank was too pessimistic in his dismissal of the other techniques for winterkill alleviation.

TRIALS WITH THE USE OF WATER PUMPS

1. Turk Lake, 1953.

The first attempt to employ the technique suggested by Greenbank was conducted on Turk Lake, Chippewa Co., Wisconsin (Fig. 2). On 31 Jan. 1953 about 230 m^2 of the lake's surface was flooded with water pumped from just beneath the ice surface. The 14 cm of snow on the lake at that time was reduced to a thin, milky-crust in the flooded area. During the pumping operation and for the subsequent 30 hours, air-temperatures of below -20° C. prevailed. Owing to these low air temperatures, the pumping equipment became inoperative and the scheduled physical and chemical sampling of the lake water became impossible.

2. Water pumping trials, 1954-56.

Periodic measurement of snow, ice, temperature and dissolved oxygen were made on various experimental lakes. In this way it was possible to predict the arrival of critical oxygen tensions for trout.[1] The species of trout maintained in all of the experimental lakes dealt with in this study was the rainbow trout (*Salmo gairdnerii*). For purposes of this study, the metabolic requirements of *Salmo gairdnerii* and *Salvelinus fontinalis* are considered to be similar.

It was considered desirable, at the prevailing winter temperatures, to maintain a minimum of at least 2 ppm and preferably 3 ppm of dissolved oxygen as a margin of safety.

[1] The upper limit of the "zone of tolerance" for speckled trout (*Salvelinus fontinalis*) is about 1.4 ppm of dissolved oxygen at 10° C. at a level of acclimation of 4 ppm (Shepard, 1955). The "zone" is defined as that zone in which the fish can exist indefinitely.

The measurement of biological oxygen demand (BOD) was not used as a technique for anticipating the expected arrival of winterkill-conditions. Its use was suggested as a crude measure of anticipated oxygen demand by Greenbank (*op. cit.*). However, a preliminary test of its usefulness in Turk and Cather lakes in 1953 gave conflicting results. It has been shown that the BOD is highest in strata containing the greatest numbers of phytoplankton and zooplankton. Such strata also contain the highest DO tensions (Greenbank, *op. cit.*) (Schmitz)[1]. Any increase in light transmission through the ice could, therefore, serve to increase the BOD. Such effects would possibly make the prediction of oxygen concentrations based on the BOD, impossible.

The high costs of the water pumping method precluded its use as a preventive measure for the alleviation of winterkill.

In all of the pumping trials in 1954 through 1956, light, portable water-pumps of the same type employed for the circulation of Sawmill P. in 1954, were used. Water was pumped from under the ice onto the surface of each lake. A typical arrangement of the apparatus is shown in Fig. 10. During the period of pumping, changes in the dissolved oxygen concentrations were measured. The treatment was

[1] Unpublished data, 1953, U. W. Dept. of Zoology.

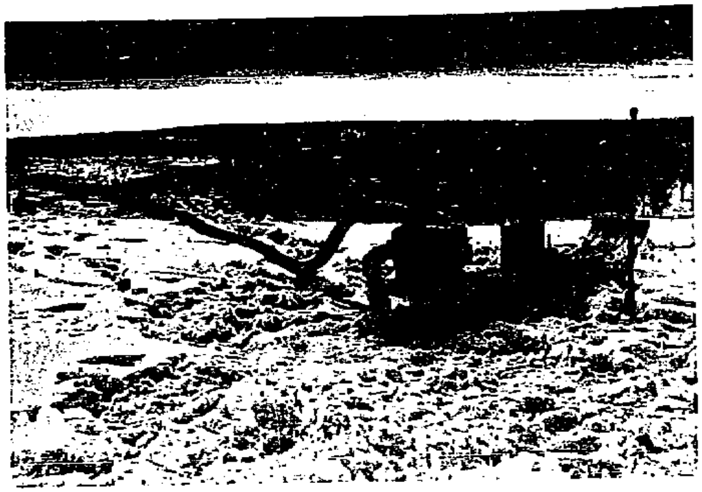

Fig. 10. Apparatus used for pumping water from beneath the ice-surface

ordinarily continued until the rate of oxygen depletion was arrested or reversed.

