Original: Fish Division
cc: Educ.-Game
Inst. for Fish. Res.
Rifle R. Station
Hunt Cr. Station
M. H. Patriarche
Region III-Fish
Region II-Fish
Region I-Fish

INSTITUTE FOR FISHERIES RESEARCH
DIVISION OF FISHERIES
MICHIGAN DEPARTMENT OF CONSERVATION
COOPERATING WITH THE
UNIVERSITY OF MICHIGAN

GERALD P. COOPER PH.D.
DIRECTOR

ADDRESS
UNIVERSITY MUSEUMS ANNEX
ANN ARBOR, MICHIGAN

September 20, 1961

Report No. 1628

AIR-INDUCED WINTER CIRCULATION OF WATER IN TWO SHALLOW MICHIGAN LAKES[1]

By Mercer H. Patriarche

The prevention of periodic winterkills of fish in shallow, eutrophic lakes has been the object of considerable interest for many years. It is generally agreed that depletion of dissolved oxygen under the ice late in the winter is the fundamental cause of these winterkills (Greenbank, 1945; Cooper and Washburn, 1946; Scidmore, 1957). Greenbank listed a number of possible remedies proposed by various workers which included: (1) diverting a flow of water into a lake, (2) raising the water level of a lake, (3) cutting holes in the ice, (4) pumping air into the water, (5) removing vegetation, and (6) removing snow from the ice.

In recent years workers have experimented with compressed air as a means of rejuvenating the oxygen supply in a lake (Hemphill, 1954; Schmitz and Hasler, 1958; Schmitz, 1959; Burdick, 1959; Rasmussen, 1960). The release of compressed air through a series of holes in an air conductor laid on or near the bottom of the lake creates vertical currents which bring the warmer bottom water into contact with the ice

---

[1] A somewhat shorter version of this report has been submitted for publication in the Journal of Wildlife Management.

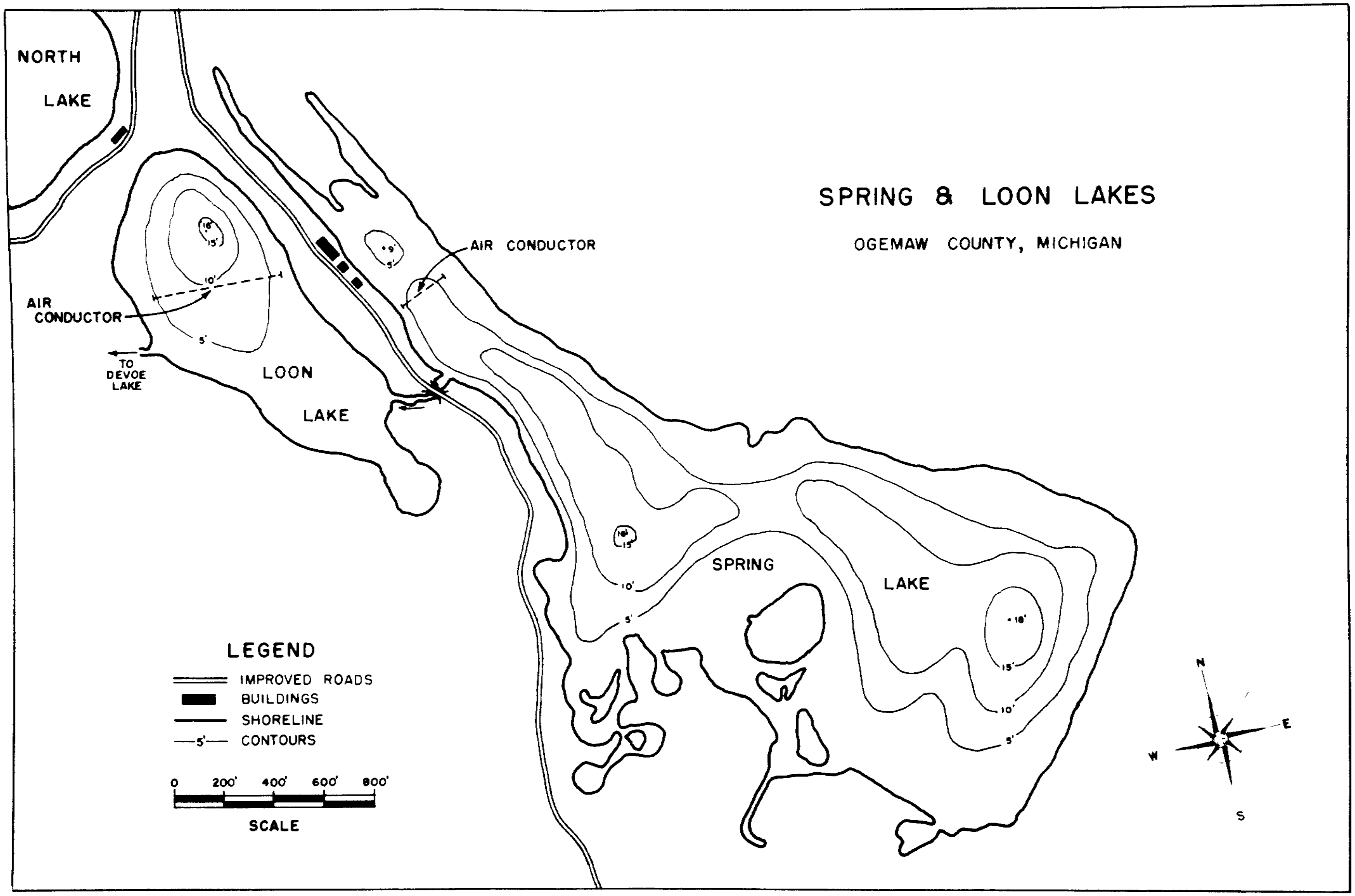
cover. Holes are melted through the ice and shortly thereafter a channel of open water is created above the air conductor. This opening allows water to come in contact with the air and absorb oxygen from the atmosphere.

The feasibility of preventing winterkill of fish by the use of compressed air was tested in two lakes at the Rifle River Fisheries Research Station, Ogemaw County, Michigan. Spring and Loon lakes were selected because of their past histories of winterkills of fish. Both lakes are located within 100 yards of a source of electricity for operation of a compressor.

Spring Lake is a rich, shallow, 72.5-acre lake which contains an abundance of aquatic vegetation (Fig. 1). An intermittent outlet connects this lake with Loon Lake; there is no well-defined inlet. It was selected for exploratory work in the winter of 1957-58. Frequent winterkills had virtually eliminated yellow perch, Perca flavescens, the only important game species, leaving only large populations of black bullheads, Ictalurus melas, and forage fish (chiefly northern redbelly dace, Chrosomus eos). In this initial study on Spring Lake, no attempt was made to prevent a winterkill. Instead, the air conductor was installed across one end of the lake, where the effects would be localized.

During the winters of 1958-59 and 1959-60 the work was performed in Loon Lake. This 16.8-acre lake (Fig. 1) has an abundance of aquatic vegetation, a soft bottom of organic ooze mixed with marl, and a fish population composed principally of largemouth bass, Micropterus salmoides, and a number of species of pan fish. Both the inlet (from Spring Lake) and the outlet have intermittent flows. Attempts to prevent winterkill conditions from developing in Loon Lake were unsuccessful. However, the experiments

Figure 1. --Hydrographic map of Spring and Loon lakes, showing locations of air conductors.



SPRING & LOON LAKES
OGEMAW COUNTY, MICHIGAN
NORTH
LAKE
AIR CONDUCTOR
AIR
CONDUCTOR
TO
DEVOE
LAKE
LOON
LAKE
SPRING
LAKE
LEGEND
IMPROVED ROADS
BUILDINGS
SHORELINE
CONTOURS
0
200'
400'
600'
800'
SCALE
N
E
W
S

Figure 1

demonstrated how the temperature and oxygen regimes beneath the ice cover of a lake are affected when an aerator is used, and pointed out some of the difficulties encountered in using compressed air.

Frank F. Hooper suggested the project and advised on certain procedures. Arthur W. DeClaire assisted in setting up the equipment, performed most of the oxygen analyses during 1959 and 1960, and took the photographs in Figure 2. Other station personnel who assisted in various phases of the project included Howard Gowing, Charlie J. Kohn, Keith R. Sammons and George Smith, Jr. Gerald P. Cooper, Paul H. Eschmeyer, Frank F. Hooper and David S. Shetter read the manuscript and offered suggestions. Harold Hughes, Superintendent of Drayton Plains Hatchery, provided an air compressor for the work. William C. Cristanelli and Paul M. Earl prepared the charts and map.

Methods

Methods and equipment used for circulation of water under the ice differed only slightly during the three winters of operation. In Spring Lake during 1957-58, a 250-foot section of 1/2-inch (inside diameter) rubber garden hose was laid across the northern end (Fig. 1), where the maximum water depth is approximately 6 feet. The hose was perforated with 20 holes of 1/32-inch diameter at intervals of 12 1/2 feet and weighted with 8-foot sections of 1/4-inch steel rod (about 3 pounds per 25 feet of hose). The distal end of the hose was plugged so that no air could escape. This air line was held in place by stakes at the two ends. A 300-foot length of hose connected this line to the air compressor, which was housed in a work shop. An electrically powered DeVilbiss air compressor of 4-5 c. f. m. capacity, a type of unit commonly used in gasoline stations or commercial garages, was operated continuously from February 24 to March 26, 1958. A smaller, auxiliary compressor (capacity unknown) also was hooked into the system and used frequently. Preliminary trials, after a 4 1/2-inch ice cover had formed early in December, revealed that the perforations in the air line were too small to prevent frequent stoppages. Enlargement of the holes to 1/16 inch and insertion of a basketball inflation valve in each hole corrected this difficulty.

