VARIATION IN THE MAXIMUM DEPTH AT WHICH FISH CAN LIVE DURING SUMMER IN A MODERATELY DEEP LAKE WITH A THERMOCLINE

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During several summer sessions the writer served on the staff of the University of Michigan Biological Station, which is on the shore of Douglas Lake, about 17 miles south of the Straits of Mackinac. During the last few years of service he was responsible for instruction work, which included among other things a study of the habits and distribution of fishes in the lake. This led to a desire for a more precise knowledge concerning the vertical distribution of fish in places where the depth is sufficient to permit the establishment of a definite thermocline. During the latter part of the sessions of 1920 and 1921 attempts were made to determine the maximum depth at which fish could remain alive for any considerable length of time in such places and to ascertain what relation such maximum depth might have to the position of the thermocline and to the correlated oxygen and hydrogen-ion conditions. These attempts led to results sufficiently definite and interesting to make publication seem worth while. It became evident that one could predict, within 2 or 3 feet, what such maximum depth would be if furnished accurate data on the temperature, amount of dissolved oxygen, and the acidity conditions existing at levels having 2 or 3 foot intervals in the upper part of the thermocline. From the temperature data alone one could predict nearly as closely. Variations in the depth at which the thermocline is established are accompanied by similar variations in the maximum depth at which fish can remain alive.

Douglas Lake is approximately 4 miles in length, with its long axis extending in a northwest-southeast direction, and the average width is somewhat less than half as much. With the exception of about a half dozen small isolated areas, in which the water is 60 to 90 feet in depth, the water of the lake is too shallow to have a thermocline established. In the deep places or holes, as they are termed in station parlance, a thermocline is ordinarily present during July and August, when the station is in operation. The depth at which the thermocline is established varies considerably in the different holes and in any given one of them is subject to some fluctuation. The depth is apt to be greater in the latter part of the season, and long-continued, strong winds tend to depress the level of the upper part of the thermocline, if not of the entire stratum. For the observations described in this

paper the two deep places nearest to the biological station were selected. One of them, which will be designated as Station A, is but a quarter of a mile away, and the other one, Station B, is about a mile from headquarters. Station A differs from the other stations in being partially sheltered by a high wooded bluff from the full force of the frequent, strong, northwest winds, while Station B is in a position to get the maximum effect of such winds. The thermocline at Station B was ordinarily several feet deeper than that of Station A.

The general plan of operations included the submergence of a series of wire cages attached at different levels to a rope which was suspended from a wooden buoy or float. The float was anchored in the desired situation, and the rope to which the cages were attached had a weight fastened to its lower end to keep the rope taut and maintain a constant depth for the cages. The cages were made of galvanized wire netting of about ½-inch mesh and were cubical in form, with each surface 1 foot square. Fish of several kinds were placed in each of the cages, and they were let down to the desired depths, where they remained until the next visit. Temperature readings and tests for the oxygen content and the hydrogen-ion condition at approximately the same levels as those at which the cages were placed made a part of the records. Subsequent visits at varying intervals of time were made for the purpose of examination of the condition of the caged fish, the removal of dead ones, and the addition of others. Not infrequently additional chemical and temperature examinations were made for comparison with the former ones.

For hearty cooperation in the provision of equipment and in the securing of necessary assistance thanks are due Dr. G. R. La Rue, the director of the biological station. Dr. P. S. Welch generously made the few chemical tests that were necessary the first season. In 1921 Dr. Minna Jewell, who was a member of the station corps of assistants, rendered most valuable service in making all of the chemical determinations and records. For this work she was particularly well fitted because of much previous experience in such chemical studies on this lake and elsewhere.

During the first season the observations were of a preliminary sort for the purpose of finding out whether the limiting depth is very definite, and whether the fish that were obtained in shallow water were suitable for the tests at greater depths. The results seemed to show that the lower limit of the body of water, which had the conditions necessary for sustaining the life of fish, was very sharply defined, and also made it apparent that the fish from shallow water were suitable for the tests.

The first test was made July 26, 1920, at Station A. Data of Doctor Welch, taken three days earlier, showed a thermocline between 45 and 53 feet, with plenty of oxygen at 45 feet. Two specimens of *Lepomis gibbosus* were placed in each of three minnow pails at depths of 40, 55, and 65 feet at 4.30 p. m. At 6.45 p. m. of the same day in each of the pails at the two lower levels one fish was dead and the other one nearly dead. Those in the pail at 40 feet were in good condition and were still living 24 hours later.