Accounts of the individual trials are not described here, but rather a summation of the various observations is presented.

The oxygen content of Katharine L. (6.1 ha) in Vilas Co., Wis., was measured on 5 Feb., 28 Feb. and 12 March 1954. The rate of oxygen depletion indicated that concentrations of about 1 ppm could be anticipated in the upper 1.2 m strata (as measured from the upper surface of the ice) by approximately 15-20 March. On 12 March the average DO value was 2.0 ppm. During the period of 12-20 March, about 4.32×10^3 m^3 of water were pumped from beneath the ice-surface to flood an area of about 2.0 ha. This amount of water would, if retained on the surface, have covered the flooded area to a depth of 21 cm.

The transmission of light through the ice-cover and snow in both the flooded and unflooded portions of the surface was measured on 20 March (see Table XII). The flooded portions of the lake were not reduced to a layer of clear ice. On 20 March the flooded portion actually consisted of 2.5 cm of milky ice-crust, 7.6 cm of a water-air-slush mixture and 33 cm of moderately clear ice (as measured downward from the uppermost surface). This flooded surface transmitted a greater per cent of the

Table XII. Transmission of light through the ice cover of a flooded lake. Katharine L. 1300 CST, 20 Mar. 1954.

Depth m	% of surface illumination** Flooded area (ave of 2 stations)	Unflooded area (one station)
surface	100	100
0.0*	6.6	0.34
0.2	4.0	0.21
0.4	2.6	0.13
0.6	1.7	0.09
0.8	1.1	0.06
1.0	0.65	0.04

*Measured downward using the lower surface of the ice as reference.

**From curve of readings at three levels, using a Whitney photometer mounted on an offset arm.

surface illumination than did the unflooded surface which consisted of 12.7 cm of snow above 31 cm of ice.

The phytoplankton was sampled before and after pumping in the flooded and unflooded areas. Three liter samples were obtained from just under the ice. These were filtered through #20 silk bolting cloth, preserved in formalin and analyzed according to the method of Loeffler (1954). (See Table XIII.)

The major portion of the water pumped, returned to the lake through holes cut for admission of the intake hose. The oxygen-content of the water was measured as it passed through the pump and again as it returned to the basin. The average gain in dissolved oxygen was 7.2 ppm.

The presence of the cold (.14° C.), oxygenated, returning water was detected in the upper meter of water in the entire flooded portion of the basin. Lesser amounts were detected in the remote, unflooded section. This distribution indicated that the returning water was essentially "floating" over the more dense bottom strata (4.6° C.).

During the period of pumping the average oxygen-content of the water in the first 1.2 meters below the ice surface of the entire lake increased from 2.0 to 2.3 ppm. The oxygen-content of the flooded portion increased from 2.0 to 3.3 ppm, and the unflooded section decreased

Table XIII. Phytoplankton in a lake before and after flooding. Katharine L. 1954.*

Date	Cells per liter: Pre-flooding	Post-flooding: Flooded area	Post-flooding: Unflooded area
12 Mar.	1061 (ave 3 sta)		
12 Mar.		955 (1 sta)	
20 Mar.		318 (ave 4 sta)	955 (ave 2 sta)

*Includes the following genera: Staurastrum, Hyalotheca, Radiophilum, Gleocystis, Fragilaria, Peridinium and Ceratium.

from 2.0 to 1.8 ppm. Similar results were obtained when this type of treatment was applied to other lakes during the period of ice cover.

There is an advantage to be gained in any aeration procedure if the water involved has a low percentage of oxygen-saturation. The absorption rate for oxygen in water decreases exponentially as the saturation point at any given temperature is approached. Various expressions of this phenomenon are discussed by Rand (1957). From this it is presumed that the rate of oxygen-absorption would be greater if water from the lower strata were aerated on the ice surface.