Essentially the same equipment was used in Loon Lake during the winters of 1958-59 and 1959-60, except that the perforated air line was 500 feet in length, and only 175 feet of hose was necessary to connect the air line with the compressor. During 1958-59 the submerged hose lay on the bottom, in water 3 to 10 feet deep, but in 1959-60 it was suspended from wooden floats at a depth of 5 feet. The compressors were operated from December 30, 1958 to April 1, 1959, and from December 8, 1959 to March 14, 1960. A complication during the two winters of work at Loon Lake was periodic stoppage (about every 5 to 7 days) in the connecting hose near the building, caused by freezing of condensation moisture. This required thawing out the frozen section each time that a stoppage occurred (usually whenever a relatively warm spell was followed by a night of near-zero temperature).

Two methods of laying the hose were tried during the three winters of work. In Spring Lake the hose was laid on the bottom prior to the freeze-up. In Loon Lake (1958-59) a rope was laid on the bottom of the lake before the lake froze over; and after an ice cover had formed, the hose was stretched out on the ice, prepared for use, tied to one end of the submerged rope, and pulled across the lake under the ice. The method used in Spring Lake is preferable, especially if a long air line is used, or if there is danger of snagging the air line as it is pulled along the lake bottom.

Observations were made on the physical, chemical, and thermal effects of the artificial circulation of water in Spring Lake during 1957-58. Water samples were collected semiweekly at one station in the open water, and at paired stations located 50, 100, 200 and more than 400 feet from the open channel. The water samples were collected about 2 feet below either the water surface or the bottom of the ice. All samples were analyzed for dissolved oxygen (Winkler method) and some for carbon dioxide (NaOH titration). Temperatures were taken at irregular intervals with a Whitney resistance thermometer.

In Loon Lake during 1958-59 and 1959-60, a similar pattern of water sampling was followed, except that two stations were established in open water and most of the additional stations were 200 feet from the air line. The Winkler method of oxygen analysis was again used, but carbon dioxide values were determined from a nomograph (Moore, 1939), which requires data on pH and total alkalinity. During 1959-60, the sampling was modified to the extent of obtaining samples above and below the 5-foot level (depth of air conductor) and a Negretti-Zambra reversing thermometer was used to obtain water temperatures. Several temperature series were taken in the open water and under the ice 200 feet away.

Data were collected in Loon Lake during 1958-59 to ascertain the effects of water circulation on behavior of fish. Four small, cylindrical, wire traps, 3 feet long and made of 1/4-inch hardware cloth, were set along opposite shores of the lake for 30 days in March (two traps in open water and two beneath the ice about 200 feet away) to determine whether or not small fish were attracted to the open water. Also, three large wire traps, capable of taking large fish, were set in open water. The traps were lifted 5 times per week.

During 1958-59 and 1959-60, two anglers fished twice a week in Loon Lake, both on open water and through the ice. Catches were extremely poor, however, and the results were inconclusive.

Weather conditions

The winter weather of 1957-58 and 1959-60 may be considered as normal for this vicinity, except that unusually cold weather in March, 1960, delayed the break-up of ice cover and the replenishment of oxygen in the lakes. During 1958-59, however, mean monthly maximum and minimum air temperatures in December, January, and February were mostly 6° to 16° F. below normal (Table 1).

The number of nights of subzero temperatures and the lowest temperatures during the three winters of this study were: 1957-58, 23 nights, minus 23° F.; 1958-59, 44 nights, minus 35° F.; and 1959-60,

Table 1. --Average monthly maximum and minimum air temperatures (°F.) taken at Rifle River Area weather station, December-March, 1957-1960

Item	Winter		
	1957-58	1958-59	1959-60
Maximum:			
December	35.9	26.3	34.9
January	30.7	24.3	29.8
February	28.2	29.6	31.9
March	42.5	39.4	35.4
Minimum:			
December	17.7	2.3	19.9
January	9.6	3.5	13.0
February	4.3	0.0	9.8
March	21.5	13.0	6.9

25 nights, minus 20° F. Correspondingly, the numbers of days in January and February during which the temperatures rose above 32° F. were 24 in 1958, 18 in 1959, and 22 in 1960.

Snowfall was much greater in 1958-59 than in either of the other two winters. Total amounts for the 4-month period (December-March) were 32.5 inches in 1957-58, 63.0 in 1958-59, and 44.6 in 1959-60. The maximum accumulation on the ground was 14 inches in 1958, 26 in 1959, and 16 in 1960. On the lakes, where the accumulation of snow was not so great because of wind activity, the maximum depths measured were 5 inches in 1958, 12 in 1959, and 6 in 1960.

Ice removal

In 1958, water circulation was started in Spring Lake on February 24, when there was an ice cover of 14 to 15 inches, topped by 3 to 5 inches of snow. (Prior to this time there had been a permanent snow cover since January 20.) Within 5 hours much of the ice was melted above the air line. Small holes (4 to 6 inches in diameter) which had been opened for water sampling were enlarged, as a result of water circulation, to a diameter of 18 inches. By the following morning (20 hours after the compressors were started) only a thin crust of ice and snow remained above the bubbling air conductor and this was easily broken up with an ice spud. The overnight minimum temperature was 29°. Three days later a channel 3 to 5 feet wide extended across the lake above the hose line. Later this expanded to a mean width of about 15 feet (range, 10-21 feet), as shown in Figure 2.

Figure 2.--Views of open channels in Spring Lake (A and C, March 7, 1958) and Loon Lake (B, March 17, 1959) created by pumping compressed air into a submerged, perforated hose line.

A

B

C

Figure 2

The average width was increased considerably by moving the hose line to the edge of the channel, although the portion of open water farthest removed from the bubbling action froze during cold nights. The maximum ice thickness on Spring Lake was 16 inches during the second week of March. With the advent of warmer weather near the end of March, the air line produced an open channel 100 feet wide. A complete break-up of the ice cover on the lake, due primarily to the spring thaw, occurred on April 5.

The severe weather during the winter of 1958-59 provided a better test of the ability of compressed air to maintain open water. The compressor was started on December 30, 1958, at which time Loon Lake had 10 inches of ice plus 3 to 4 inches of snow. On the following day there was open water above about one-third of the air line (the overnight low was -9° F.). Despite extremely cold weather during the following week, an open channel was created, bridged in the center by a 20-foot strip of ice above two holes in the air line that were not functioning properly. As on Spring Lake during 1957-58, a channel 10 to 20 feet wide was opened by the upwelling water (Fig. 2). However, during periods of extremely cold weather (-10° to -32° F.), this channel was restricted to a series of 5-foot open circles above the air holes. For most of the winter of 1958-59 the channel was about half as wide as during the previous winter. Maximum ice thickness observed on Loon Lake was 23 inches, on March 12, 1959.

During the winter of 1959-60, the circulation of water in Loon Lake was started on December 8, when the ice was 6 inches thick and there was practically no snow. The overnight low temperature was only 17°, but 4 days were required to open up holes, apparently because of extensive air pockets beneath the ice cover. An open channel 10 to 20 feet wide was maintained until mid-February, after which the channel narrowed for a time to a width of 4 to 8 feet, because of continuous cold weather.

