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Relation of dissolved oxygen to winter mortality of fish in Michigan lakes[1]

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[1] Contribution from the Institute for Fisheries Research

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Abstract

Winterkills of fish in southern Michigan lakes during 1944-45 provided an opportunity to study the effect of different degrees of oxygen depletion on the extent of mortality and survival of several common species of fish. Eleven lakes were investigated. Several inches of snow cover remained on the lakes from December 11 to February 15. This abnormal persistence of snow cover was accompanied by oxygen depletion in some of the lakes to mid-winter lows occurring about February 14. The maximum concentration of oxygen in vertical series taken at about the time of greatest depletion ranged from 0.2 to above 5.0 p.p.m. in the different lakes. Where oxygen depletion was severe this maximum occurred only in a thin stratum immediately beneath the ice. Heavy winterkills occurred only in those lakes in which the dissolved oxygen was depleted to approximately 0.6 p.p.m. or less. The mortality was greatest among bluegills and largemouth bass, apparently 100 percent in some lakes. Among the pumpkinseeds, mud pickerel, northern pike, chub suckers, bullheads, and golden shiners there was a large rate of survival even in lakes where the

oxygen was reduced to 0.3 or 0.2 p.p.m. No instance was encountered of a complete kill of all fish in a lake.

Introduction

Winterkills of fish on an important scale, occurred in many Michigan lakes during the winters of 1935-36, 1939-40, 1940-41, and 1944-45. The lakes involved are very shallow, with muck and peat bottom, and with abundant vegetation. Most winterkills in this state have involved lakes in the southern half of the Lower Peninsula. The reasons for this geographical distribution are not apparent, but might depend on a greater fertility of the more southern lakes or a general geographical difference in the character of the cover of ice and snow.

The returns from a questionnaire sent to the Michigan Conservation Officers, together with our own observations, resulted in a tabulation of 51 lakes with a heavy kill in 1944-45; and judging from subsequent reports, the actual number probably exceeded 75. For the winters 1935-36, 1939-40, and 1940-41, Greenbank (1945; Fig. 2) plotted the distribution of the "most serious instances" of reported winterkills, recording 34, 12, and 11 lakes, respectively.

Presumably the true numbers of lakes which experienced important kills during these years were considerably greater. In the 1944-45 kill, with counts of dead fish on seven lakes used as a basis, the fish mortality in the 51 lakes was estimated at two million or more fish, of which a substantial portion was of game species.

The present paper deals with events of the winterkill in 1944-45. The study was begun in January, 1945 when it was suspected on the basis of prevailing weather conditions that a winterkill might take place.

The field studies involved numerous lakes, and the collection of information of four types: (1) the results of analyses of dissolved oxygen during January to March of 1945; (2) some direct observations on mortality and survival and on behavior of fish at the time of reduced oxygen; (3) a determination of the kinds and numbers of dead fish that floated to shore at the time the lakes were cleared of ice in the spring; and (4) the results of gill netting and/or seining during 1945 and 1946 to determine the kinds and relative abundance of fish that survived. The present account is limited mostly to the results obtained on six lakes in which some mortality took place. Several other lakes in which little or no mortality occurred are cited for comparison. The aim of this paper is to describe the relationship between the degree of oxygen depletion and the extent of mortality and survival of the various species of fish in the several lakes.

The results of an intensive study of the limnological conditions related to winterkill in lakes of southern Michigan were the subject of a recent paper by Greenbank (1945). That author also summarized much of the literature on the subject.