This presumption was tested in the 1955 water-pumping trial. In this trial, although the pumped water was rapidly aerated, it was not cooled enough to sufficiently reduce its density. As a result, the returning water, by virtue of its density, descended through the colder water thus serving to increase the DO-content of the lower strata. It had no apparent effect upon the oxygen-content of the upper zone (see Fig. 11). As a remedial treatment for the protection of fish-fauna this procedure was of little use.

Whether or not oxygen was contributed to the lakes as a result of direct aeration or as a result of photosynthesis is not clear. Although there was a decided

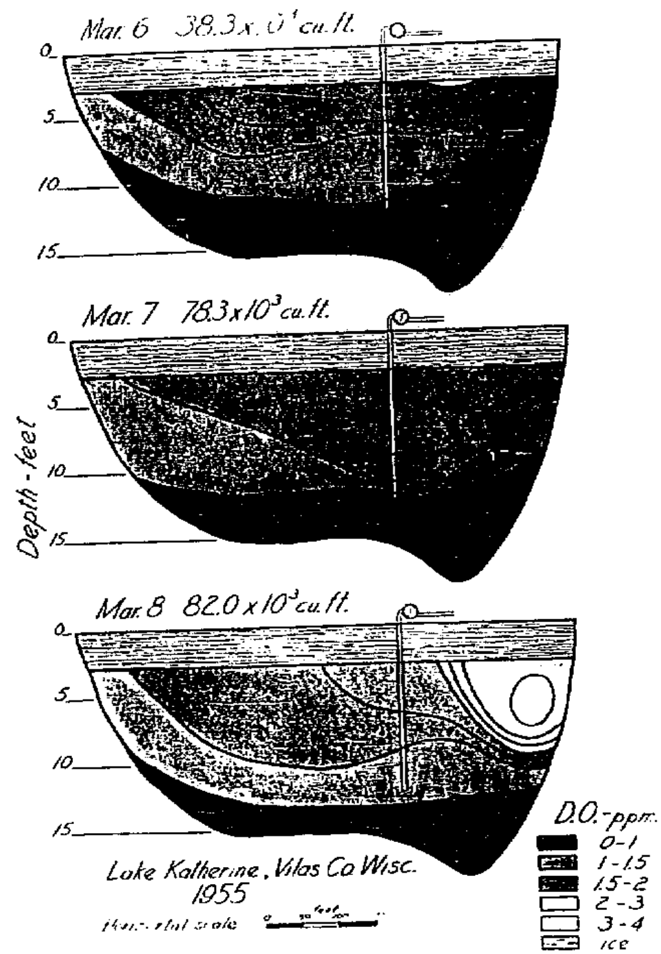

Fig. 11. The effect of pumping water from the lower strata, on the distribution of oxygen. Katharine L., 1955

increase of light-transmission through the ice-cover during the treatment period, there was no change in the number of algal cells per unit volume (Table XIII). The fact that the increase of oxygen measured was of the same order of magnitude as the amount of oxygen returned through the surface of the ice suggests that the increase resulted from surface aeration. This view was supported by the 1955 pumping trial (Fig. 11). Dense, warm water was drawn from the lower strata, spread onto the lake-surface in the usual manner and then returned to the bottom. No definite increases in oxygen-concentration were measured just below the ice where the intensities of light were highest.

EXPERIMENTS WITH THE USE OF THE "AIR-LIFT" TECHNIQUE

As soon as ice forms over the surface of a lake in the autumn, the water becomes thermally stratified. The stratification is inverse; the coldest water of 0° C., by virtue of its low density, is immediately beneath the ice. The warmest water is found in the lower strata. It is for this reason, that any disturbance which tends to bring water from the lower strata into contact with the under-surface of the ice causes the ice to be melted.

Hemphill (1954) successfully exploited this phenomenon to induce an early exodus of the ice cover on a shallow lake of 233 ha in Arizona. He introduced compressed air bubbles into the lower strata through a long perforated pipe. In this trial the primary intent appeared to be the early initiation of the vernal break-up of ice.

The removal of ice-cover with compressed air has been in general use for the elimination of ice in navigation channels, power dams, storage ponds for logs, etc.

