WINTER CONDITIONS IN THREE LAKES WITH SPECIAL REFERENCE TO DISSOLVED OXYGEN

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WINTER CONDITIONS IN THREE LAKES WITH SPECIAL REFERENCE TO DISSOLVED OXYGEN

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ABSTRACT

Three lakes in the Edmonton area were studied during the winter from October 17, 1956 to May 5, 1957. The oxygen content of the water was determined by the unmodified Winkler method.

All three of the lakes underwent an oxygen depletion to a level at which fish would be expected to asphyxiate. Only in one of the lakes did a winter-kill occur. The fish present in the lakes became acclimatized to the low oxygen level. This level was shown to be about 1.25 p.p.m..

The oxygen demand of the water was determined. The experiment showed that the aerobic decomposition of organic material within the water is the greatest factor in the depletion of the lake oxygen.

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INTRODUCTION

(1) The Local Importance of Winter Conditions

During the past few years the provincial government has undertaken an extensive fish planting program in and around the Edmonton area. This program was designed to give the local fisherman a good game fish within a relatively short travelling distance of home. At the same time it put to a useful purpose bodies of water that were either producing an inferior variety of game fish or in some cases no game fish at all. The fish planted in these lakes are rainbow trout (*Salmo gairdneri*) and the lakes are small "pot-holes" that average 15 feet in depth.

The program has been received with great enthusiasm by the local fishermen. Before trout were planted in Cottage Lake (one of the study lakes) the lake was visited only by people who had cottages in the vicinity. Now that trout have been planted, on one particular Sunday, 600 cars, averaging three people per car, were counted visiting the lake. It was also estimated that at least one quarter of the people present fished the lake on that day. The second lake studied, Star Lake, is also enjoying an increase in popularity since it has been stocked with trout. This popularity lasted the year around, even when the temperature registered 30 degrees below zero. On warmer winter days there were as many as 30 people on the lake fishing. Muir Lake, the third lake studied, also attracts fishermen. According to local residents, fishing is very popular especially during the summer months.

The program has not been an unqualified success. Knowledge of the management of these fisheries is extremely scanty and many problems have arisen. One of the most pressing of these is the determination of the limnological conditions that lead to winter-kill; i.e. death of trout under the ice or in early spring. The study, reported here, is an attempt to find some of the basic factors involved. It was believed that a study of dissolved oxygen depletion, biological oxygen demand of the water, the organic content of the bottom mud, and the movements of the fish, might reveal some of these basic factors. From this information a field worker might be able to predict whether or not a barren body of water could maintain a fish population for a number of years. An example was visualized as follows: A lake or "pot-hole" (from now on to be called lake) to be planted is sounded to determine its depth. Samples of water are taken after the fall overturn but before freeze-up, to determine the oxygen content. During the winter, periodic oxygen samples and biological oxygen demand determinations are made. These findings are plotted on a prediction chart and, by spring break-up, the lake can be tabled as suitable or unsuitable for planting. A chart of this type is not yet available; a purpose of this study was to try to provide the necessary data for constructing one. A second consideration which prompted this research was the fact that a lake in winter has a set of conditions entirely different from those existing in summer. The cover of ice (and often snow) isolates the water from most of the external environmental changes. Thus aeration by wind and wave is arrested and the diffusion of other gases out of the water is prevented.

This interference with the oxygen supply results in severe stagnation and oxygen depletion in most shallow eutrophic lakes. The extreme stagnation that may develop at times has been characterized in the past by the mortality of game or food fish. This mortality is called winter-kill or winter suffocation.

In order to learn how depletion of dissolved oxygen occurs, an attempt was made to find out (1) how fast the dissolved oxygen disappeared in the various lakes and (2) the reasons for the depletion, such as: (a) the biological oxygen demand of the water, and (b) the amount of organic material in the ooze.

(2) A Review of Literature on Winter Conditions

An attempt to understand what actually happened after the ice covered the lake was made by Hazzard (1941). He analyzed the effect of winter fishing and concluded that the isolation of many lakes by deep snow and impassable roads prevents winter fishing from depleting the crop in northern lakes. Clarke (1939) extended these investigations to southern Michigan lakes. Based upon population estimates and creel census records, he concluded that even though the catch in winter on such lakes may be high, only a small percentage of the legal fish is removed by winter fishing and that there is no immediate danger of depleting the stock in these waters. These men also stated that winter was the best time to investigate and map lakes and stressed that more work should be done in winter surveys.

W. G. Moore (1942) studied the oxygen requirements of certain fresh-water fishes. He reported that in winter the metabolic activity decreased due to the low temperature, with consequent lessened oxygen requirements of the poikilothermous fishes. Not only was the absolute oxygen consumption markedly reduced, but the oxygen threshold below which fishes could

not extract sufficient oxygen from the water to sustain life was also depressed. Irving, Black, and Safford (1941) also showed that the affinity of the haemoglobin of fish blood for oxygen increased as the temperature declined.

Cooper and Washburn (1946) reported on the relation of dissolved oxygen to winter mortality of fish in Michigan lakes. Although they found oxygen levels as low as 0.3 or 0.2 p.p.m., no complete kill of all the species of fish in a lake was encountered. They concluded that fish of different species differ in their minimum oxygen requirements.

One of the most extensive reports published was that of Greenbank (1945) who studied the limnological conditions in ice-covered lakes, especially as related to winter-kill of fish. The studies were carried out during the winters of 1937-38, 1939-40, 1940-41, and 1942-43. His report covered many limnological aspects, some of which were: dissolved oxygen, biochemical oxygen demand, light penetration, oxygen consumption and replenishment, winter suffocation of fish and finally preventive and remedial measures. (The work reported in this thesis was largely patterned after Greenbank's methods, except that no studies of light penetration were made.) According to Greenbank it is probable that the respiration of fish and other animals and plants plays an insignificant part in the depletion of the oxygen. The main consumption comes from the bacterial decay of organic matter, either suspended or dissolved in the water or deposited on the bottom as ooze. The production of oxygen is mainly from the phytoplankton. The winter-kill of fish is mainly due to lack of sufficient dissolved oxygen together with high concentrations of carbon dioxide or other harmful gases. Different species show different

tolerances to low amounts of oxygen. Once a lake has developed severe winter stagnation, usually little relief can be secured from the application of artificial measures such as cutting holes in the ice or pumping air into the water.

The effect of oxygen depletion on fish has been extensively studied, e.g., Jahoda (1947), Shaw (1947), Shepard (1954). Scidmore (1956) has investigated the influences of other gases on winter-kill.

II DESCRIPTIONS OF THE STUDY LAKES

Three lakes in the Edmonton area were examined over a period of eight months, October 1956 to May 1957, inclusive. In this portion of the report the location, areas, depths, contours and sampling stations will be described.