Winterkills are not only confined to shallow, mud-bottom, weedy lakes, but occur generally only during winters when lakes are covered for an unusually protracted period by cloudy ice and heavy snow. Cloudy ice and snow greatly inhibit the penetration of sunlight into the lake water. Where such a condition prevails without interruption for several weeks on shallow and organically rich lakes, the loss of dissolved oxygen due to organic decomposition so exceeds the production of oxygen by photosynthesis that oxygen values are eventually reduced almost to the vanishing point. Winter oxygen profiles on rich lakes typically show much less oxygen in deep than in surface waters, and in instances of extreme depletion the oxygen may be limited to mere traces in surface waters. Winterkills usually have been found associated with low dissolved oxygen. The majority opinion of various investigators has been that the fish die because of a lack of oxygen, although some have suggested that death might be due to the presence of "poisonous" gases such as hydrogen sulfide, methane, and carbon dioxide which is usually concurrent with low oxygen values. The question has not been settled by controlled experiments on the effect of each factor alone. Thus it is not certainly established whether the fish die because of lack of oxygen, because of the presence of harmful gases, or because of a combination of the two. However, the question is perhaps of limited importance to the present paper, in which the most significant contribution is information on the extent to which fish will survive at very low oxygen values.

Methods

Sampling for determinations of dissolved oxygen was started on four lakes on January 12 and was continued at approximately weekly intervals to the first week in March. The seven additional lakes were sampled on one or two dates during the first part of February. In the four lakes that were sampled weekly, the extreme in oxygen depletion was reached immediately preceding the thaw which occurred on February 14 to 15. It may be assumed, therefore, that the samples from the other seven lakes in mid-February gave oxygen values which were near the winter minima.

Samples were taken at several stations on Green Lake, at two stations on First Sister, and at one station on each of the remaining lakes. The stations on Green Lake were at scattered points in both shallow and the deeper water and in an area near the inlet. On the remaining lakes the stations were near or over the deepest water and/or near the lake centers. Holes were spudded through the ice with as little agitation of the water as possible. Samples were taken from the surface (upper foot) and usually at the bottom and at intermediate depths, by means of the can type of sampler described by Greenbank (1945). Oxygen tests were made by the unmodified Winkler method.

Some observations were made on fish activity and mortality at sampling stations and at larger holes cut in the ice for this purpose. Examinations of the lake bottom for the presence of dead fish were aided by the use of a canvas covering over the observer. During late February observations were made on dead fish lying against the under surface of the ice in places where the ice was transparent. At Green Lake the concentration of live fish in the inlet during the time of greatest oxygen depletion in the lake was investigated.

On Green Lake it was observed that a heavy mortality occurred during January and February, that large numbers of the dead fish were lying against the under surface of the ice during late February, and that these fish drifted to shore en masse when the lake was cleared of ice. A similar sequence of events was noted for dead fish on other lakes. It is concluded that a large portion of the dead fish will appear along the leeward shore of a lake when the ice clears.

When the lakes cleared of ice about March 16, the presence or absence of dead fish along shore was noted, the fish were identified as to species, and counts were made of their numbers. The counts of fish along measured, representative sections of shore served as a basis for estimating total mortality. Our figures on total mortality are recognized as considerably below the true values, since it is believed that some of the dead fish do not come to the surface and also that many of the smaller ones are disintegrated by wave and ice action as they drift shoreward.

During the spring and summer of 1945 and 1946, the lakes which suffered a winterkill were netted (by fyke nets, gill nets, and seines) to determine the kinds and general abundance of the species that had survived.

The species of fish to which reference is made in this paper are as follows: largemouth bass (*Huro salmoides*), bluegill (*Lepomis machrochirus*), black crappie (*Pomoxis nigro-maculatus*), pumpkinseed (*Lepomis gibbosus*), warmouth (*Chaenobryttus coronarius*), mud pickerel (*Esox vermiculatus*), northern pike (*Esox lucius*), brown bullhead (*Ameiurus nebulosus*), yellow bullhead (*Ameiurus natalis*), black bullhead (*Ameiurus melas*), tadpole madtom (*Schilbeodes mollis*), lake chubsucker (*Erimyzon sucetta*), yellow perch (*Perca flavescens*), Iowa darter (*Poecilichthys exilis*), golden shiner (*Notemigonus crysoleucas*), blackchin shiner (*Notropis heterodon*), blacknose shiner (*Notropis heterolepis*), western mudminnow (*Umbra limi*), blackstripe topminnow (*Fundulus notatus*), brook silverside (*Labidesthes sicculus*), and bowfin (*Amia calva*).