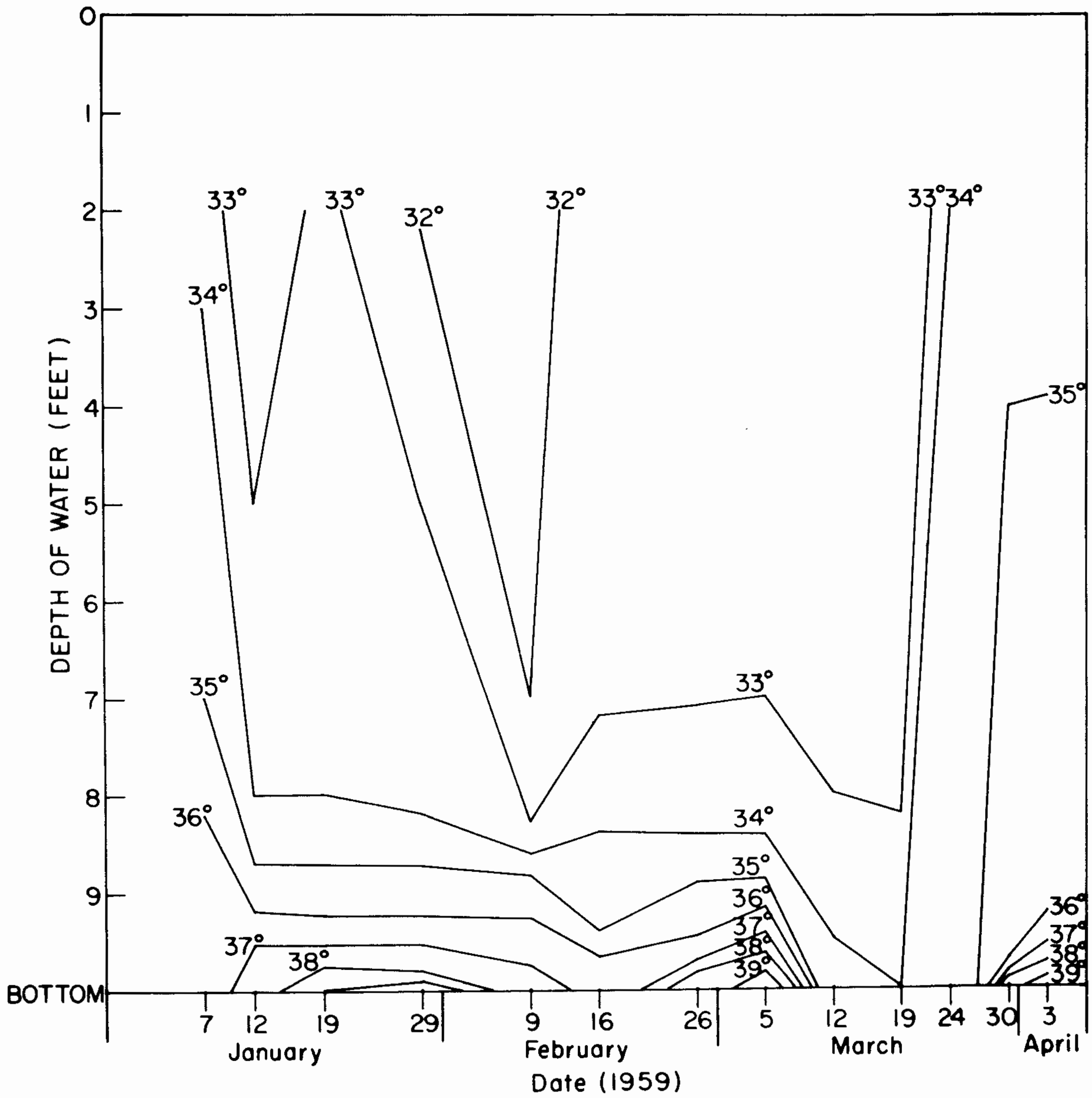
Water temperature

Water temperatures (°F.) were taken frequently in Loon Lake in 1958-59, at 1-foot intervals, commencing at a depth of 2 feet below the surface and extending into 1 foot of bottom ooze (Figs. 3, 4 and 5). On December 29, 1958, the day before circulation was started, water temperatures beneath the ice ranged from 35.4° at the 2-foot depth to 39.9° at 11 feet; the temperature of the bottom ooze was 42.6°. On January 7, after 8 days of water circulation, temperatures in the open water were only 33.8° at a depth of 2 feet, 35.9° at 8 feet and 36.8° in the bottom ooze. The water temperature continued to drop and become more uniform with depth as operation of the air line continued. The wide spacing between the 32° and 34° isotherms in Figure 4 reflects this uniformity. A protracted period of very cold weather between January 20 and February 9 culminated in supercooling of the open water. During this period the average minimum air temperature was -5.5° (range, 22° to -30°). On February 9 the open-water temperature ranged from 31.4° to 31.8° down to a depth of 6 feet.[2] On March 19 the temperature of the circulating water down to a depth of 8 feet was a uniform 32.8°; below this level, a gradual increase in

---

[2] When these unusually low temperatures were observed the alignment of the Whitney thermometer was rechecked and the temperature series repeated with the same results. There was very close agreement, also, with readings taken at the surface with a pocket thermometer. Thus it appears that there was true supercooling of the water in this instance.

Figure 3. --Water temperatures (°F.) in Loon Lake, in the immediate vicinity of the air conductor, January 7-April 3, 1959.



DEPTH OF WATER (FEET)
0
1
2
3
4
5
6
7
8
9
BOTTOM
33°
33°
32°
32°
34°
33°34°
35°
35°
36°
33°
34°
35°
36°
37°
38°
39°
36°
37°
38°
39°
37°
38°
7
12
19
29
9
16
26
5
12
19
24
30
3
January
February
March
April
Date (1959)

Figure 3

Figure 4.--Water temperatures (°F.) in Loon Lake, beneath the ice 200 feet from air conductor, December 29, 1958-April 3, 1959.

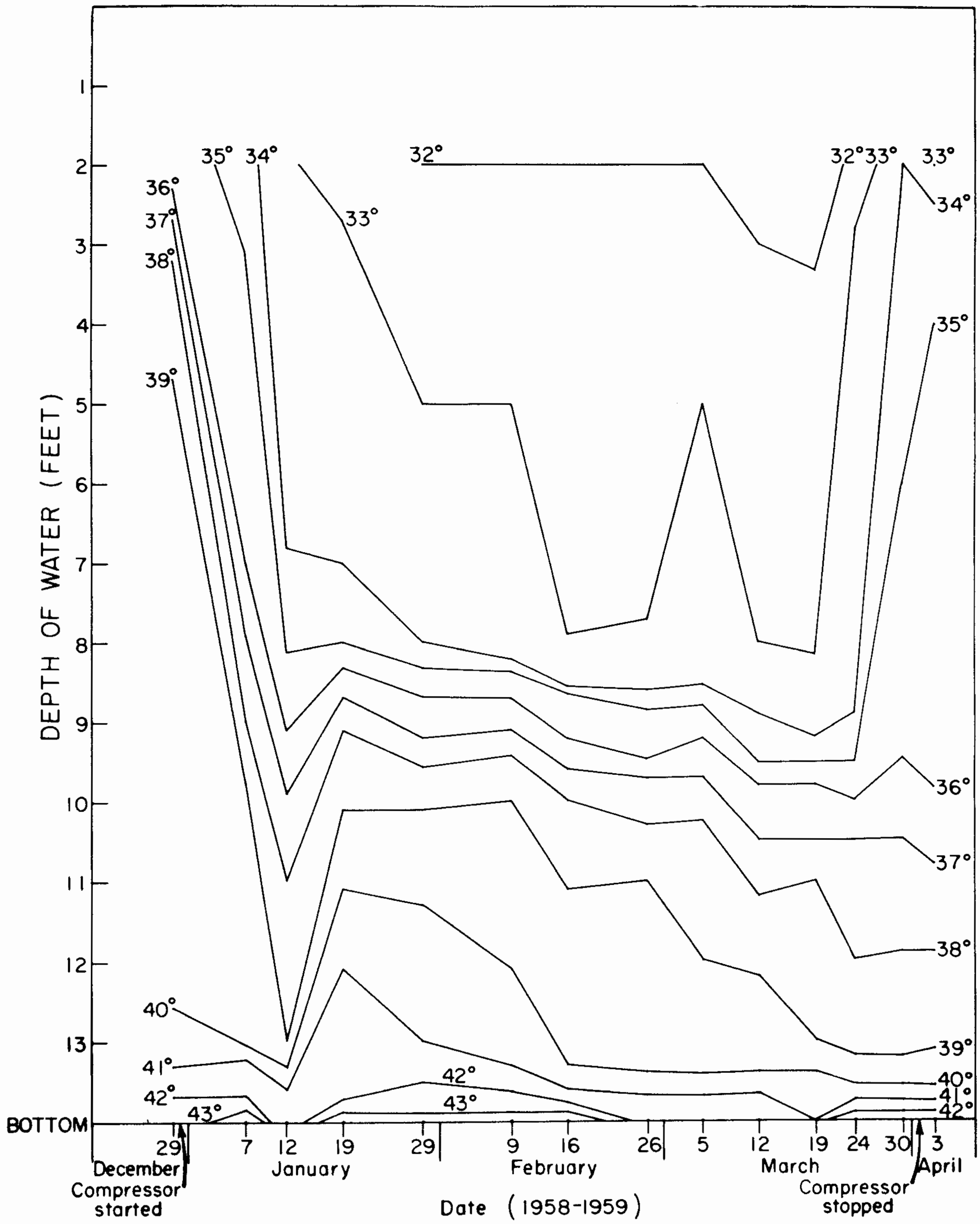

DEPTH OF WATER (FEET)
1
2
3
4
5
6
7
8
9
10
11
12
13
BOTTOM
32°
33°
34°
35°
36°
37°
38°
39°
40°
41°
42°
43°
29
December
7
12
19
29
January
9
16
26
February
5
12
19
24
30
March
3
April
Compressor started
Compressor stopped
Date (1958-1959)

Figure 4

Figure 5. --Water temperatures beneath the ice, 200 feet from air conductor, Loon Lake, 1958-59.