(1) Cottage Lake

This lake lies in section 30, township 52, range 1, west of the fifth meridian. It has an area of approximately 230 acres. The surrounding country is rolling prairie, partly wooded, with patches of sandy soil. Miller and Macdonald (1949) examined this lake to determine angling conditions within it.

The lake shore is mostly of mud and the lake bottom is fairly soft. One beach of fine sand is present on the southeast side.

Soundings were made in order to determine the best locations for the sampling stations. The depths found and the resulting stations are shown on the accompanying maps (Fig. 1a and 1b). The greatest depth on the southeast side was 25 feet. There is a considerable area of water

of twenty feet or more in depth. A shallow sandy bar runs across the southern end and divides the lake into two basines. The area of the northern basin is cut down considerably by an island. According to local people the lake level has been dropping for the last 30 years. There are no outlets or inlets at the present time but it is reported that at one time the lake was fed by creeks.

The lake becomes uniformly warm from top to bottom in the summer.

(2) Star Lake

This lake lies in section 19, township 52, range 2, west of the fifth meridian. It has an area of approximately 60 acres. The surrounding country is rolling parkland. There are trees all around the lake except on the southwest shore. The shoreline is irregular with one small treed island on the west side.

The lake shore is mostly mud and the lake bottom is very soft. There are no sandy beaches.

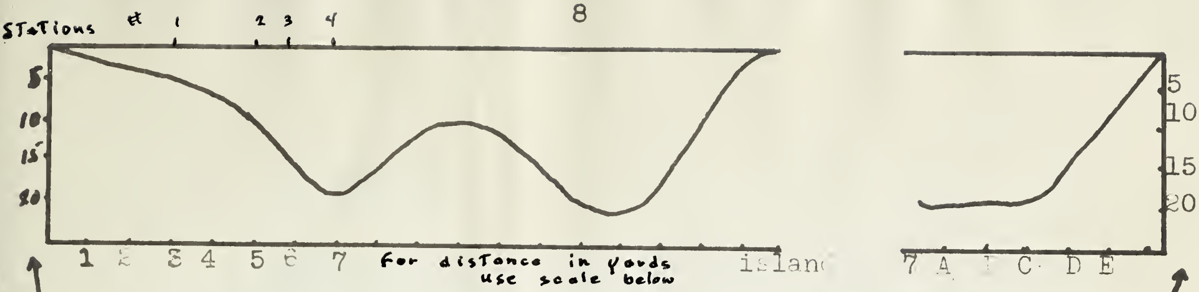
Soundings were made in order to determine the best sampling stations. The depths found and the resulting stations are shown on the accompanying maps (Fig. 2a and 2b). The greatest depth recorded was 24 feet. The average depth of the lake is estimated to be about 10 to 12 feet. The banks are quite steep on all sides, especially on the north and east, with a gradual shallowing to the west and south. There are no inlets or outlets at present.

Figure 1a

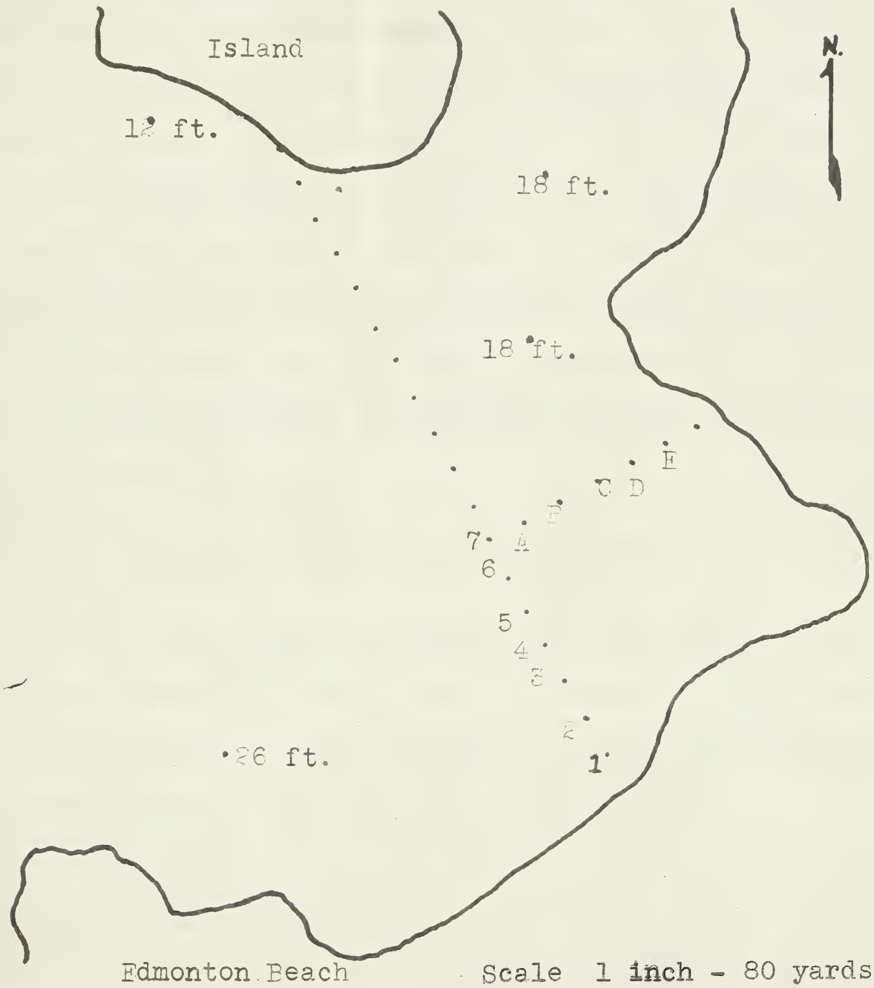
COTTAGE LAKE

Scale
1 inch - 0.15 miles

Numbers 1, 2, 3 and 4 indicate the positions of the regular sampling stations



Bottom profiles of Cottage Lake



Sketch showing the points sounded to obtain the profiles above. The soundings are 20 yards apart.

Fig. 1b

(3) Muir Lake

Muir Lake lies six miles north and two miles east of Stony Plain on the north half of sections 31 and 32 and the south half of sections 5 and 6, townships 53 and 54, range 27, west of the fourth meridian and comprises approximately 72 acres. It is an elongate lake with the shores heavily wooded except on the northwest. There is one island. North of the island lies a shallow mud bar with weeds which divides the lake into north and south basins. The northern basin is larger in area but somewhat shallower with an average depth of ten feet. The southern area is more circular in shape, smaller in area, and has an average depth of 15 feet. It was this latter area that was extensively surveyed. The map (Fig. 3a and 3b) shows the depths and contours.