Aitken (as cited by Greenbank, op. cit.), Schaeperclaus (1947) and Puke (1950) report various degrees of success or failure with the use of compressed air delivered beneath the surface of the ice. The primary concern in their trials was to have the introduced air surrender its oxygen to the water. Schaeperclaus, in fact, plugged the space around the air-pipe where it entered the lake, in an effort to retain the air beneath the ice surface.

In 1956 compressed air was used in this study to artificially circulate Sawmill P. (see p. 21). The results of this experiment suggested a further extension of the "air-lift" technique for use in ice-bound lakes - to serve as a method of experimental manipulation as well as a method for improving the environment for fish.

It was thought that the opening of channels in small lakes would not cause the early disappearance of the ice in spring. It was also thought that sufficient quantities of air to provide any significant amount of aeration could

not be retained beneath the ice. Rather, it was anticipated that the overall result of artificially induced turbulence, e.g., surface aeration as well as air-bubble absorption, would serve to provide significant quantities of oxygen.

1. Theoretical considerations.

Whether or not a reasonable amount of compressed air could be expected to accomplish the tasks of winter circulation and subsequent aeration was the first question to be considered. The oxygen-demand observed in Katharine L. during the winter period was used as a point of departure. Decreases of oxygen in Katharine L. in 1954 and later in 1957 were 1.12 kg/ha/day (5 Feb.-12 Mar., 1954) and 1.36 kg/ha/day (27 Dec.-4 Feb., 1957).

A cubic meter of air at 20° C. contains 0.28 kg of oxygen. Engineering practices show that bubble aeration systems can utilize 10% of this amount (Wagner, 1956). The resulting air requirement for Katharine L. then becomes 48.6 m^3/ha/day. This quantity amounts to 33.8 l/ha/min or, for the entire lake (6.1 ha), 206 l/min.

The above calculation makes no provision for additional amounts of oxygen obtained through surface aeration or photosynthesis. Likewise it does not account for changes in either the biological demand for oxygen or in the oxygen-saturation resulting from the treatment.

Nevertheless, it is anticipated that the factors ignored were mainly of a positive nature. The exception is the effect of oxygen saturation.[1] The latter factor is of concern only at higher degrees of oxygen saturation and hence, for the present purpose, presents no problem.

The calculated amount of compressed air required, i.e., 206 liters/min (at 1 atm, 20° C.) would be sufficient to maintain the concentrations of oxygen in Katharine L. without any other additional sources of oxygen. This amount of air could be provided by an indicated horsepower of 0.112 (metric) (O'Neil, 1939).

Continuous exposure of the water to the winter atmosphere was expected to significantly reduce the temperature of the lake to below normal. Hence the second question to be considered was whether or not the reduced temperatures would be untenable for the fish. The lethal low temperatures for salmonid fish are on the order of 0.2-0.5° C. according to Fry, Hart and Walker (Brett, 1956), while the lower limit for a percid fish is 1.1° C. according to Hart (Brett, 1956). This indicates that damage to the resident rainbow trout would be unlikely. No allusions to problems

[1]An expression for the rate of oxygen absorption by water in a given system is:

$U_2 = U_1 \, e^{-(\Delta t)(\text{const.})}$, U_1 = undersaturation at the start of an aeration process, U_2 = the undersaturation at the end of an aeration process, t = elapsed time (modified from Rand, 1957, p. 1285).

of low temperature in connection with the artificial circulation process were found in the literature.

The two general approaches were open, i.e., preventive or remedial treatment of the lake basin. Various investigators maintained that preventive application is the most reasonable. Kusnetzow (as cited by Greenbank, op. cit.) also supported this view. He argued that the production of methane and hydrogen by anaerobic bacteria actually causes an acceleration of the activity of the anaerobes. It was known that the products of anaerobic metabolism serve to diminish the oxygen supply (Waksman, 1941). Hence, it would be expected that the rate of oxygen consumption in an ice-bound lake would be decreased, if anoxic conditions were never allowed to develop. The purpose of the first tests conducted with the use of compressed air was two-fold: first, to measure the major effect of the air turbulence upon the oxygen concentrations and the water temperature, and second, to determine, if possible, to what extent the prevention of anoxic conditions would ameliorate the losses of oxygen.