On July 28 at 10.40 a. m. yearling bullheads and suckers were placed in the pails at the same depths as before, and at 7 p. m. those in the two lower pails were dead, while those in the upper one were in good condition, and most of the latter were still living 24 hours later.

At Station B, August 3 at 10.35 a. m., four wire cages were placed at 40, 49, 55, and 65 foot levels. Each contained some minnows, perch, and a young smallmouth black bass. The cages were examined at 1.45 p. m., and it was found that all of the fish in the two upper cages were living while those in the two lower cages were all dead. Late in the afternoon of the same day, with the aid of Doctor Welch, records of temperatures were made and water samples taken from the 49 and 55 foot levels. The temperature at 49 feet was 62½°; at 55 feet, 51.6°; and at 65 feet, 50°. The oxygen content at 49 feet was 5.28 c. c. per liter and at 55 feet 2.6 c. c. At 49 feet pH was 7.6, and at 55 feet 7.1. These data indicated that the lowest limit at which fish could live was somewhere in the thermocline.

Tests made August 6 at Station A, in connection with class work, indicated that fish could not live at as great a depth as at Station B, and also that the thermocline was not as far down. In the afternoon of the following day, with the aid of Doctor Welch, who made the chemical examination, the following data were secured:

August 7, 1920, Station A

	Depth			
	45 feet	47½ feet	50 feet	52½ to 70 feet
Temperature, °F	65.8 to 70.4	64	58	51.6 to 46.5
Oxygen, c. c. per liter	5.52 to 7.29	4.33	2.28	0.028 to 0
pH	7.8 to 8	7.7	7.3	7.0 to 6.9

At 4.25 p. m. fish were placed in baskets at 37½, 42½, 47½, and 53½-foot levels. At 8.30 p. m. the fish in the two upper baskets were in good condition; some of those at 47½ feet were all right and some were ailing; all at 53½ feet were dead. During the two following days (August 8 and 9) the tests were continued, with some shifting of depths of the cages, with the general result that it was shown that fish lived very well at 45 feet; at 47½ feet some would live for a day or more but not in good condition; and at 50 feet, or below, all soon died. A young sucker and a young bullhead were left at the 45-foot level until August 17, when they were still in good condition and were released.

During August, 1921, tests were made at Station A on five different dates and at Station B on three dates. Two of these latter tests were unsatisfactory because of the continued high wind and rough water which subjected the buoys to which the cages were attached to constant motion. This presumably accounted for the death of most of the fishes in the upper cages, which, under normal conditions, should have lived. In the tests made in 1921 the cages were placed at 2½-foot intervals. Where slight discrepancies occur between the depths of the cages and the levels at which temperature and chemical records were made, they are due to the fact that on checking up the distances on the rope to which the baskets were attached and by taking for a standard the rope used in taking water samples for analysis such discrepancies were found to exist. Different ropes of varying texture and previous treatment often differ in the amount of change in length which they undergo when subjected to tension under water.

The chemical data in the following records were all obtained by Dr. Minna Jewell. The first of the tests in the summer of 1921 was at Station A on August 5, when the following data were secured:

	Depth					
	37½ feet	40 feet	42½ feet	45 feet	47½ feet	50 feet
Temperature, °F	70.6	68	63	59.5	55.6	53.6
Oxygen, c. c. per liter	4.24	2.35	0.95	0.09	0	0
pH	7.8	7.5	7.3	7.2	7	7

Fish in cages placed at 38 and 40½ feet remained in good condition until the end of the test, several hours later. All of the fish of each of two different sets, including perch, minnows, and mud minnows, died within two hours when put in cages placed at 43 and 45½ feet. One week later the thermocline was somewhat deeper, as shown by the following data:

August 12, 1921, Station A

	Depth					
	40 feet	42½ feet	45 feet	47½ feet	50 feet	52½ feet
Temperature, °F	68.5	68	65.4	58.3	54.9	52.6
Oxygen, c. c. per liter	5.47	5	1.7	0.96	0	0
pH	8.4	8	7.3	7	7	6.9

At 3.08 p. m. about 15 perch (young of the year) were put in each of the cages and placed at 42, 44½, 47, and 49½ feet. At 4.23 p. m. all of those in the two lower cages were dead and all of those in the two upper cages were in good condition except one that had died in the uppermost cage. Those left in the two upper cages were in good condition when examined again at 7 p. m. At 7.45 a. m. of the following day 9 fish were in good condition at 42 feet and 8 at 44½ feet. At 1.45 p. m. only 4 were living at 42 feet and 1 at 44½ feet. A test made August 16 and 17 gave data similar to others and need not be described.