(4) The Planting History of the Lakes

Prior to this investigation the three lakes had been already stocked with rainbow trout. The history of these plantings is shown in Table I (Alberta Department of Lands and Forests Lake Planting Reports, Mimeos 1953, 1954, 1955 and 1956).

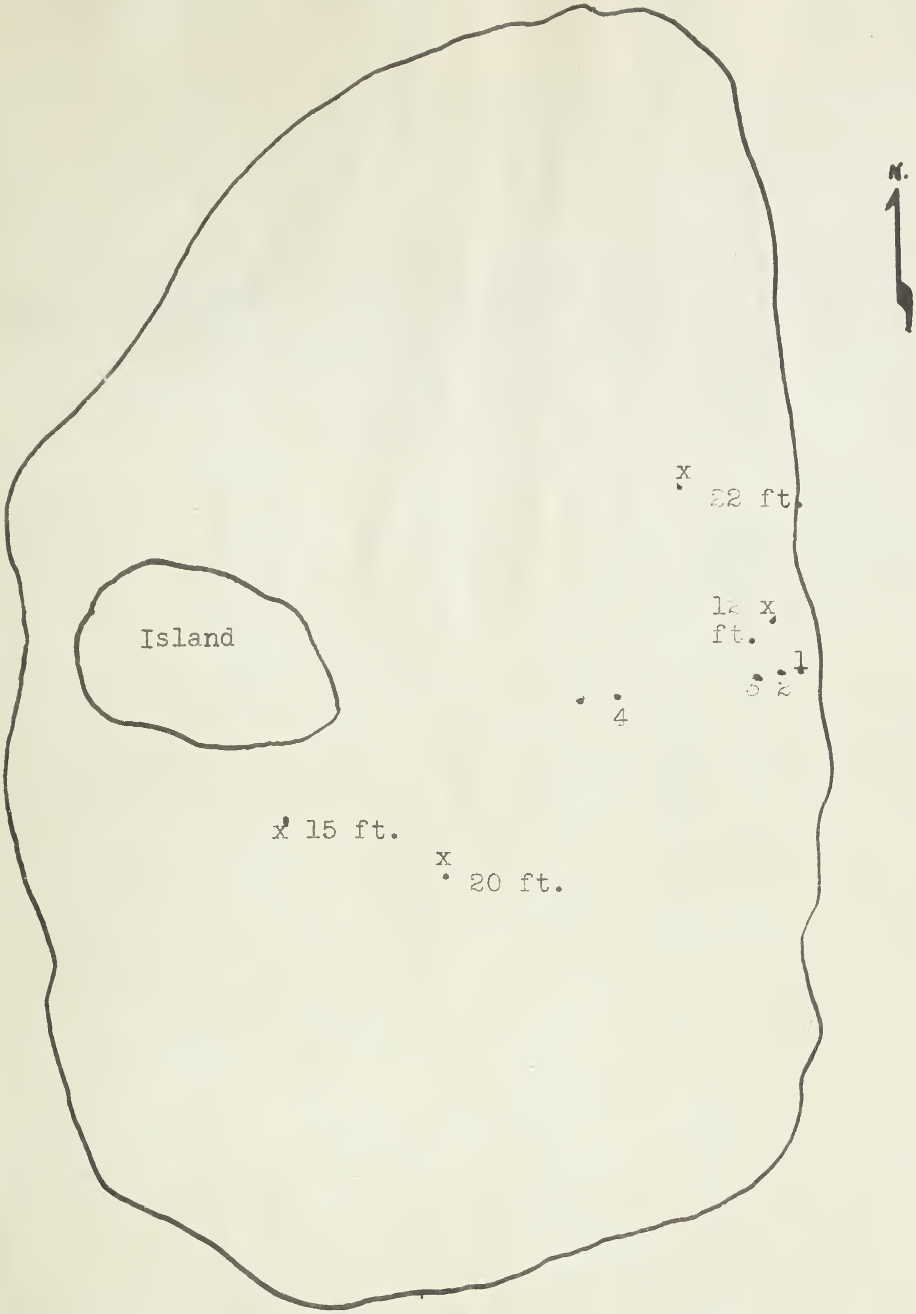
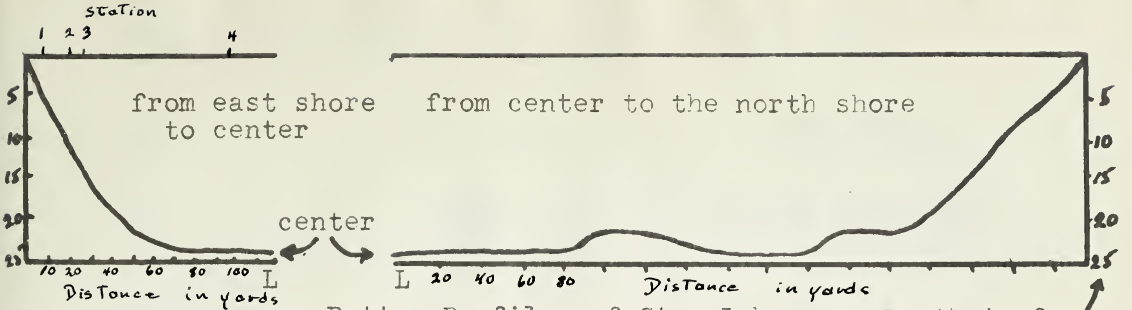
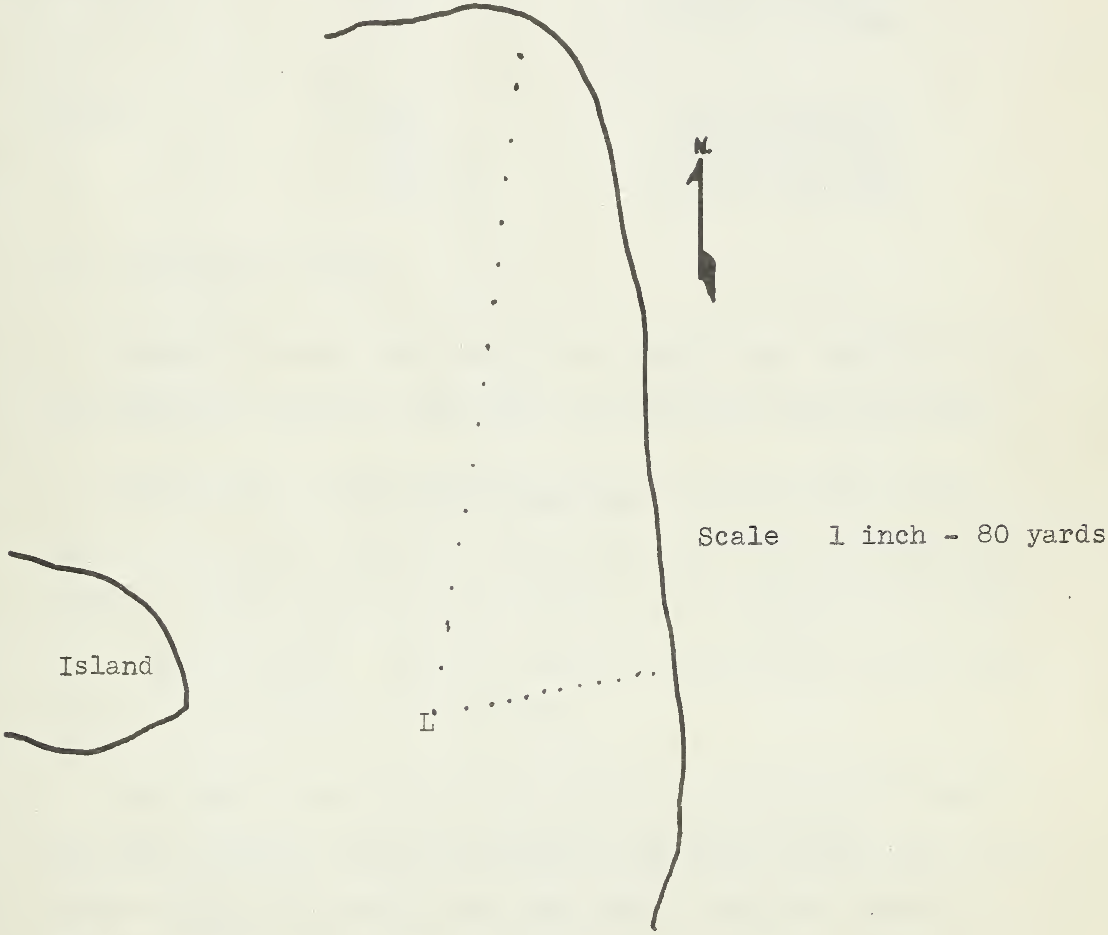