It was proposed to apply a volume of air to two lakes in approximate accord with the theoretical considerations as calculated above. The treatment of one lake was to begin as soon as the ice-cover formed, and the treatment of the second was to begin later in the winter when relatively low oxygen concentrations prevailed.

2. Field experiments.

In the following two experiments, both preventive treatment (treatment initiated at the time the ice-cover formed) and remedial treatment (treatment initiated after the oxygen concentrations became less than 3 ppm) were tested. Two experimental lakes were employed: Turk L. (Chippewa Co.) and Katharine L. (Vilas Co.). It was planned to alternate the type of treatment in the two lakes in two succeeding years. Unfortunately, in both years, the work in Turk L. was abandoned as a result of early thaws and the accompanying high oxygen concentrations.

Forty, 20-foot sections of plastic pipe (31.8 mm I.D.) were each perforated with a single small hole (1.32 mm diam.). In November 1956, the sections were assembled, appropriately weighted, and submerged in Katharine L. The pipe was suspended so that it would at no place be below the 3.5 m contour. The holes were oriented downward to facilitate the discharge of water.

A piston-type, electrically driven air compressor was placed on the shore of the lake and connected to the air pipe. The compressor delivered approximately 204 liters/min of air (1 atm, 0° C.) to the lake. A theoretical horsepower of approximately 0.70[1] (computed from tables of

[1]Computed for adiabatic, single stage compression of normal air (20° C., 36% rel. humidity, n = 1.3947, density = 1.2015 mg/cc).

O'Neil, 1939) was required. Preventive treatment was begun on 17 Nov. 1956, and continued through 25 Jan. 1957.

Katharine L. was completely covered with a thin layer of ice on 10 Nov. 1956. The air compressor was turned on for a brief period on that day and subsequently the lake remained open until 17 Nov. The pump was then run continuously until 25 Jan. 1957.

A test of remedial treatment was made in the same lake during the following winter. The same physical installation was used. However, in this trial only 111 liters/min of air (0° C., 1 atm) was delivered to the lake. A theoretical horsepower of approximately 0.19 was required. The remedial treatment was begun on 5 Feb. 1958 and continued through 7 Apr. 1958.

About 24 hours after pumping commenced, the warm water that rose over the pipe melted a hole through the ice-cover, and subsequently created a channel similar to the one shown in Fig. 12.

The final water temperatures in the preventive test were below 1° C., and in the remedial test between 1-2° C., both considerably lower than normal. Fig. 13 shows the temperature profile for the preventive test on 13 Jan. 1957, together with a normal temperature profile for this lake. The temperatures for the remedial test are shown in Fig. 14.

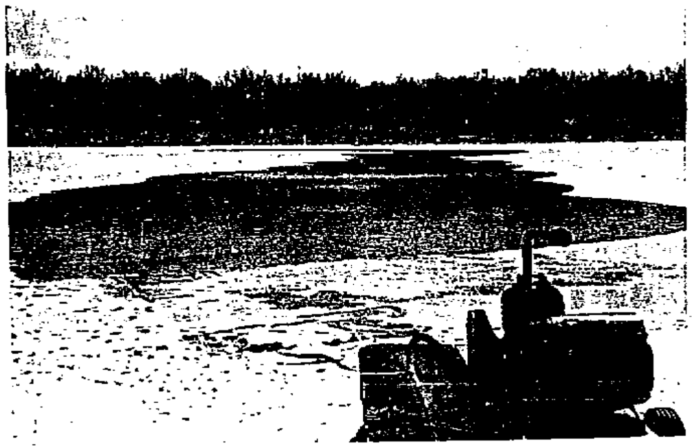

Fig. 12. An open channel in the ice cover created by air induced turbulence.