Another depression of the thermocline is shown by the following data:

August 19, 1921, Station A

	Depth			
	45 feet	47½ feet	50 feet	52½ feet
Temperature, °F	66.2	63	54.9	53.8
Oxygen, c. c. per liter	3.6	1.84	.59	.42
pH	8.1	7.4	7.0	6.9

The above records were made at 6.30 a. m., and at 8.15 a. m. fish were placed in three cages at the following depths: In a cage at 45 feet were four perch, a log perch, and a young smallmouth black bass. These had already been in the cage at that depth for two days and still seemed in good condition. A cage containing

a young bullhead, a young smallmouth black bass, and three 2-year-old perch was placed at 47½ feet. A cage with similar contents was placed at 50 feet. At 11.20 a. m. the fish at 45 feet were in good condition. At 47½ feet the bass and one perch were dead but the others seemed to be in good condition. At 50 feet all the fish were dead. At 3.30 p. m. all of the fish at 47½ feet were dead and those at 45 feet were in good condition. At 6.40 p. m. those at 45 feet were still all right, and in the cage at 47½ feet were placed young perch, young *Lepomis gibbosus*, and young rock bass. At 7.30 a. m. of the following day all of the fish at 47½ feet were dead, and in the cage at 45 feet a young bass and two perch were still living, but the others were dead. The fish of that cage had been confined at that depth for three days. The lowest limit at which fish could live was very definitely between 45 and 47½ feet, and in the upper portion of the thermocline.

The last test of the season at Station A showed a still further depression of the thermocline and a corresponding change in the depth at which fish could live.

August 22, 1921, Station A

	Depth				
	45 feet	47½ feet	50 feet	55 feet	70 feet
Temperature, °F	64.4	64	61	51.4	48.8
Oxygen, c. c. per liter	4.84	3.70	2.35	----------	0
pH	8.4	8.0	7.3	----------	6.8

At 1.05 p. m. fish were placed at 45, 47½, and 50 feet, as follows: A cage placed at 45 feet contained 7 young perch, 1 yearling sucker, 2 yearling rock bass, and 2 young bullheads. A cage placed at 47½ feet contained 5 young perch, a half-grown sucker, a young *Lepomis gibbosus*, 2 minnows, and 3 young bullheads. A cage placed at 50 feet contained 2 young perch and 3 young bullheads. The perch used were mostly 2-year-olds and the remainder were yearlings. At 3.15 p. m. the fish at 45 feet were all in good condition, and those at 47½ feet were also, except the two minnows, which were ailing. In the cage at 50 feet the perch were dead and the bullheads nearly dead. At 7.05 p. m. the fish at 45 feet were in good condition and were transferred to Station B for a test to be described later. At 47½ feet the two minnows were dead and the *L. gibbosus* was ailing. These were discarded and the others, still in good condition, were transferred to Station B. The fish at 50 feet were all dead. The lowest limit at which fish could live at Station A was about 7 feet deeper than on August 5, two and one-half weeks previous.

As already stated, high winds and rough water made two of the three tests at Station B in 1921 quite unsatisfactory. The fish were necessarily confined in a relatively small "live box" in a rowboat for an hour or more, while journeying to the station and while temperature and chemical records were being made. During all of this time they were being jostled about because of the motion of the boat, due to the rough water. After they were submerged, the cages containing them were being continually jerked about because of the action of the waves on the float from which the cages were suspended. Although unsatisfactory, the records are not without significance.

In connection with the first test of the season at Station B we have the following data:

August 13, 1921, Station B

	Depth				
	47½ feet	50 feet	52½ feet	55 feet	60 feet
Temperature, °F		66.3		56.5	53.9
Oxygen, c. c. per liter	4.69	2.95	0.77	0.3	0.06
pH	8.2	7.5	7.2	7	7

At 3.15 p. m. four or five perch (1 or 2 years old) were put in each of the four cages, which were placed at the 47½, 50, 52½, and 55 foot levels. About one hour later the cages were raised and examined as well as the rough water would permit without undue rough treatment of the fish. Of those in each of the two upper cages about one-half seemed to be in good condition and the others were ailing. Those of the two lower cages were all dead or dying. The cages were next raised on the morning of the 15th, when the fish were all found to be dead and more or less bruised.