Figure 2 a STAR LAKE Scale 1 inch - 0.045 miles

Numbers 1, 2, 3 and 4 represent the positions of the regular mpling stations. x designates additional soundings taken March 8, 1957.



Bottom Profiles of Star Lake Depth in feet



Points sounded to obtain the profiles shown above. Point L is taken to be the center. The distance between each point from L to the east shore was ten yards. These points correspond to the profile in the upper left corner. The distance between the points going to the north shore is twenty yards.

Fig. 2b

Table I. Trout stocking in Star, Cottage and Muir Lakes

Lake	Year stocked	Number of fish
Star	1955	15,900 fingerlings
	1956	21,550 yearlings
Muir	1956	23,860 fingerlings
		17,945 yearlings
	1957	43,260 fingerlings
Cottage	1953	1,800 fingerlings
	1954	10,000 yearlings
	1955	51,300 fingerlings
	1956	50,900 fingerlings

(5) Previous Fish Faunae

Although no records are available on previous game fish populations that might have inhabited these lakes, the following facts are known:

Cottage Lake: Perch (Perca flavescens) is now abundant in the lake. It is believed that these entered the lake when inflowing creeks existed. Recently there have been reports of pike (Esox lucius) having been caught by anglers. Mr. M. J. Paetz has told me that two pike were taken in government gill nets in 1956.

Star Lake: There are no other species of game fish in the lake at this time. However, from mud dredgings in which perch scales were found (Thomas 1954), it is evident that these fish at some time inhabited the lake.

Muir Lake: No known previous game fish fauna.

No records could be found concerning smaller fish but five-spined sticklebacks (Eucalia inconstans) were seen in Star Lake and found in the stomach contents of the larger fish caught in all three lakes.

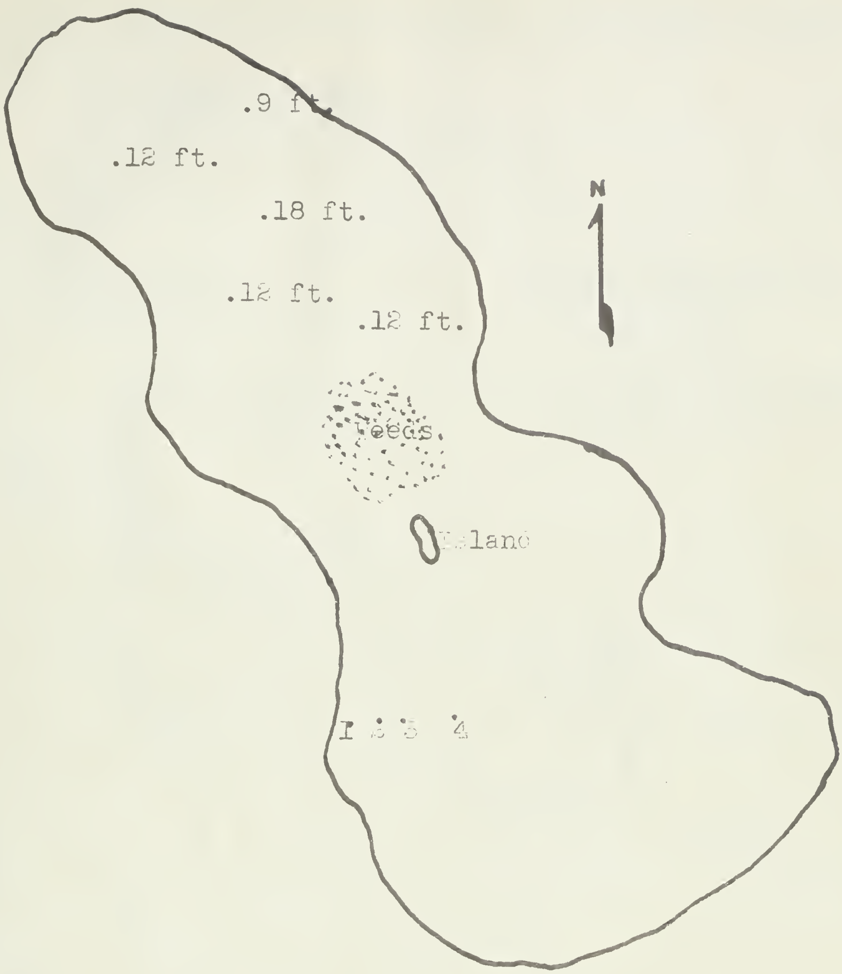


Figure 3a MUIR LAKE Scale 1 inch - 0.093 miles

The numbers 1, 2, 3 and 4 represent the regular sampling stations.