Description of the lakes

The lakes, with which this paper deals, are located in the southeastern corner of the Lower Peninsula in Washtenaw and Jackson Counties. Their names, locations, and some of their physical features are given in Table 1. The last five lakes listed are those in which an extreme oxygen depletion was accompanied (in all except one) by heavy mortality of fish. These lakes range in size from 4 acres up to about 400 acres. Their maximum depths are mostly less than 20 feet, and their average depths about 3 to 7 feet. They have either

Table 1.--Locations and some physical features

of lakes considered in this report

Lake	County	Township and range	Area (acres)	Maximum depth (feet)	Approximate average depth (feet)	Inlet and outlet
Cavanaugh	Washtenaw	2 S., 3 E.	217	20	6	None
Four Mile	"	1 & 2 S., 4 E.	256	18	5	Both small
Mill	"	2 S., 3 E.	142	25	8	" "
Sugarloaf	"	1 S., 3 E.	180	20	4	Inlet 100 g.p.m.[2], and springs, large outlet
Cassidy	"	1 S., 3 E.	46	12	4	No inlet, small outlet
Grass	Jackson	2 S., 2 E.	360	[1]10	[1]5	Both small
Batteese	"	1 S., 1 E.	100	[1]16	[1]7	" "
First Sister	Washtenaw	2 S., 5 E.	4	20	7	None
Goose	Jackson	2 S., 1 & 2 E.	425	[1]8	[1]3	Both small
Green	Washtenaw	1 S., 3 E.	90	11	4	Inlet 50 g.p.m.[2], dam at outlet
Merkle	Jackson	1 S., 2 E.	88	12	4	None

[1] Figures are estimates based on casual observations. Intensive surveys have not been made.

[2] Gallons per minute

very small inlets and outlets or none at all, and consequently there is no appreciable displacement of water during the winter. Rooted plants are abundant in most of them. In most features the six lakes that did not suffer heavy winterkill are closely similar to those that did have winterkill.

Time and nature of the snow and ice cover

These lakes were frozen over by early December in 1944 and were blanketed by several inches of snow on December 11. They remained completely covered by snow almost continuously until February 15, 1945. The thickness of the snow cover, which was measured frequently from January 12 to February 14, varied from 2 to 5 inches and averaged about 3 inches. Additional snowfall on January 22 and February 7 compensated for occasional light thaws and packing. There was little rain or thaw water on the ice; thus the snow and ice remained dry throughout the period. The thickness of ice averaged approximately 6 inches on January 12, 10 inches on January 29, and 12 inches on February 12.

On February 14-15 there occurred a 24-hour thaw and light rain which cleared most of the snow from the lakes. As a result the ice surface was covered with large amounts of water which poured into the lakes through fractures in the ice. This thaw initiated a period of oxygen rejuvenation in those lakes which up to February 14 were experiencing a considerable oxygen depletion. Subsequent thaws, in late February and early March, added more surface water to pour into the lakes. The lakes were clear of ice on March 16. February 14 marked the end of the downward trend in dissolved oxygen.

Severity of oxygen depletion and reactions of the fish

In the vertical series of oxygen samples at the various stations, the surface samples (taken at a depth of from 6 inches to a foot below the surface) almost invariably had the most oxygen. In the following discussion only the surface oxygen valuesare cited in most instances.

Maximum oxygen values on Green Lake at two stations on January 12 were 2.2 and 4.7 p.p.m.; at the one station sampled on January 22, the maximum was 0.9 p.p.m.; at two stations on January 29, the highest values were 0.4 and 0.1 p.p.m.; at eight stations on January 31, oxygen in surface samples ranged from 0.05 to 0.8 p.p.m.; and at seven stations on February 5 to 7, surface values ranged from 0.1 to 0.3 p.p.m.