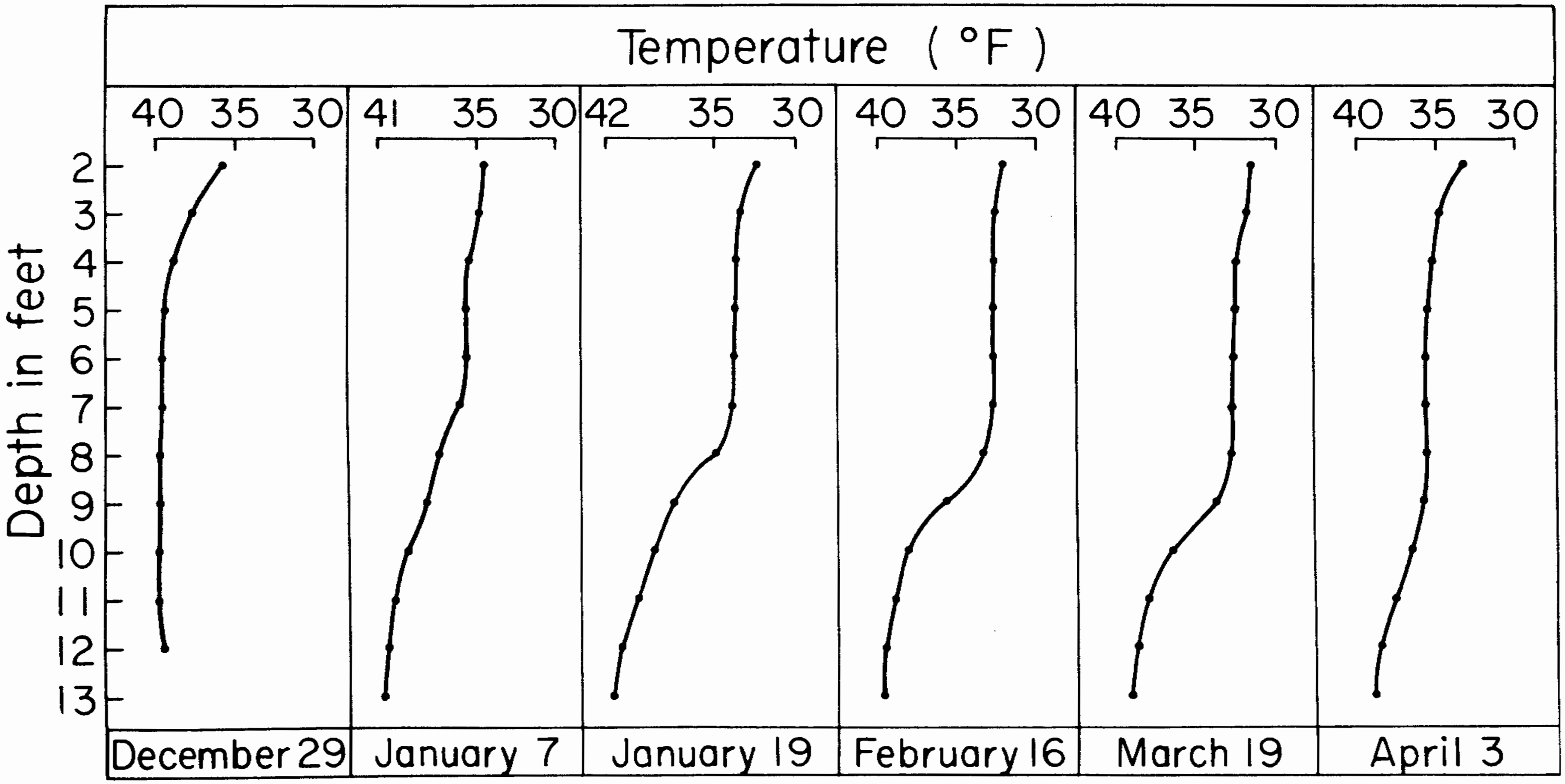

Temperature (°F)
40 35 30
41 35 30
42 35 30
40 35 30
40 35 30
40 35 30
Depth in feet
2
3
4
5
6
7
8
9
10
11
12
13
December 29
January 7
January 19
February 16
March 19
April 3

Figure 5

temperature with increasing depth was observed. Most of the perforated hose lay at water depths of 8 to 10 feet and the temperature at the 9-foot level was slightly higher than in shallower water until March 24.

Beneath the ice 200 feet away from the air line there also was a marked drop in temperature after the first week of operation, to a range of 34.4° to 37.1° in 8 feet of water. There was a trend towards uniform temperatures within the 2- to 8-foot stratum similar to that over the air line (Fig. 5); temperatures in this stratum differed by no more than 1.5 degrees for 45 days (February 16-April 1) and were at a minimum on March 19, when they ranged from 31.3° to 32.8° F.

In 1959-60, when the air conductor was suspended in Loon Lake at a depth of 5 feet below the surface, water temperatures above it varied less than 1.0° between January 29 and March 14. (Temperatures were not taken prior to January 29.) Similarly, beneath the ice 200 feet away, less than 0.5° separated the temperature readings at the 2- and 4-foot depths in February and March. On March 9 a minimum range of 32.0°-32.2° was recorded. Two temperature series taken in March, 400 feet from the air conductor, disclosed the same uniformity. At all sampling sites, water temperatures were much higher at greater depths (maximum, 41.7° at 14 feet).

Thus it appears that the turbulence created by the rising air bubbles induced lateral currents similar to those which are generated by wind action during open-water seasons. These currents, together with accompanying eddy diffusion, formed an isothermal zone to a depth corresponding roughly to the depth of the air conductor (Figs. 5 and 6). A narrow depth zone of considerable temperature gradient was established between the 8- and 10-foot contours in 1959 and between the 5- and 7-foot contours in 1960. Temperatures of the warmer (and denser) water beneath this temperature gradient were less affected but were lowered gradually to 38.3° near the bottom (water depth, 13 feet) on March 24, 1959. Virtually no change was detected at the 14-foot depth in 1960, presumably because the temperature gradient formed at a higher level than during the previous year.

The temperature of the bottom ooze beneath the air conductor in Loon Lake during 1958-59 fluctuated considerably but gradually became colder, reaching a low of 34° F. on March 19, 1959 at a time when the water temperature also was at a minimum. Two hundred feet away the ooze-temperature decline was less pronounced but perhaps it was enough to be important to bottom fauna. There was a drop of 2.2° between January 29 and March 19, while in nearby Dollar Lake the temperature of the bottom ooze dropped only 0.7° in a similar period of time.

Schmitz and Hasler (1958) observed that, under summer conditions, circulation produced an almost homoiothermal condition within 4 1/2 hours in a 0.3-acre lake to a depth of 23 feet. A similar condition developed above the 8-foot level in Loon Lake in mid-February, 1959. Probably a noticeable temperature drop occurred shortly after circulation was started.

Only three temperature observations were made in Spring Lake in 1957-58. One week after the start of operations a uniform temperature

Figure 6.--Water temperatures beneath the ice, 200 feet from air conductor, Loon Lake, 1960.

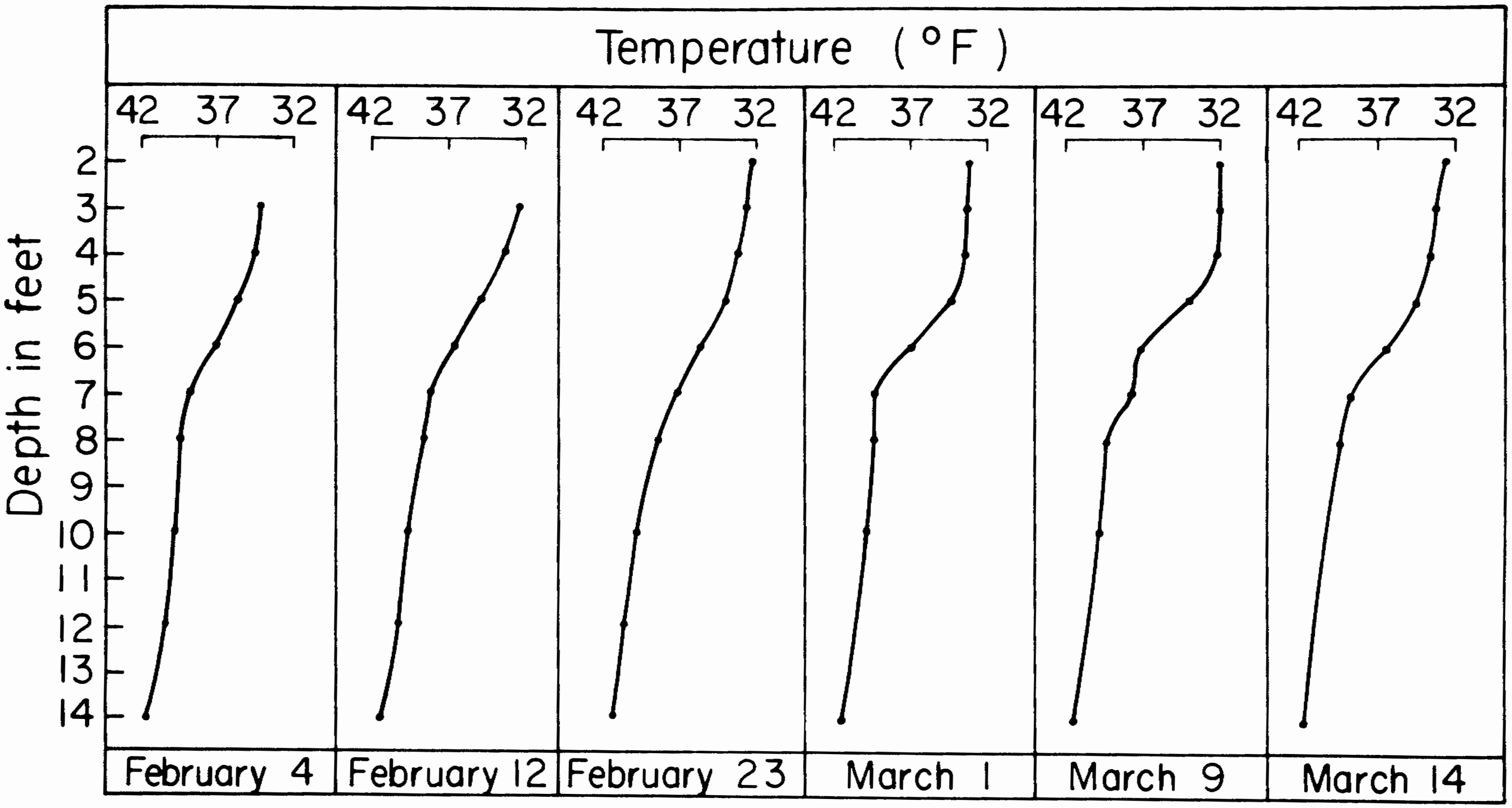

Temperature (°F)
42 37 32
Depth in feet
2
3
4
5
6
7
8
9
10
11
12
13
14
February 4
February 12
February 23
March 1
March 9
March 14