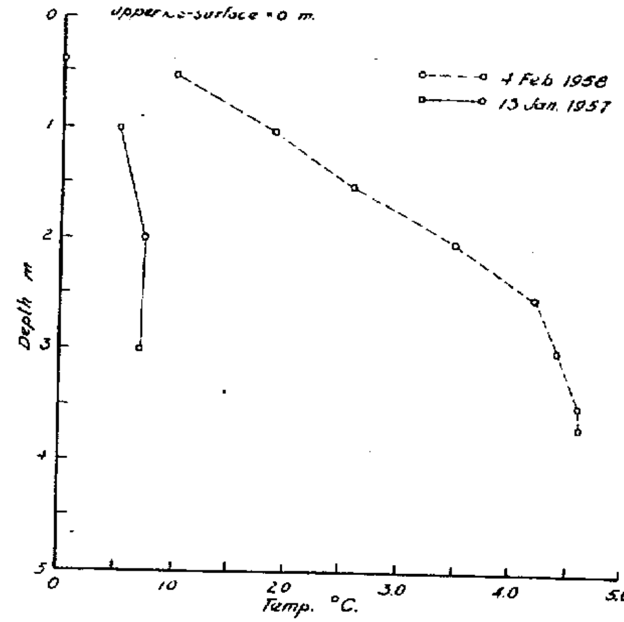

Fig. 13. Normal water temperatures vs. post-treatment water temperatures in Katharine L., 1957 (preventive "air-lift" treatment).

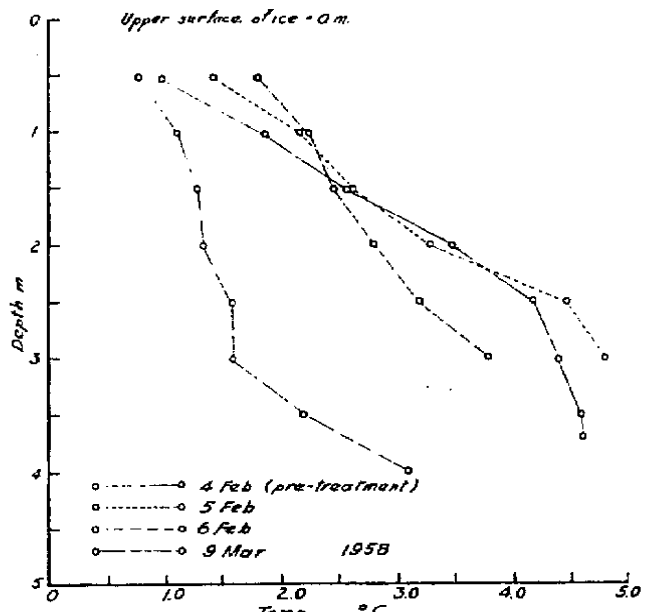

Fig. 14. Changes in the temperature of Katharine L. (remedial treatment, 1958)

In spite of the reduced water temperatures, great increases in the thickness of the ice did not occur. Normal ice thickness from Dec. through Mar., in this lake, is from 25 to 33 cm.[1] After 57 days of preventive treatment the ice was 38 cm thick (12 Jan. 1957). In the remedial test, the ice at the beginning of the treatment was 34 cm thick (5 Feb. 1958). After 32 days of treatment it was 44 cm thick (9 Mar. 1958).

Temperature and oxygen records from stations located over the entire basin, indicated that after 24 hours of treatment mixing occurred to some extent throughout the lake. The average values for oxygen in the remedial test are shown in Fig. 15.

The effect of the preventive treatment upon the oxygen concentrations was astonishing. On 13 Jan. 1957, after 57 days of treatment, the oxygen concentration was 7.1 ppm in one of the stations located in shallow water. Under normal conditions, at that time of year, 1-2 ppm of oxygen would have been expected.

In both tests the rate of depletion of the oxygen was reduced. Table XIV shows the average oxygen concentrations, absolute oxygen content and the relative areal oxygen deficit, during both of the tests.

[1]Unpublished data, U. Wis. Hydrobiological Laboratory.