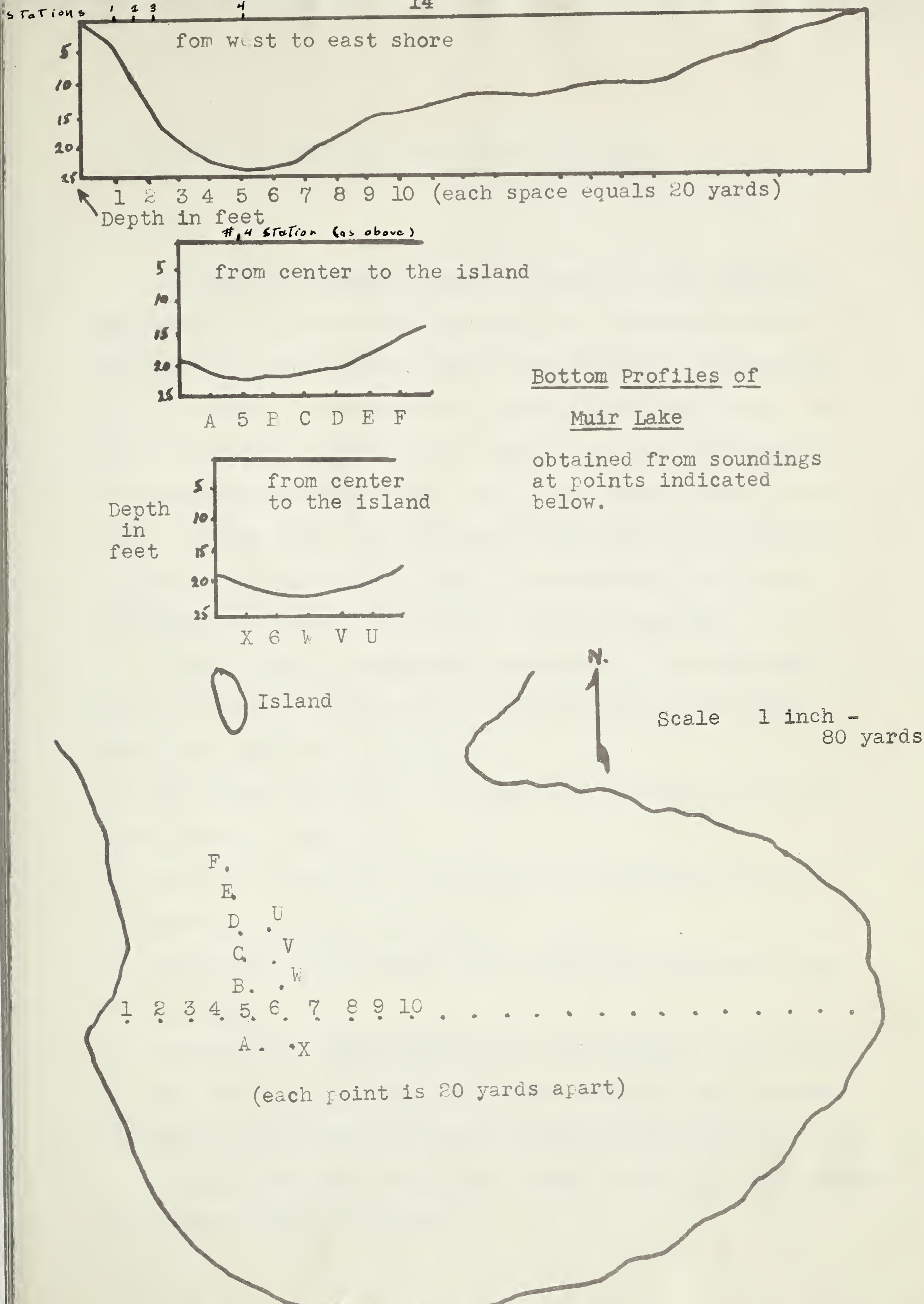

Stations 1 2 3 4
fom west to east shore
5
10
15
20
25
1 2 3 4 5 6 7 8 9 10 (each space equals 20 yards)
Depth in feet
#4 Station (as above)
from center to the island
A 5 B C D E F
Bottom Profiles of
Muir Lake
obtained from soundings
at points indicated
below.
from center
to the island
Depth
in
feet
X 6 W V U
Island
N.
Scale 1 inch -
80 yards
F.
E.
D.
U
C.
V
B.
W
1 2 3 4 5 6 7 8 9 10
A.
X
(each point is 20 yards apart)

Fig. 3b

III THE STUDY OF OXYGEN CONDITIONS DURING THE WINTER

1 Methods

The water was sampled by means of a Kemmerer bottle with care being taken to see that no mud was caught up in the deepest samples. Some difficulty was encountered with ice forming within the apparatus. This was overcome by submerging the apparatus briefly before use. In order to prevent the freezing of the samples, they were transported in a corrugated cardboard box in which was placed a gallon jar full of hot water. The heat given off by the water within the jar was sufficient to prevent the samples from freezing but was not enough to raise the temperature of the samples above their original temperature.

Regular sampling stations were established on the three lakes early in December, when the ice was strong enough to support weight. The station depths were as follows:

#1 - Five feet to lake bottom. Two samples were taken here, one at the surface and one at five feet.

#2 - Ten feet to lake bottom. Two samples were taken one at the five foot depth and the other at ten feet.

#3 - Fifteen feet to lake bottom. Three samples were taken one at each five foot level.

#4 - Maximum depth. Samples were taken at the surface and then at each five foot level until the bottom was reached where one sample was taken even though there was not a five foot difference from the previous level.

It should be mentioned that the stations were not the same distances apart at the surface of the lake.

The maps (Figs. 1a, 2a and 3a) show the locations of the stations on lakes Cottage, Star and Muir respectively. Figures 1b, 2b and 3b relates the stations to the bottom profile of the lakes.

During the last week of October and through November, each lake was sampled weekly. During December, January, February and March, each lake was sampled two weeks out of every three, e.g. December 14 Star and Muir, December 19 Star and Cottage, December 28 Cottage and Muir, and so on.

A reversing thermometer was used to take the water temperatures. The temperature was recorded at the same depth and time at which the sample was taken. However if it was not possible to do this simultaneously the water sample was always taken first to insure the least amount of mixing of the water. The samples were always taken from the surface first and then at each subsequent lower level.

A plankton haul at station #4 was made after all the samples and temperatures had been taken.

After the water samples had been transferred as quickly as possible to the univerisyt, the primary reagents (Alkaline-iodide reagent, manganous sulfate, and concentrated sulfuric acid) were immediately added. The oxygen determinations made were based upon the unmodified Winkler method (Standard Methods for the Examination of Water, Sewage and Industrial Wastes, 1955 p.p. 252-255).

It was found that upon addition of the primary reagents the solution could stand indefinitely in glass bottles before titration and no significant change would occur in the oxygen titrations. This is not true when polyethylene bottles are used; in these the oxygen

titre decreases after about twelve hours due to absorption of iodine by the plastic.

Records of the ice and snow cover were not kept in detail. However, they were recorded from time to time in order to get an idea of the overall conditions. Table II shows the conditions observed.