Figure 6

(35.8°) was noted from top to bottom in 5 feet of water above the air conductor. One month later a range of 38.0°-39.5° was recorded at depths 2 to 5 feet, 50 feet from the open water, where the water depth was 5 feet.

Dissolved oxygen

The principal question to be answered by this investigation was whether or not an adequate supply of oxygen could be maintained by artificially circulated water in a shallow Michigan lake subject to the winterkill of fish.

The start of the experiment in Spring Lake in 1957-58 was delayed until late in the winter to see if it would be possible to rejuvenate the oxygen supply in the upper end of the lake. On February 24, before the compressor had been operated, the oxygen content ranged from 0.0 to 1.1 ppm. within 200 feet of the air conductor, and averaged 2.6 ppm. at two stations 400 and 800 feet away (Table 2 and Fig. 7). During the ensuing 26 days, with the compressor in operation, only a slight increase in dissolved oxygen occurred in the open water (maximum observed, 1.8 ppm.); whereas there was a pronounced rise elsewhere in the lake between February 26 and March 5, caused by a thaw. Even at the 100-foot stations a marked increase was detected, although this increase lagged behind that in other parts of the lake farther from the air line. It was apparent that the influence of the turbulent water extended no further than about 100 feet at this time. The benefit from the February 26-March 5 thaw was short-lived. By March 7 the oxygen readings dropped back to "pre-thaw" levels. During the next 2 weeks the oxygen

Table 2. --Dissolved oxygen (ppm.) in open water, and mean values at paired sampling stations beneath the ice in Spring Lake, 1958

[Samples were taken about 2 feet beneath lower surface of ice[1]]

Date	Distance of stations from open water (feet)				
	Open water	50	100	200	400-800
Feb. 24	0.0	...	0.7	1.1	2.6
25	0.2	...	0.4	...	...
26	0.9	...	0.8	1.3	2.3
28	0.8	...	1.8	3.3	3.0
March 3	1.2	...	3.5	4.5	3.9
5	1.0	1.3	2.0	1.4	2.6
7	0.9	1.2	1.4	1.3	1.8
10	1.2	1.5	1.3	...	1.5
12	1.8	1.8	1.9	...	1.5
14	1.5	1.6	1.5	1.5	1.7
17	1.7	1.7	2.2	2.2	1.8
19	1.7	2.2	2.8	2.8	2.4
24	2.6	3.5	3.6	4.1	4.6
31	4.4	4.5	4.6	5.2	7.3
April 3	6.4	...	...	...	...

[1] The air compressor was operated from February 24 to March 26.

Figure 7. --Oxygen values at sampling stations in open water, and beneath the ice, Spring Lake, 1958.

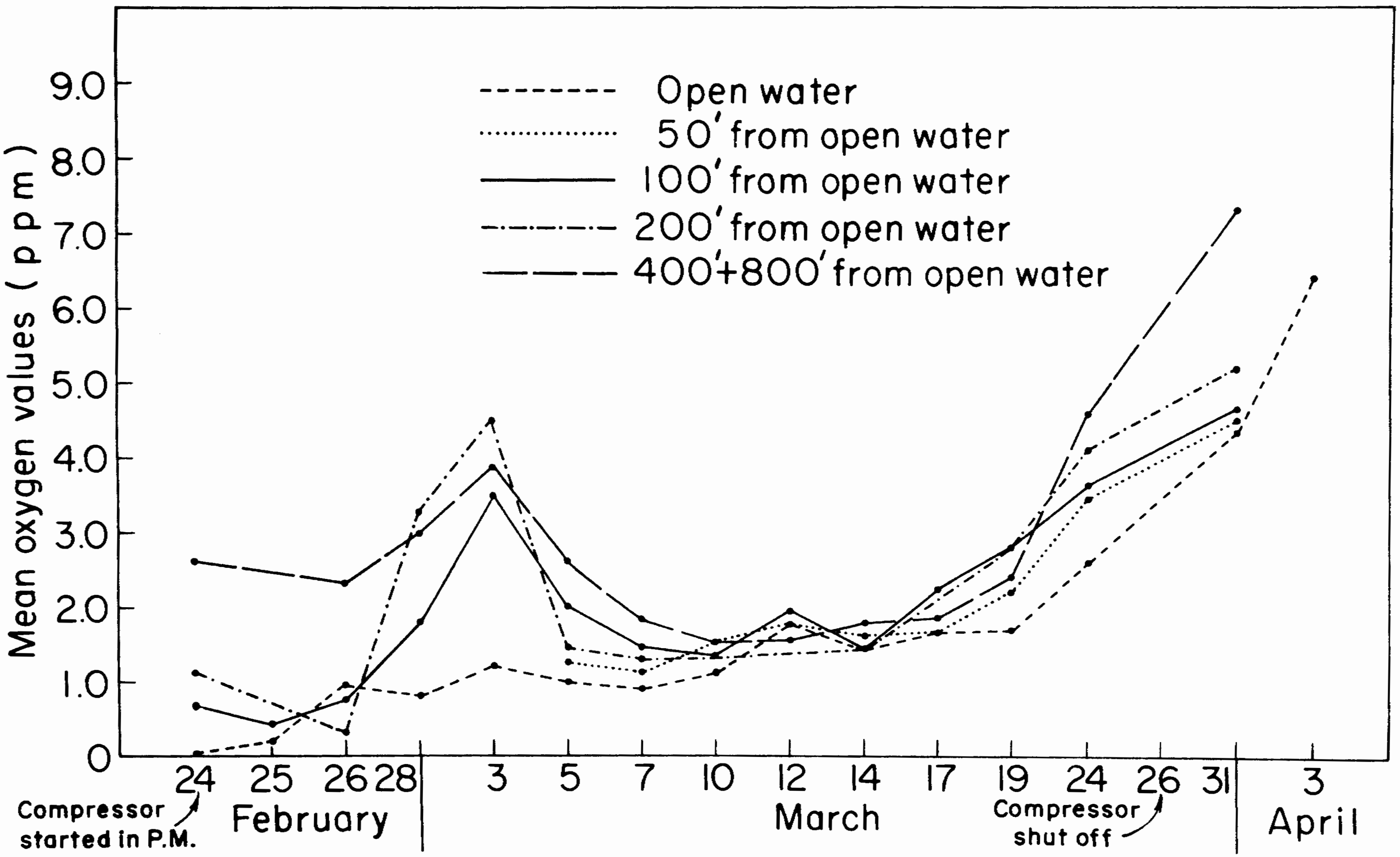

Open water
50' from open water
100' from open water
200' from open water
400'+800' from open water
Mean oxygen values (p p m)
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
24 25 26 28
3 5 7 10 12 14 17 19 24 26 31
3
Compressor started in P.M.
February
March
Compressor shut off
April

Figure 7

level remained quite uniform throughout the lake (mostly below 2.0 ppm.). Late in March the supply was replenished by the beginning of the spring thaw, but during this recharging period the open water above the air conductor was the last to be affected. These observations on Spring Lake suggest that the air line had the effect of reducing dissolved oxygen, rather than increasing it, because of the biological oxygen demand of upwelling water.

In Loon Lake, on December 29, 1958, the oxygen content at two stations in the center of the lake 3 feet below the ice ranged from 6.5 to 6.8 ppm. Water circulation was started the following day and water sampling was begun 1 week later, after a channel of open water had appeared. A marked downward trend in oxygen started the first week (Fig. 8) and continued until about March 20, when the spring thaw began. Since the dissolved oxygen 2 feet below the ice appeared to be fairly uniform throughout the lake, sampling at the 50- and 100-foot stations was done at irregular intervals after January 29, 1959. Semi-weekly sampling was done only in the open water and at two stations beneath the ice, 200 feet on either side of the open channel. Mean values are shown in Table 3.[3]

---

[3] Although most water sampling was done 2 feet below the bottom of the ice, a few deeper samples were taken in both open water and at the 200-foot stations. These data indicated a uniform deficiency of oxygen in open water, but beneath the ice the oxygen content at 10 feet was 0.5 ppm. lower than at the 2-foot level on March 12, and 3.8 ppm. lower on March 30.