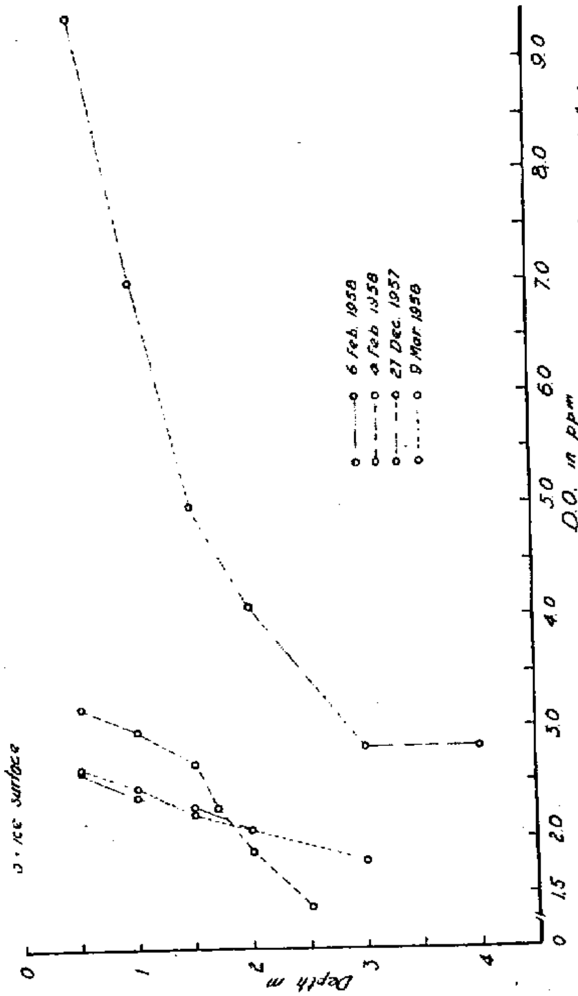

Fig. 15. Changes in the concentration of oxygen in Katharine L. (remedial "air-lift" treatment, 1958).

Table XIV. The effect of air-induced turbulence in winter on the concentration of oxygen in Katharine L.*

Date	Ave. DO	O_2 mg/cm² of lake surface	Relative areal O_2 deficit/day in mg $O_2/cm^2/day \times 10^{-3}$
Preventive treatment			
17 Nov. 1956**	9.8	1.71	
17 Nov. 1956	Treatment begun		1.2
13 Jan. 1957	7.2	1.01	
25 Jan. 1957	Treatment halted		
Remedial treatment			
27 Dec. 1957	5.6	0.865	13.2
4 Feb. 1958	2.3	0.352	
5 Feb. 1958	Treatment begun		0.81
9 Mar. 1958	2.1	0.326	
7 April 1958	Treatment halted		

* Data for the upper 3 m of water.

**No measurements are available for this date. 9.8 ppm represents the oxygen concentration present if the water were 80% saturated with oxygen at 5° C., at the end of the autumnal overturn.

The amount of work used during the treatment to induce circulation in the basin in the two tests, was as follows:

	Preventive	Remedial
Work[1] applied to cm^3 of water/day	5.35 gm-cm	1.45 gm-cm
Daily air supply (0^o C., 1 atm)	3.44 liters/m^3 of water	1.87 liters/m^3 of water
Approx. DO-level maintained	7 ppm	2 ppm

Apparently the low temperatures did not affect the trout adversely. On 12-13 Jan. 1957, when the water temperatures varied from 0.0 to 1.0° C., the fish were sufficiently active to take bait offered to them.

No known mortalities of fish occurred during the preventive test. However, a partial winterkill was experienced during the remedial test. About 200 fish were reported dead upon the departure of the ice in late April. These mortalities were believed to have occurred between 9 Mar. and 7 April, while the treatment was in progress. The average oxygen concentrations during this period were below 3 ppm.

[1]The equivalent of work done by air bubbles rising through the basin.

CONCLUSION

The amount of light available in a lake for photosynthesis is sharply reduced when the ice on the lake becomes covered with snow. In these experiments the snow was reduced to frozen slush by pumping water from beneath the ice onto the surface of the lake. Following the experiment an increase in oxygen concentrations was noted. This increase appeared not to be the result of increased photosynthesis. The increase was instead attributed to the pumped (aerated) water which had returned to the lake.