Table II: The ice and snow depths recorded for the three lakes during the winter of 1956-57.

Date	Depth of ice (inches)	Depth of snow (inches)
Oct. 31	$\frac{1}{2}$	0
Nov. 21	1	$1\frac{1}{2}$
Dec. 5	2-3	0
Dec. 8	4	drifted up to two feet
Dec. 28	12	0
Jan. 2/57	-	$\frac{1}{2}$
Jan. 11	-	0
Feb. 2	18	-
Feb. 22	24	-
Mar. 27	42	0
Mar. 31	48	-
Apr. 7	42	-
Apr. 14	36	-
Apr. 19	27	-
Apr. 28	0 at shore 12 at 20 yds. from shore	0
May 5	lakes free of all ice	

- means no records kept

2 Results

Samples were taken from the stations every two weeks out of three, as explained on the previous page. The results of oxygen determinations are shown in the Appendix, Figs. 4, 5 and 6 and in Table XIV. Each horizontal division represents one p.p.m. of dissolved oxygen. Each vertical division is equivalent to five feet of depth. The stations from which the samples were taken are marked at the top.

From Fig. 4 it may be seen that the oxygen of Star Lake was

was first depleted at the lower levels. It may also be seen that the oxygen decreased steadily until March 8 when the minimum oxygen tension was reached. By March 27 there was a sudden increase in oxygen and on the following week a marked decrease. From this date on there was a steady increase in the oxygen content.

Figure 5 (Appendix) shows the oxygen content of Cottage Lake for each sampling date for the entire period of investigation. It is to be read in the same manner as Fig. 4. In this chart it is seen that there was a steady decrease in dissolved oxygen, though not as rapid as in Star Lake. The minimum oxygen level was reached during the week of April 3, but from that point on, there was a slow but steady increase in oxygen until final break-up of the ice.

The oxygen content for Muir Lake for the year may be found by referring to Fig. 6 (Appendix). This chart is read in the same way as those of the two other lakes. The chart shows that the dissolved oxygen of this lake was depleted much more rapidly than that of the other lakes. The lowest oxygen tension was reached during the last weeks in February; it remained at this level until March 8 when a slight increase in the oxygen content occurred. From this time on there was rapid increase in oxygen.

In order to compare the oxygen depletion in the three lakes, the average of the oxygen content of all of the samples taken on one day was computed. This average was considered as the average oxygen content of the lake for that date since sufficient data were not obtained to calculate the actual average oxygen content of each lake. The data are shown graphically in Fig. 7 (Appendix). The average oxygen content shown on this

graph is in parts per million. The chart will be discussed in more detail later.

IV BIOLOGICAL OXYGEN DEMAND OF LAKE MUDS AND WATER

1 Mud of Muir Lake

A sample of bottom mud was obtained from the ten-foot depth of Muir Lake on February 7, 1957. The mud was used to set up the following experiment:

Seven one-quart sealers were used; fifty g. of ooze were weighed out, mixed with 250 ml. of tap water and put into each of sealers 1, 2, 3 and 4. The sealers were then shaken for one minute, one hundred and fifty mls. of water were added to each, the sealers sealed, and allowed to stand.

In sealers five and six the same procedure was followed but the mud had been made sterile. This was done by treating it with 50 ml. of ten percent formalin for a period of 24 hours.

Sealer Number Seven was used as a control. No mud was added but the water was treated in the same way as in sealers 1, 2, 3 and 4.

After the sealers stood for a few minutes the first titrations were made. The results obtained are shown in Table III.

The data in Table III indicate:

1) Lake mud has a high biological oxygen demand (B.O.D.).

2) Treating the mud with formalin reduces the B.O.D. but does not eliminate it entirely. Either some organisms are not killed (i.e. the mud was not sterile) or there is a chemical as well as a biological oxygen demand.

3) Apparently tap water has a small, but measurable oxygen demand.

Table III: Dissolved oxygen content (p.p.m.) of sealers of lake mud and water after various time lapses.

Sealer No.	Original Oxygen Content	Hours Until Second Titration	Oxygen Content at Second Titration	Oxygen Consumption	Mud Sterilized
1	7.46	6	1.4	6.06	No
2	7.64	7	2.0	5.64	No
3	7.76	23	2.0	5.76	No
4	7.95	23	2.0	5.95	No
5	8.46	7	4.25	4.82	Yes
6	8.40	23	3.58	4.82	Yes
7	8.70	23	8.35	0.35	Control (no mud)

2 Quantity of Organic Material in Lake Muds

On March 3rd an Ekman dredge was used to obtain mud from the 10-foot depths of all three lakes. Samples of the mud were air-dried by leaving them in open beakers at room temperature until they reached constant weight (May 6).

The amount of organic material in each sample was obtained by incinerating the dried mud. The loss in weight was considered to be the organic matter burned away. The method used to obtain the weight loss was as follows: the first sample (Star Lake) was incincerated to constant weight and then the subsequent samples were incincerated for the same period of time.

Table IV shows the results.

It is clear that the three lake muds vary with respect to organic matter; Muir Lake mud contains the most and Cottage Lake the least. The differences between the nature of the lake bottoms fit in

well with these findings. Cottage Lake bottom is of sand and is relatively free of organic material. On the other hand Muir Lake mud is relatively free of sand but high in dead or rotting vegetation.

Table IV: Organic matter (loss on incinceration) of three dried lake muds.

	Star Lake	Cottage Lake	Muir Lake
Weight of freshly collected mud (gm.)	10.3	16.1	8.9
Weight of air dried mud	6.5	15.8	8.0
Weight of burned mud	4.0	12.2	4.0
Amount of organic matter	2.5	3.6	4.0
Organic matter/gm. dry mud	0.385	0.228	0.500

3 The Oxygen Demand of the Lake Waters

To obtain the B.O.D. of the water under winter conditions, samples were taken, placed into 500 ml. reagent bottles, and lowered to the exact depth from which they came. The bottles were held at their respective levels with cords which were tied to the markers at each station. At the same time a sample of water was taken from each level at which a bottle was placed. This sample was titrated and the oxygen content determined. In this way the water in the bottles was subjected to exactly the same conditions as the water around it, except that there could be no oxygen loss by diffusion to the bottom mud. It was planned to leave the bottles for an equal period of time before the water within them was titrated for oxygen content. However, some of the bottles were cut loose by vandals so it was thought wise to remove the remaining bottles from Muir Lake after a week. The bottles in Star Lake

were removed after four weeks and those in Cottage after five weeks.

The results of this experiment are presented in Table V.

The data in Table V reveal that the lake water, independent of the mud, has a substantial oxygen demand; also that some oxygen reaches the lake water during winter, possibly from photosynthesis.

V <u>The Activity of Trout in Winter</u>

1 The Nets and the Catches

In order to get an idea of the effect decreased oxygen content might have on the trout, nets were set in all three lakes at various times.