The single inlet to Green Lake was about 150 yards in length, and had a flow of about 50 gallons per minute; the current was mostly sluggish. This inlet served as a refuge for many fish while the lake was at a low point in dissolved oxygen. On January 29 it contained an estimated 2 to 4 thousand fish, 3 to 8 inches long. Included were mud pickerel, bullheads, chubsuckers, golden shiners, pumpkinseeds, yellow perch, and mudminnows. No bluegills, crappies, or bass were seen, however, among hundreds of fish identified. On January 31 the number of fish "packed" into the inlet was estimated at 15,000. At the head of the inlet, above the 15,000 fish, the dissolved oxygen was 7.1, while at the mouth of the inlet it was 0.05 p.p.m. The estimated 10,000 fish, which had moved from the lake into the inlet between January 29 and 31, had been living in the lake during a period, probably of at least several days, when the oxygen was below 1 p.p.m.

On January 29, many dead fish were observed on the bottom of Green Lake through large holes cut in the ice. Oxygen in the lake had been below 1 p.p.m. for at least a week. Several live bluegills (adult and young), bullheads, pumpkinseeds and perch appeared in one of the openings on January 29. These fish apparently were distressed, but otherwise normal. The oxygen concentration was 0.4 p.p.m. at the surface in this opening. At one of the holes, reopened on January 31, five live adult black crappies were observed; the surface oxygen was 0.8 p.p.m. On February 1, many bullheads and one golden shiner were observed in an opening where the surface oxygen was 0.8 p.p.m. On February 5, several dead bullheads and one live one were observed in a reopened hole where surface oxygen was 0.1 p.p.m.

The observations at Green Lake indicated that by the time dissolved oxygen had been reduced to less than 1 p.p.m. (quite uniformly over the lake and in the lower part of the inlet) there had been a considerable mortality of fish. Many fish were still living, however, in the lake including some bluegills and black crappies and (those which subsequently moved into the inlet) many perch, mud pickerel, bullheads, pumpkinseeds, chubsuckers, and golden shiners.

In Third Sister Lake, which is without inlet or outlet, dissolved oxygen at the two stations was down to less than 0.5 p.p.m. for at least a week in February. The surface values were 0.4 and 0.2 p.p.m. on February 5 and 0.2 and 0.3 p.p.m. on February 14. For the following two weeks the oxygen concentration was mostly less than 1 p.p.m. A wind-driven air pump had been installed at the lake, with the air vent near the lake bottom in about 8 feet of water. The upwelling of water caused by the release of air from this vent kept a twelve-foot opening in the ice almost continuously. The air pump was not accomplishing its intended purpose of maintaining a high oxygen concentration in the lake, but it provided an opening for frequent observations. One of the two sampling stations was at this hole above the air-pump vent. On January 12 and 29 surface oxygen values were

2.9, 2.3, and 1.1 p.p.m., and there was no concentration of fish at the air hole. On February 5, when the surface oxygen was 0.4 p.p.m. at the center of the lake and 0.2 p.p.m. at the air hole, live fish were observed at this opening. These fish included several young bluegills and chubsuckers, several hundred golden shiners, and several adult mud pickerel. The fish were distressed and were crowding near the surface, but they were sufficiently wary to be readily frightened away. On February 14 the surface oxygen was down to 0.2 and 0.07 p.p.m. at the two stations, and a sample secured by skimming the surface film at the air hole gave only 0.3 p.p.m. of oxygen. At this time there were an estimated 10 to 20 thousand fish milling around at the surface of the air hole. They were distressed, but still wary and easily frightened. The fish were mostly golden shiners and bullheads, plus a few chubsuckers, pumpkinseeds, black crappies, mud pickerel, and mudminnows, and one northern pike. About a dozen dead golden shiners and bullheads were at the surface. It is concluded that in this lake many thousands of fish, mostly golden shiners and bullheads, lived for at least a week at oxygen concentrations of less than 0.5 p.p.m.

On Batteese Lake the surface oxygen concentration was 7.8 p.p.m. on January 12, 1.6 p.p.m. on February 5, and 0.05 and 0.6 p.p.m. at two stations on February 13. Presumably the February 13 values represented the low point for the season. In a fish shanty near one of the stations on February 13, we observed about a dozen juvenile bluegills pass beneath us during a period of ten minutes. Fishermen reported seeing no dead fish up to this date, but they had observed that fish were unusually near the surface.