Figure 8. --Mean oxygen values at paired sampling stations in open water, and beneath the ice 200 feet from open water, Loon Lake, 1958-59.

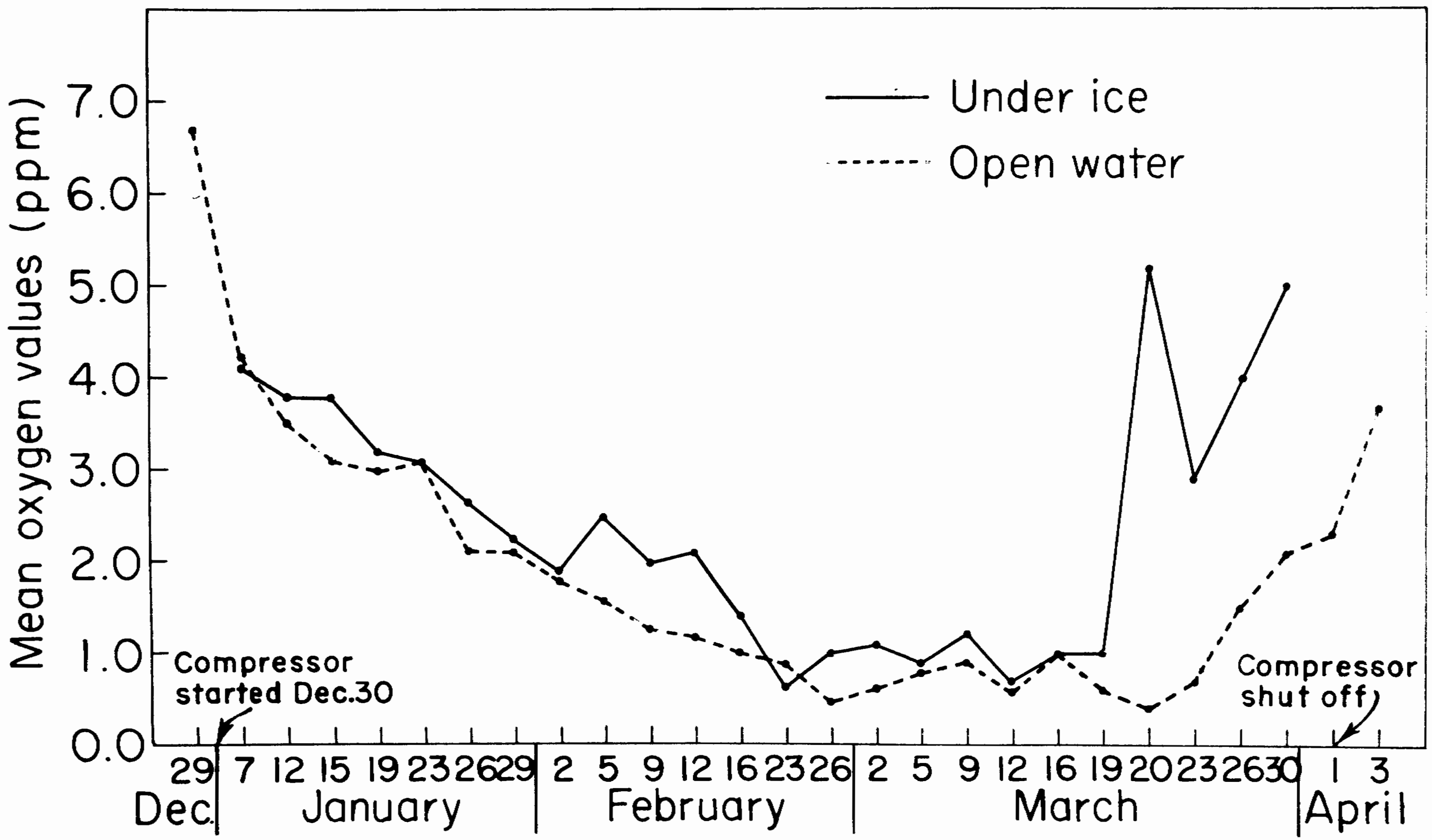

Under ice
Open water
Mean oxygen values (ppm)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Compressor started Dec.30
Compressor shut off
29 7 12 15 19 23 26 29 2 5 9 12 16 23 26 2 5 9 12 16 19 20 23 26 30 1 3
Dec. January February March April

Figure 8

Table 3. --Mean oxygen values (ppm.) at paired sampling stations in open water and beneath the ice in Loon Lake, 1959[1]

[Samples taken about 2 feet beneath lower surface of ice]

Date	Distance of stations from open water (feet)			
	Open water	50	100	200
Jan. 7	4.1	4.0	3.8	4.2
12	3.5	3.8	3.5	3.8
15	3.1	3.7	3.9	3.8
19	3.0	3.1	3.3	3.2
23	3.1	2.9	3.2	3.1
26	2.1	2.8	2.6	2.7
29	2.1	2.2	2.3	2.3
Feb. 2	1.8	...	...	1.9
5	1.6	...	...	2.5
9	1.3	...	...	2.0
12	1.2	...	...	2.1
16	1.0	...	...	1.4
23	0.9	...	...	0.6
26	0.5	0.6	...	1.0
March				
2	0.6	...	...	1.1
5	0.8	...	...	0.9
9	0.9	...	...	1.2
12	0.6	...	...	0.7
16	1.0	...	...	1.0
19	0.6	...	...	1.0
20	0.4	1.7	5.4	5.2
23	0.7	2.3	1.6	2.9
26	1.5	4.1	3.8	4.0
30	2.1	5.2	...	5.0
April 1	2.3	6.1	...	...
3	3.7	...	...	...

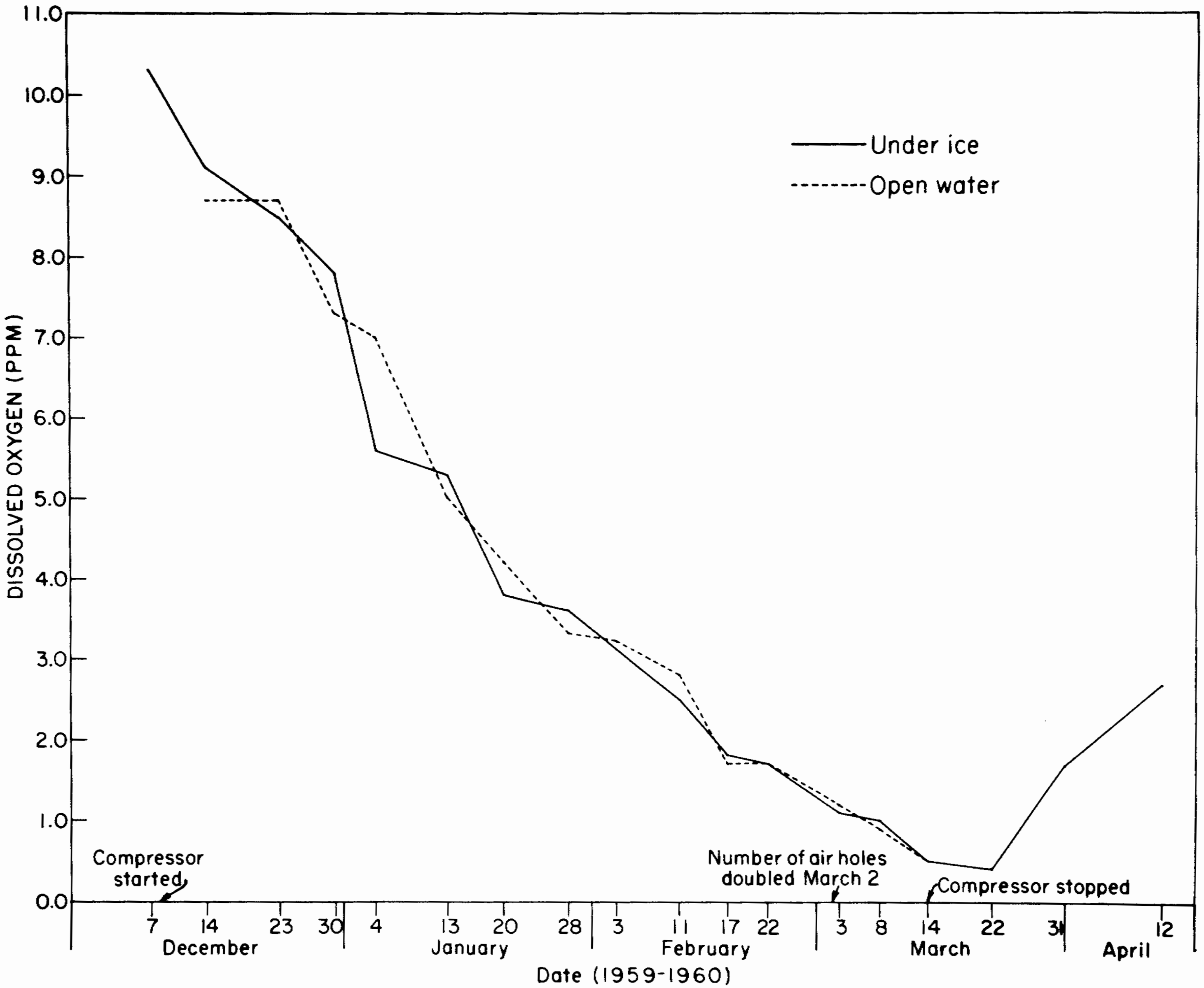
[1] Three samples taken through ice above air conductor on December 29, 1958 (before operation of the compressor was begun on December 30) had an average dissolved oxygen content of 6.7 ppm.