A hole approximately two feet in diameter was drilled using a needle bar and a shovel. A jigger (Sprules, 1949) was used to string a running line under the ice. When the proper length of line had been run out, another hole was drilled and the jigger pulled out. The nets were weighted so that they floated about a foot under the ice. The starting depth was usually at the ten-foot level but the depth at the far end was unknown until the jigger was pulled out and the depth measured. The nets were of one-and-three-quarters-inch mesh nylon. Two 50-yard lengths were used.

The first nets were set in Muir Lake on January 12, 1957 at 4:30 p.m.. The first fifty yards ran almost parallel to the west shore. The next fifty ran north-east toward the island. The nets were lifted the following morning at 11:00 a.m.. The first net yielded 14 trout, none in the first twenty-five yards; the number removed gradually increased until in the last two yards five trout were found. The second net caught 11 trout which were fairly evenly spaced along the length of the net.

Table V: Oxygen loss in sealed bottles of lake water suspended at various depths below the ice.

Star Lake

Station No.	Depth in ft.	Oxygen day 1	Lake oxygen day 32	Bottle oxygen day 32		Loss in lake	Loss in bottle
1	5	3.74	1.75	0.39		1.99	3.35
2	5	3.62	2.34	2.94		1.28	0.68
	10	3.58	2.18	2.44		1.40	1.14
3	5	3.84	1.95	2.08		1.89	1.74
	10	3.84	2.88	1.20		0.96	2.64
	15	3.26	1.96	1.40		1.30	1.86
4	5	4.06	1.96	1.06		2.10	3.00
	10	3.93	1.50	0.33		2.43	3.60
	15	3.40	1.50	1.75		1.90	1.65
	20	2.42	1.25	0.88		1.17	1.54
	24	0.0	0.88	0.0	X	0.88	0.0
Muir Lake		day 1	day 7	day 7			
1	5	2.05	1.56	1.60		0.49	0.45
2	5	2.40	2.08	-		0.32	-
	10	2.30	2.10	-		0.20	-
3	5	2.53	2.13	-		0.40	-
	10	2.40	1.95	-		0.45	-
	15	2.04	1.80	-		0.24	-
4	5	2.91	2.14	2.48		0.77	0.43
	10	2.75	1.96	1.64		0.79	1.14
	15	2.21	1.50	0.85		0.31	1.36
	20	1.70	0.75	0.0		0.95	1.70
	23	0.95	0.75	0.0		0.20	0.95
Cottage Lake		day 1	day 39	day 39			
1	5	8.31	3.08	6.70		5.23	1.61
2	5	7.93	3.04	-		4.89	-
	10	8.08	3.58	6.09		4.50	1.99
3	5	7.93	3.84	-		4.09	-
	10	8.01	3.84	5.93		4.17	2.08
	15	7.60	2.62	5.60		5.02	2.00
4	5	7.80	3.58	5.60		4.28	2.20
	10	7.88	3.58	-		4.30	-
	15	7.80	3.04	-		4.76	-
	18	7.65	1.68	5.60		5.92	2.05

Day one on Star was Jan. 23, Day one on Muir and Cottage was Jan. 16. X at the 24 ft. depth of Star indicates an increase not a loss. - indicates a bottle lost. The oxygen content is in p.p.m.

In both lengths the fish were caught at a depth of about five to seven feet. The approximate oxygen content at this level was 3 p.p.m..

The stomach contents of six of the trout are listed in Table VI.

Table VI: Length, weights and stomach contents of six trout from Muir Lake, caught January 12, 1957.

Length in mm.	Weight in gms.	Stomach contents
276	255	3 *Gammarus* 1 small stickleback 3 *Chaoborus* (dead)
252	190	1 beetle elytra, plankton
281	310	7 sticklebacks 1 *Physa*
292	292	4 *Gammarus* 2 sticklebacks 3 beetles 1 caddis
275	248	2 sticklebacks
278	283	1 caddis 25 *Chaoborus* (living) 3 *Chaoborus* (dead)

(All the fish were one year old)

On the following day, January 14th, the same nets were set in Star Lake, parallel to the east shore, in 12 to 24 feet of water. Forty-eight fish were removed; most of them had been swimming at the 7 to 10-foot depth (approximate oxygen content, 4 p.p.m.).

On January 19th, the nets were set again in Muir Lake; ten fish were caught (oxygen 2.5 p.p.m.). A later setting in Muir Lake on January 26th, caught no fish (oxygen 2.2. p.p.m.). The nets were set again in Muir Lake on February 3rd; after 12 hours in the water, only

one fish was caught. The nets were immediately moved to Star Lake. At the same time that the nets were being set a short line (24 feet) was stretched south of the nets in Star Lake. On it were seven hooks all baited with shrimp but hanging at different levels. On February 4th the first 50 yards of net pulled out yielded 12 fish while the remaining 50 yards caught 14. No fish were taken on the hooks and the shrimp had not been touched. The oxygen content was about 3.5 p.p.m..

The next setting was on March 10th, in Star Lake. Three fish were caught (oxygen 1.5 p.p.m.).

The only setting of nets in Cottage Lake took place on March 24th. On March 25th, the first 50 yards pulled yielded 180 perch and 5 trout. Twenty trout were caught in the second 50 yards. The perch had an average length of 9.25 inches and an average weight of 150 gm.. The lengths and weights of the fish caught are shown in Table VII. The records of the trout caught and oxygen content of all the lakes are given in Table VIII.

The final settings in Muir Lake, May 3rd, and Star Lake, May 5th, were made from a boat. The nets were put in Muir Lake at 12:00 noon. However, two local men removed the nets at about 5:00 p.m. on the same day. A provincial biologist caught the men removing the net and salvaged it along with 12 of the fish. A total of 25 fish had been caught during that five hour period. No dead fish were seen on or near the shore at the time. No fish kill was evident for the winter season in this lake.

Table VII: Lengths and weights of the trout caught in Cottage Lake, March 24, 1957.

Length in inches	Weight in grams	Length in inches	Weight in grams
$7\frac{1}{4}$	76	8 7/8	132
7 5/8	96 84	9	150
7 7/8	88	9 7/8	185
8	90 100	$12\frac{1}{2}$	428
8 1/8	102	$13\frac{3}{4}$	544
8 3/8	120 124	14	550
$8\frac{1}{2}$	144 120 108	$16\frac{3}{4}$	895 1014
8 5/8	126	$17\frac{3}{4}$	1205
$8\frac{3}{4}$	112 132	17 7/8	1060

Star Lake was netted on May 5th, the nets were in the water from 8:00 a.m. until 7:00 p.m. of the same day. Thirty-four fish were caught in that period and 50 dead trout were counted along a hundred yard length of shore. It was estimated that a fifty percent winter-kill had occurred.