The last test at Station B and the last of the entire series was in some ways quite significant. Fish were placed at 7.30 p. m. on August 22, but the records were obtained on the following day.

August 23, 1921, Station B

	Depth					
	52½ feet	55 feet	57½ feet	60 feet	62½ feet	65 feet
Temperature, °F		65	64.5	64	60	54.6
Oxygen, c.c. per liter	4.87	4.87	4.87	4.65	1.93	0.35
pH	8.3	8.3	8.2	7.7	7.3	7.1

Five bullheads, 1 smallmouth black bass, and 8 young perch were put in a cage, which was placed at the 52½-foot level. The fish that had been in a cage at the 45-foot level at Station A were placed at 55 feet. The fish and cage that had been at 47½ feet at Station A were placed at 57½ feet. Several young bullheads of the season were also included in this cage. At 10 a. m., after the data in the table above had been secured, the cages were raised, and it was found that the fish that had been at 52½ feet were in good condition, with the exception of one perch that had died and was removed. Those that had been at 55 feet were in good condition, except a perch and a yearling sucker that had died and were removed. Those that had been at 57½ feet were in good condition, except a perch that had died and one that was ailing. These were removed and several fresh specimens were added to this cage, including a few perch, a smallmouth black bass, and two mud minnows. Each of the cages was now placed at a level 5 feet below that which it had previously occupied. The one that had been at 52½ feet was now placed at 57½ feet and the others at 60 and 62½ feet, respectively. At 2.10 p. m. the cages were again raised, and it was found that in the one that had been at 57½ feet all of the fish were in good con-

dition except two perch. Of those that had been at 60 feet all were in good condition except one perch that had died and another perch and a rock bass that were ailing. Of those that had been at 62½ feet all were dead except a few bullheads which were nearly dead.

The fish in the 60-foot cage had been confined for over 24 hours, having been at the 45-foot level at Station A for 6 hours on the previous afternoon and then transferred to Station B, where they were at the 55-foot level for over 14 hours and then at the 60-foot level about 4 hours; and yet the majority were in good condition, although they had originally been obtained from shallow water. Some of the fish in the 62½-foot cage had had an experience similar to that just described, and others were fresh specimens put into the cage only about 4 hours before; but the difference of 2½ feet meant the difference between life and death. The data in the last table furnish the explanation. The fish in the 62½-foot cage were in the thermocline with reduced oxygen and unfavorable hydrogen-ion conditions.

A similar change in conditions 20 feet nearer to the surface was found at Station A on August 5, with a corresponding effect on the fish. Fish could live at 40½ feet but died at 43 feet, just as in the last test they could live at 60 feet but died at 62½ feet.

The results of these observations very definitely answered one question that was in mind when the tests were planned. The lowest limit of the body of water that supplies the conditions necessary for fish to remain alive and in good condition is in the upper portion of the thermocline. In this upper part of the thermocline there is a marked decline in the amount of available oxygen and a rapid adverse change in the hydrogen-ion conditions, indicated by the reduction in the numerical value of the pH index. The expression "upper portion of the thermocline" is somewhat indefinite, and further tests may show that a statement placing the lowest limit of the habitable region in the upper quarter or upper third of the thermocline layer is warranted. No attempt was made to determine which of the various factors involved may be most potent in fixing the lower limit of the habitable part of the lake.

SUMMARY

The results of a considerable number of tests made in Douglas Lake, Mich., show a very definite and close correlation between the lowest limit of the body of water in which fish could remain alive and the upper portion of the thermocline. During August, 1921, the position of the upper portion of the thermocline at one station shifted from a depth of about 40 feet to one of 47 feet, and there was a corresponding variation in the depth at which fish could live. At another station, where the depth of the upper portion of the thermocline shifted from about 50 to 60 feet, there was a corresponding change in the depth at which fish could remain alive. They remained in good condition in cages placed at the depths mentioned, while those in cages placed at a level 2½ feet lower down soon died. In each instance the fish in the lower cage were in water having decidedly less oxygen and less favorable acidity conditions, and these factors, rather than that of mere depth alone, determined the lowest limit at which the fish could live. No attempt was made to discover which of the unfavorable factors was most potent.