The results in both Spring Lake in 1957-58 and Loon Lake in 1958-59 suggested that a large demand for oxygen by decay processes in the rich, organic, bottom sediments was too great to be overcome by the circulating water, and any oxygen absorbed from the air by the turbulent water was rapidly consumed; very little, if any, was retained in the upper strata. Thus, a low-oxygen condition could neither be prevented nor corrected in either lake by the methods employed. Furthermore, the rapid decline of oxygen in Loon Lake in 1958-59, during the first week following the start of circulation (Fig. 9), suggests that oxygen depletion was accelerated by the upwelling and circulation of bottom water and organic material with a high B. O. D., the same as in Spring Lake.

Experiment with suspended air conductor

It seemed possible that the method of artificial circulation employed in 1958-59 might be used successfully if certain modifications were made to avoid the upwelling of bottom water and to obtain more aeration. Suggested modifications were: (1) installing the air conductor closer to the ice cover; (2) an earlier start--either before or immediately after ice formed; and (3) increasing the number of openings in the line. If, for example, the line lay 5 feet below the surface instead of at a greater depth, only this upper stratum would be circulated. The denser, warmer water beneath would be unaffected because of the temperature gradient which presumably would be established at approximately the 5-foot level. Near-normal winter water temperatures would prevail near the bottom. (What effect, if any, the colder bottom temperatures

Figure 9.--Mean oxygen values at paired sampling stations in open water, and beneath the ice 200 feet from open water, Loon Lake, 1959-60.



DISSOLVED OXYGEN (PPM)
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Under ice
Open water
Compressor started
Number of air holes doubled March 2
Compressor stopped
7
14
23
30
December
4
13
20
28
January
3
11
17
22
February
3
8
14
22
31
March
12
April
Date (1959-1960)

Figure 9

that existed in Loon Lake in 1958-59 had on the benthos is not known, but it is doubtful that the subnormal condition was beneficial.)

In Loon Lake in 1958-59, when the air conductor lay at a maximum depth of 10 feet, about 95 percent (72.4 acre-feet) of the total volume of water in the lake was being circulated. These observations suggested that about 71 percent (54.4 acre-feet) of the total volume would be circulated if the line were suspended at the 5-foot level. It seemed probable that the velocity of the lateral current would be increased and, of course, less bottom area would be exposed to the circulating water, thereby lessening the oxygen demand.

Therefore, during 1959-60, the air line in Loon Lake was held at a depth of 5 feet below the surface, by wooden floats. Circulation was begun on December 8, 1959. (An ice cover had formed on November 15 but very little snow had fallen and the weather was warm during several days of the first week of December.) Oxygen values averaged 10.3 ppm. at a depth of 4 feet and 4.4 ppm. at 10 feet (averages for two stations).

Despite the changes in procedure, a downward trend in oxygen at the 4-foot level developed immediately in the zone of circulation both in open water and beneath the ice 200 feet away--almost identical to that which occurred in Loon Lake in 1958-59 (Fig. 9). Below the 5-foot level the decline of oxygen was even more rapid. Values of 0.5 ppm. or less were first recorded at a depth of 12 feet on January 13; 8 feet on February 3; 7 feet on February 22; and 6 feet on March 3. On March 2, with oxygen values of 1.2 ppm. just below the ice, the number of holes in the air conductor was doubled but this too failed to halt the decline. On March 14, when the oxygen was reduced to 0.5 ppm. at the 4-foot depth both in open water and as far away as 400 feet, the air compressors were shut off. Not until March 28, following a 24-hour warming period, did the oxygen level start to rise.

Schmitz and Hasler (loc. cit.) described rates of aeration in 2 successive years for a Wisconsin lake. At daily rates of about 1/17 and 1/10 cubic feet of air per minute per acre-foot, dissolved oxygen was maintained at about 2 and 7 ppm., respectively. Their rates of aeration closely approximated the rates used in Loon Lake (1/16 in 1958-59 and 1/12 in 1959-60), but the results were quite different.

Carbon dioxide, pH, and methyl orange alkalinity

Measurements of carbon dioxide, pH, and methyl orange alkalinity were made at irregular intervals on water samples collected at 2 feet below the water surface in Spring Lake in 1957-58 and in Loon Lake in 1958-59, and at depths of 4, 8 and 12 feet in Loon Lake in 1959-60.

Carbon dioxide values are shown in Table 4. In Spring Lake, the carbon dioxide was slightly higher in the open water over the air line (and oxygen was lower) than elsewhere in the lake (averages of 8 and 6 ppm., respectively, for the six paired samples from the two areas). However the difference is not statistically significant ($t = 2.077$ with 10 d.f.).

In Loon Lake mean carbon dioxide values were nearly identical (13 and 14 ppm.) in open water and beneath the ice during January-March,

Table 4. --Carbon dioxide values (ppm.) at various water depths, in the vicinity of the air conductor and at a distance of 200 feet, in Spring and Loon lakes during the winter

Date	Lake and year, station location, and depth of sample (feet)								
	Spring (1957-58)		Loon (1958-59)		Loon (1959-60)				
	Open water	200 feet from open water	Open water	200 feet from open water	Open water		200 feet from open water		
	2'	2'	2'	2'	4'	8'	4'	8'	12'
Dec. 17	..	..	..	..	28	33	31	31	34
Jan. 4	..	..	..	..	..	34	28	33	35
12	..	..	11	11	..	..	..	..	..
18	..	..	..	..	39	26	35	27	43
29	..	..	11	12	..	..	..	..	..
Feb. 1	..	..	..	..	34	34	26	26	28
5	..	..	11	12	..	..	..	..	..
25	11	..	..	..	28	27	37	41	50
26	..	..	15	15	..	..	..	..	..
28	10	5	..	..	..	..	..	..	..
March 3	8	5	..	..	..	..	..	..	..
5	8	7	..	..	..	..	..	..	..
7	12	6	..	..	..	..	..	..	..
10	..	..	..	..	27	29	42	26	32
12	9	..	16	17	..	..	..	..	..
17	6	8	..	..	..	..	..	..	..
19	..	..	16	16	..	..	..	..	..
24	5	2	..	..	..	..	..	..	..
April 1	..	..	19	12	..	..	..	..	..
Mean	9	6	14	14	31	31	33	31	37

1959, further evidence of circulation in the lake. As the season progressed (from January 12 to March 19), the carbon dioxide increased (a logical trend in view of the steady decline of oxygen). On April 1, 1959 the carbon dioxide in the open water was substantially higher (19 ppm.) than beneath the ice (12 ppm.), but by this time the oxygen had started to rise throughout the lake except in the vicinity of the air conductor.

In Loon Lake during the winter of 1959-60, carbon dioxide values were consistently much higher than in 1958-59. There was little difference between the strata above the air conductor (sample at 4 feet), and below it (samples at 8 and 12 feet). In open water the mean value (for samples collected from December 17 to March 10) was 31 ppm. at depths of 4 feet and the same at 8 feet; beneath the ice, at corresponding depths, the average values were 33 and 31 ppm. There appears to be no tenable explanation, from the data at hand, for the difference in carbon dioxide in Loon Lake for the two winters.

After aeration was terminated on March 14, 1960, there was a steady rise in carbon dioxide in the deeper water (up to 48 ppm. at the 8- and 12-foot depths on April 12), and a downward trend at the 4-foot level (20 ppm. on April 12). These changes were in the direction of establishing a carbon dioxide profile presumably typical of Loon Lake during the winter (i. e., in the absence of artificial circulation).

The mean methyl orange alkalinity of water taken in Loon Lake was generally similar at comparable depths for the two winters of study and was not affected appreciably by the distance of the sampling station from the air conductor (Table 5). The direct relationship between depth of

Table 5.--Methyl orange alkalinity (ppm.) at various depths in Loon Lake, in the vicinity of the air conductor and at a distance of 200 feet, during the winters of 1958-59 and 1959-60

Year, date, location of station, and water depth (feet)										
1958-59				1959-60						
Date		Open water	200 feet from open water	Date		Open water		200 feet from open water		
		2'	2'			4'	8'	4'	8'	12'
Jan.	12	113	113	Dec.	17	108	123	119	118	126
Jan.	29	110	123	Jan.	4	131	125	107	123	130
Feb.	5	114	123	Jan.	18	140	149	126	155	148
Feb.	26	146	146	Feb.	1	124	124	149	153	157
March	12	155	160	Feb.	25	158	156	134	143	165
March	19	155	155	March	10	172	162	146	153	176
April	1	172	122	...		...	...	...	...	...
Mean		138	135			136	140	130	141	150

water and its total hardness which is commonly observed in eutrophic lakes during periods of thermal and chemical stratification was maintained, however. In both 1958-59 and 1959-60 the alkalinity tended to increase as the winter season advanced, paralleling the rise in carbon dioxide. The pronounced drop in alkalinity beneath the ice on April 1, 1959, probably resulted from dilution by softer melt water (thawing began on March 19).