At Grass Lake oxygen concentration at the surface was 0.7 p.p.m. on February 14 (presumably the low point for the season). On this date and near the sampling station live bluegills were observed beneath thin ice in a frozen-over fishing hole. On February 27 transparent ice provided a good opportunity to observe any dead fish lying against the under surface of the ice. Since we counted only a few dozen centrarchids and perch, there apparently had been only a very light kill.

On February 5 surface oxygen on Merkle Lake was 0.2 p.p.m. and on Goose Lake it was 0.5 p.p.m. No observations of mortality were made on these two lakes at the time of oxygen sampling.

On Sugarloaf Lake oxygen values at the one station were 5.4 p.p.m. on January 12, 7.9 p.p.m. on January 22, 4.4 p.p.m. on January 29, 2.6 p.p.m. on February 5, and 1.8 p.p.m. on February 12. On February 19, the values were 1.8 p.p.m. at a depth of 3 inches and 0.7 p.p.m. at a depth of from 6 inches to a foot. The latter figures presumably represent the minimum for the winter. In early March a very few dead fish were seen through the ice. Fishermen (several) reported seeing no distressed fish around their fishing holes.

Oxygen samples on Cassidy Lake were taken only on February 19, four days after the thaw on February 15. The surface oxygen was 1.1 p.p.m., and judging from the observed oxygen changes on other lakes during this period, it is probably that this figure for Cassidy Lake was not much above the winter low. The surface oxygen value for Mill Lake on February 12 was 4.1 p.p.m., for Cavanaugh on February 14 it was 9.2 p.p.m. and for Four Mile on February 16 it was 7.4 p.p.m.

The probable winter minima of oxygen values for these three lakes were about 4, 9, and not below 5 p.p.m., respectively. Accordingly no mortality was anticipated on these three lakes.

Extent of the winterkill in the various lakes

At the time the ice went out in March, no significant numbers of dead fish were observed along the shores of Cavanaugh, Four Mile, Mill, Sugarloaf, Cassidy, and Grass Lakes. It was concluded that these lakes had no kill at all or else sustained only a very light one. No dead fish were observed at Third Sister Lake; and it is considered unlikely that any heavy mortality took place.

On Batteese, Goose, Green, and Merkle Lakes the windrowed dead fish were estimated to number 330,000. This figure represented an average of several hundred fish per acre. The fish were mostly half-grown and adult; there were relatively few young. The bluegill predominated among the dead fish. Pumpkinseeds, bullheads, largemouth bass, chubsuckers, yellow perch, and northern pike were the other principal species represented. Subsequent netting in these four lakes has shown that of the largemouth bass and bluegills, a fair number survived in Batteese Lake, a few in Goose Lake, and apparently none in Green and Merkle Lakes. Among the yellow perch, chubsuckers, and northern pike there was a considerable mortality, but nevertheless a considerably better survival than of bass and bluegills. Bullheads and golden shiners had the best survival. The selectivity of the kill by species was against the interests of fishermen as the more desirable game species suffered the heaviest mortalities, and the least desirable species had the highest rate of survival. The same type of selective winterkill was noted by Eddy and Surber (1943), presumably for lakes in Minnesota.

The examination of the records of mortality and survival of fish in relation to minimum winter oxygen values for the several lakes (Table 2) leads to the conclusion that a heavy mortality among the warm-water lake fishes, at near-freezing water temperatures, occurred only in lakes where the dissolved oxygen was depleted to considerably less than 1 p.p.m. The critical point for some species seemed to be in the range of 0.5 to 0.7 p.p.m. Among other species it was near 0.3 p.p.m. or even less.