Oxygen concentrations were increased in the upper stratum only when the density of returning water was such that it would not "fall" back into the lower deoxygenated zone.

It is possible to return an average of 7 units of oxygen for each million units of water pumped. Mechanical difficulties make this method extremely cumbersome as well as costly.

The "air-lift" technique can be used for artificially circulating and oxygenating lakes which are inversely stratified. This method was superior in most respects to the water pumping procedure.

The resulting low temperatures induced by this method suggest that further examination of its use is warranted in lakes which contain certain species of fish. The loss of heat in the two tests varied with the amount of work applied to the water. In both cases the final water temperatures were less than or approximately equal to the lethal low levels for certain warmwater fish. They did not exceed the lethal low limits for salmonids.

It was concluded from the "air-lift" tests that the estimated supply of compressed air[1] was sufficient to ameliorate the demand for oxygen within the basin. During both the preventive and the remedial tests the relative areal deficit was markedly reduced, as shown in Table XIV.

In the preventive test an oxygen concentration of approximately 7 ppm was maintained. In the remedial test an oxygen concentration of approximately 2 ppm was maintained. Since the intensity of treatment was different in each test, it cannot be deduced whether or not dissimilarity between the two oxygen concentrations was owing to dissimilar oxygen demands.

[1]The 206 liters/min. is equivalent to 3.2 liters/m^3 of water/day in this lake. 1.9 and 3.4 liters/m^3/day were delivered in the remedial and preventive tests respectively. (p. 76).

IMPLICATIONS FOR LIMNOLOGICAL EXPERIMENTATION AND LAKE MANAGEMENT

The force of the wind, exerted on the surface of a stratified lake, has a relatively small effect. An example of this is presented by Hutchinson (1957, p. 452) for Linsley P.; the thermocline in this basin was little affected by the hurricane of September, 1938. By contrast, controllable forces, applied in the manner treated in this paper, act from within a basin with, figuratively speaking, tornadic effect.

For the experimental limnologist, the "air-lift" procedures can serve as a tool in the study of lake dynamics. (The water pumping methods are summarily rejected, except for certain special situations, because of their relative inefficiencies.) He is enabled, with the expenditure of less than 18 liters of air per m^3 of water, to achieve homoiothermal or isochemical conditions down to any contour level, to establish a thermocline in a desired position, to simulate naturally occurring circulation, or to change within certain limits the average water temperature.

It is axiomatic that the physical and biological rules which govern the effects of either artificially or naturally induced turbulence, are unchanging. However, the value that is placed upon a lake basin for man's purpose is not so fixed. It is implied, therefore, that when the economic or cultural conditions warrant, artificial circulation of basins can serve the lake manager as well as the experimental limnologist.

It has been shown that artificial circulation does serve as a means of "intrafertilization" under certain conditions. Whether or not this fertilization effect is translatable into sufficiently large amounts of desirable end-products, i.e., increased zooplankton or fish production, cannot be ascertained from these experiments. At this juncture, other attributes of artificial circulation appear to hold more promise for lake management.

It is possible to assure the vernal circulation of "spring-meromictic" lakes in which trout ordinarily could not be held during the summer period. This use was initiated for the first time in Cather L. on 10 May 1958. Nine ppm of oxygen were introduced into the lower strata in less than 12 hours of artificial circulation. The resultant effects will be evaluated during the summer of 1958.

The thermal barrier inhibiting the rapid dispersal of fish toxicants or other treatment materials (Clemens and Martin, 1952) (Hooper and Grzenda, 1955) could be eliminated where complete assurance of dispersion or more rapid detoxification was desired.

The applications to problems of fish-winterkill appear to be most effective as a preventive measure. Many

details, particularly with reference to the effect of low water temperatures on the fauna, remain to be investigated.

Finally, although somewhat far removed from the immediate concerns of the fishery biologist, is the possibility for use of this technique to maintain open water as an aid in the management of migratory waterfowl.

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