In Spring Lake on March 24, 1958, the methyl orange alkalinity at a water depth of 2 feet averaged 151 ppm. in the open channel; 126 ppm. at a distance of 50 feet; and 98 ppm. at a distance of 100 feet from the channel.

Loon Lake may be classed as a hard-water lake, its high alkalinity being the result of action of carbon dioxide upon the marl deposits which are intermingled with organic ooze (Hooper, 1956). The water of Spring Lake is only moderately hard, as judged by the lower methyl orange alkalinity at a point well removed from the influence of the air conductor.

The pH of Spring Lake was 7.2 on March 24, 1958, and the same value was found for Loon Lake on December 29, 1958 and January 12 and March 12, 1959. Lower values, ranging between 6.8 and 7.0 occurred in Loon Lake in 1959-60, irrespective of depth. After the compressors were shut off on March 14, three consecutive readings 9 to 12 days apart showed pH values of 7.0 at the 4-foot depth and 6.8 at depths of 8 and 12 feet.

Effect of air-induced circulation on fishing

Data on the reaction of fish in Loon Lake to the presence of circulating open water and the resultant colder environment were obtained by trapping and angling. There was some indication that fish tended to concentrate in the open water. Small traps set under the ice in March, 1959, caught 1 Iowa darter, *Etheostoma exile*; whereas those in open water caught 70 fish (all less than 4 inches long) and 6 tadpoles. Included in the catches were 38 pumpkinseeds, *Lepomis gibbosus*; 17 bluegills, *Lepomis macrochirus* and 10 Iowa darters. Three larger wire traps set in open water caught no fish.

An attempt was made in both 1958-59 and 1959-60 to assess the effect of the experimental circulation of water in Loon Lake on angling success. In 1958-59, two anglers fished as a pair for two hours during each fishing trip; one fished through the ice for an hour while the other fished in open water, and they changed positions after each one hour of fishing. Wax worms (bee larvae) were used for bait. The men fished twice a week between January 9 and February 12. Results were extremely poor. During seven fishing trips (total of 14 hours per man), only one bluegill and one pumpkinseed were caught.

In 1959-60 the design of the angling experiment was changed somewhat to incorporate the additional variables of water depth and type of lure. Each 1-hour period of fishing (in open water or through the ice) was divided equally between water above and below the 5-foot level (depth of air conductor), and wax worms and wigglers (*Hexagenia*) were used alternately as bait.[4] The experimental angling (mostly done by the same two individuals totaled 44 hours between December 22, 1959 and February 12, 1960. Fishing success was good in December and then dwindled rapidly (Table 6). In general the angling supported the results of the trapping in demonstrating that fish tended to congregate near the air line; 97 were caught in open water and only 26 beneath the ice 200 feet away. Within the open-water zone, more than twice as many fish (68) were caught at water depths greater than 5 feet (below the level of the air conductor where normal water temperatures prevailed) than in the colder waters above (29 fish). The good catches made below the 5-foot level occurred in December when the oxygen values averaged 4.5 ppm. in open water and 4.8 ppm. at depths of 8 and 12 feet beneath the ice. The oxygen had dropped to 1.9 ppm. by January 14, after which no more fish were caught in the deeper water.

Winterkills of fish in Loon Lake

Winterkills of fish were observed in Loon Lake in both 1958-59 and 1959-60. In 1958-59, a few distressed bluegills and pumpkinseeds were observed on March 18, even though the dissolved oxygen under the ice had been around 1.0 ppm. since February 23. These fish were crowded into holes in the ice through which water samples had been taken. Dead fish of these species also were found in fish traps on

---

[4] In equal amounts of fishing time, 40 fish (22 bluegills and 18 perch) were caught on wigglers; and 83 (54 bluegills, 17 perch, and 12 pumpkinseeds) on wax worms.

Table 6.--Numbers of fish caught by experimental angling in Loon Lake during the winter of 1959-60

Date[1]	Fishing site, water depth, and species								
	Open water					Through the ice[2]			
	<5 feet		>5 feet			<5 feet		>5 feet	
	Blue-gill	Perch	Blue-gill	Perch	Pump-kinseed	Blue-gill	Perch	Blue-gill	Perch
Dec. 22, 1959	4	2	11	11	3	6	2	1	..
Dec. 28, 1959	7	1	26	7	9	4	..	9	3
Jan. 14, 1960	3	7	1	..	..	..	..	..	..
Jan. 15, 1960	1	..	..	..	..	..	..	..	..
Jan. 19, 1960	1	2	..	..	..	..	..	..	..
Jan. 21, 1960	1	..	..	..	..	..	..	..	..
Feb. 4, 1960	..	..	..	...	..	1	..	..	..
Totals	17	12	38	18	12	11	2	10	3

[1] Two anglers fished for two hours on each of 11 dates (total fishing time, 44 hours). No fish were caught on January 29, and February 5, 9, and 12.

[2] Two hundred feet from open water.

March 19, 20, and 23, after which no more fish were caught. Probably a heavy fish kill was avoided when a thaw began on March 19 and the oxygen level started to rise. The shoreline of Loon Lake was searched for dead fish during the first five days following the break-up of the ice cover (April 16-20). Twenty-nine fish were picked up--14 pumpkinseeds, 11 bluegills, 3 largemouth bass, and 1 white sucker, Catostomus commersoni. A number of dead frogs were found on the bottom in shallow water.

Public fishing in Loon Lake in 1959 was the poorest recorded for this lake during 15 years of complete creel census (1945-1959). Only 92 fish were caught in 71 fishing trips, at the rate of 0.44 fish per hour. (In contrast, 1,346 fish were caught in 318 trips during 1958, at the rate of 1.59 fish per hour.) The winterkill obviously caused some reduction in the population, but there was another factor which may have been a contributor. On August 29, 1958, Loon Lake had been treated with toxaphene at the rate of about 5 ppb. in an attempt to reduce large numbers of small sunfishes. This treatment affected mostly the small fish but also killed a number of the larger fish. Since no fish were caught in the fall of 1958 (after treatment) and very few were caught during the early part of the winter of 1958-59, it is suspected that the toxaphene mortality was greater than the winterkill. Other possible factors contributing to the poor winter angling were the abnormally cold water temperature and the low oxygen content. Presumably fish feed less under those conditions.

A moderately heavy winterkill of fish (mostly bluegills) occurred again in the winter of 1959-60. Evidence that a winterkill would probably occur was first obtained on March 9 when the oxygen had declined to 1.0 ppm. or less, at a water depth of 2 feet. On that date a number of small bluegills congregated in an open hole in the ice. Oxygen values of less than 1.0 ppm. were obtained at a depth of 1 foot below the ice between March 9 and 27 (the lowest recorded value was 0.7 ppm., on March 14). After the dispersal of the ice cover on April 17, the lake was searched for dead fish for 3 consecutive days. A total of 461 fish, 3 inches long or longer, were counted. These included 435 bluegills, 16 pumpkinseeds, 5 hybrid sunfish, 3 largemouth bass, 1 rock bass (Ambloplites rupestris), and 1 brown bullhead (Ictalurus nebulosis). Also, a number of dead frogs, yearling sunfish, and small black bullheads were seen lying on the bottom. No dead yellow perch, black crappies (Pomoxis nigromaculatus), carp (Cyprinus carpio) or white suckers (all of which occur in the lake) were found.

Literature cited

Burdick, Milton E.

1959. Open water in winter. Wis. Cons. Bull. 24(2): 21-23.

Cooper, Gerald P., and George N. Washburn

1946. Relation of dissolved oxygen to winter mortality of fish in Michigan lakes. Trans. Am. Fish. Soc., 76(1946): 23-33.

Greenbank, John

1945. Limnological conditions in ice-covered lakes, especially as related to winterkill of fish. Ecol. Mon. 5: 343-392.

Hemphill, Jack

1954. A method of winter-kill prevention. Ariz. Game and Fish Dept. 8 p.

Hooper, Frank F.

1956. Some chemical and morphometric characteristics of southern Michigan lakes. Pap. Mich. Acad. Sci., Arts, and Let., 41(1955): 109-130.

Moore, E. W.

1939. Graphic determination of carbon dioxide and the three forms of alkalinity. Jour. Am. Water Works Assoc. 31: 51.

Rasmussen, Delbert H.

1960. Preventing a winterkill by use of a compressed-air system. Prog. Fish-Cult. 22(4): 185-187.

Scidmore, W. J.

1957. An investigation of carbon dioxide, ammonia, and hydrogen sulphide as factors contributing to fish kills in ice-covered lakes. Prog. Fish-Cult. 19(3): 124-127.

Schmitz, William R.

1959. Research on winterkill of fish. Wis. Cons. Bull. 24 (2): 19-21.

Schmitz, William R., and Arthur D. Hasler

1958. Artificially induced circulation of lakes by means of compressed air. Science 128(3331): 1088-1089.

INSTITUTE FOR FISHERIES RESEARCH

Mercer H. Patriarche

Report approved by G. P. Cooper

Typed by M. S. McClure