The validity of these conclusions rests on the assumption that the minimum oxygen values obtained at single stations on most of the lakes were close approximations of the maximum amount of oxygen available throughout each entire lake. It is recognized that some variation in oxygen concentration does occur over the lake surface, and that inlets and flow from springs complicate matters by creating local areas of higher than average oxygen concentrations. The effect of an inlet carrying oxygen-rich water can be illustrated by the concentration of fish, described previously, in the stream flowing in to Green Lake. On the other hand, the fact that every one of 13 scattered stations on this same lake gave oxygen determinations of less than 0.8 p.p.m. offers strong argument for a high degree of reliability for information secured at a single station. Furthermore, Green Lake was the only lake in which fish were observed by us or reported by fishermen to concentrate in an inlet or outlet. The belief that surface oxygen conditions were relatively uniform throughout each lake received

Table 2.--Relationship between the severity of depletion of dissolved oxygen and the mortality and survival of fish in 11 lakes of southeastern Michigan

Lake	Approximate minimum concentration (p.p.m.) of dissolved oxygen in upper 1 to 4 feet of water	Extent of mortality and survival
Cavanaugh	9.2 to 3.6	No kill
Four Mile	7.4 to 2.6 (probably not below 5.0)	" "
Mill	4.1 to 3.0	" "
Sugarloaf	1.8 to 0.7	Practically no kill; largemouth bass, bluegills, and other species present.
Cassidy	1.1 to 0.7 (probably not below 1.0)	Light kill, if any. Some kill reported; none observed. Largemouth bass, bluegills, and other species present.
Grass	0.7 to 0.6	Very light kill of largemouth bass and bluegills. No kill of other species.
Batteese	0.6 to 0.5	Heavy kill of bluegills; light kill of other species. Fair survival of largemouth bass and bluegills; good survival of perch, black crappies, golden shiners, brown and yellow bullheads, northern pike, pumpkinseeds, mud pickerel, blackstripe topminnow, and brook silverside.
First Sister	0.3 to 0.2	Extent of mortality uncertain. Good survival of golden shiners and bullheads.
Goose	0.5 to 0.05	Heavy kill of bluegills and largemouth bass; light kill of other species. Some survival of largemouth bass and bluegills; good survival of perch, chubsuckers, brown and yellow bullheads, golden shiners, mud pickerel, and bowfin.
Green	0.3 to 0.1	Very heavy kill of largemouth bass, bluegills, pumpkinseeds, perch, and black crappies; lighter kill of other species. Apparently no survival of largemouth bass and bluegills; good survival of perch, chubsuckers, yellow bullheads, golden shiners, blacknose shiners, and mud pickerel; some survival of black crappies and pumpkinseeds.
Merkle	0.2 to 0.0	Very heavy kill of bluegills, chubsuckers, largemouth bass, black crappies, pumpkinseeds, warmouth, northern pike, bullheads and perch. Some survival of brown and yellow bullheads, golden shiners, bowfin, blacknose and blackchin shiners, tadpole madtom and Iowa darter. Apparently no survival of bass or bluegills.

additional support from the lack of concentrations among the fish that could be seen floating dead just below the ice.

The toleration threshold of dissolved oxygen for largemouth bass and bluegills was about 0.6 p.p.m. For perch, mud pickerel, pumpkinseeds, northern pike, and chubsuckers the toleration level, in the vicinity of 0.4 to 0.3 p.p.m., was definitely lower than for bass and bluegills. Bullheads and golden shiners survived in still lower oxygen concentrations--at less than 0.3 or 0.2 p.p.m. Some of the smaller forage fishes, specifically blacknose and blackchin shiners and Iowa darters, survived in one lake which had less than 0.2 p.p.m. of oxygen. Even with such low oxygen values of 0.3 and less, no instance was encountered of a complete kill of all fish in a lake.

That certain species of fish will tolerate lower concentrations of oxygen at near-freezing temperatures than will others has been demonstrated experimentally by Moore (1942) and mentioned by Wilding (1939), Greenbank (1945), and others (references cited by Wilding and by Greenbank). Moore determined oxygen thresholds as follows: largemouth bass and northern pike, about 2.3 p.p.m.; yellow perch, 1.5; black crappie, 1.4; pumpkinseed sunfish, 0.9; bluegill, 0.8; black bullhead, 0.3; and golden shiner, 0.0. The thresholds as indicated by the present study are notably lower than Moore's figures, especially for largemouth bass, northern pike, yellow perch, and black crappie.

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