2 Relationship of Net Returns to Dissolved Oxygen Content

The data which show the oxygen content of the various lake waters and the trout caught per hundred yards of gill net at these oxygen contents are shown in Table VIII.

(a) Cottage Lake

The oxygen content of Cottage Lake was high enough to suggest that there would not be a winter-kill in the lake. For this reason test nets were set only once. The subsequent catch proved that all the fish

were moving about freely and were not suffering from the drop in oxygen.

According to the local residents this lake is fed by springs. The springs,coupled with the fact that the B.O.D. of the water was very low (see Table V) could have provided enough oxygen for the season.

Table VIII: Trout catches and oxygen content in Muir, Star and Cottage Lakes, winter of 1956-57.

Lake	Date of Catch	Total trout catch	Approximate oxygen content (p.p.m.)
Cottage	March 24	26 (339 perch)	2.5
Star	Jan. 14	48	4.0
	Feb. 4	39	3.5
	Mar. 10	3	1.5
	May 5	34	5.5
Muir	Jan. 13	21	3.0
	Jan. 19	10	2.5
	Jan. 26	0	2.0
	Feb. 3	1	2.0
	May 3	25	4.8

b) Star Lake

Even though Star Lake did lose its oxygen quite rapidly it did not seem conceivable that a winter-kill could occur. The reasons for this belief were:

1) the decrease of oxygen did not appear to reach lethal limits, 2) a low B.O.D. (see Table V), 3) the fact that Star Lake was populated with fish of several ages, and the larger fish would be more tolerant of low oxygen (Moore, 1942).

However, the following circumstances proved the expectations wrong. During the period February 22nd to March 13th a lethal or near lethal (1.8 p.p.m.) level of oxygen was reached. This fact alone could

have accounted for a partial mortality. However, similar conditions existed in Muir Lake during the same period and no mortality took place. The following factor is believed responsible for the mortality in Star Lake: After March 13th and particularly on March 27th an unusually high oxygen content (up to 9 p.p.m. with an average of 5 p.p.m. at a depth of seven feet) was observed. A very warm spell melted the ice and permitted the oxygenated surface water to drain into the lake. This also occurred at the other lakes as shown by the records of Muir Lake (one reading of 9.6 p.p.m.). However, on the following week the oxygen content dropped to near lethal levels (highest recorded was 2.2. p.p.m. at five feet but below seven feet only 1.0 p.p.m.). This deosygenation also occurred at Muir Lake but not to as low a level so that the fish had a chance to survive. It is believed that the severe and extremely sudden change in oxygen was the main cause of the mortality. This conclusion is based upon the work of Shepard (1954) who studied the resistance and tolerance of young speckled trout (<u>Salvelinus fontinalis</u>) to oxygen lack, with special reference to low oxygen acclimation. He showed that smaller fish succumb more readily to low oxygen pressures than larger fish of the same species. He also showed that fish develop a resistance to oxygen lack if they are kept in poorly oxygenated water for any period of time. However, the increased resistance gained by this exposure to low oxygen is lost when they are returned to water containing higher concentrations of oxygen. It is, therefore, feasible to assume that the Star Lake fish could not acclimatize themselves

quickly enough to the sudden change and so suffocated. It is also reasonable to assume that if any fish did succumb to this rapid deoxygenation they were of the smaller size. However, this fact was not borne out by the final net catches. It was noticed though, that all the dead fish on the shoreline were about eight inches in length.

c) Muir Lake

Upon observing the rapid oxygen depletion of the lake after the first few months it was believed that the oxygen content would soon reach lethal levels and a winter-kill would be inevitable. This prediction seemed about to be realized when the number of trout caught became less as the oxygen content became less; also the local fishermen reported that they were not catching any fish. Taking into consideration that previous workers had reported that the lethal level for trout was about 2 p.p.m. and that the lake was much lower than this (from February 13th to March 10th, the average oxygen content was 1.5 p.p.m.; and from March 10th to March 20th it was 1.9 p.p.m.) it seemed certain that no trout could possibly survive.

However, when the ice broke up the fish were as abundant and as active as ever. No dead fish were seen on the shore and apparently no winter-kill had taken place. No experimental evidence was obtained to offer an explanation for this occurrence. The following explanations, based upon work done by other researchers, are the only ones that might help solve this phenomenon. It was shown by Irving, Black, and Safford

(1941) that the affinity of fish haemoglobin for oxygen increased as the temperature declined. This could be one reason that the fish did not die. A second reason might be that it is believed that at the low temperatures the fish did not move about; this would lead to a lower oxygen requirement. The lack of activity was shown by the fact that the fish were not feeding. The stomach contents of the last four fish caught showed nothing except a small amount of material which might have been plankton. Secondly, the decrease in catch size was probably due to the decreased activity of the fish and not to a decrease of the population. The final possible reason for the survival is based upon the work of Moore (1942) who showed that the tolerance of fish, especially larger fish, to oxygen lack, is associated with their lower matabolic rate at lower temperature.

These three facts, lower metabolism, less activity due to temperature, higher affinity for oxygen by the haemoglobin, plus the fact that no sudden fluctuations in the oxygen content occurred (as they did in Star Lake) are believed responsible for the survival of the Muir Lake fish.

VI WINTER PLANKTONIC CRUSTACEAN POPULATIONS

Plankton hauls were taken at or near the deepest part of the lake (stations numbered four) on every visit. The plankton net was number 20 silk bolting cloth and was 12 inches in diameter at the top. The 30 ml. samples obtained were preserved by adding 1 ml. of ten percent formalin and 1 ml. of 95 percent alcohol to each.

To be sure that samples did not freeze before they reached

the laboratory the bottles were always carried in the inside pocket of the coat close to the body. Precautions also had to be taken when handling the plankton net. When taken from the water the net usually froze solid immediately. In order not to damage the net it had to be transported in this frozen condition to the next lake. Just prior to taking the next sample it was partially immersed in the water thus thawing it out and making it usable.

After all the samples had been taken and the plankton had settled out, the total volume of each was measured. This was done in graduated volumetric tubes; the volume of plankton was read in cubic centimeters after it had settled in the volumetric flask for a twenty-four hour period. The volumes of the zooplankton are presented in Table IX.

Table IX: The volumes of zooplankton organisms in the water of Lakes Cottage, Star and Muir, winter, 1956-57.

Date		Cottage		Star		Muir	
		Bottle number	Plankton in cc.	Bottle number	Plankton in c.c.	Bottle number	Plankton in cc.
October	16	1	0.3				
	24			1	2.3	1	12
November	8	2	0.3	2	0.8	2	8
	14	3	0.4	3	0.6	3	5
	21	4	0.8	4	0.8	4	3.7
	27	5	0.6	5	0.6	5	3.3
December	14			6	1.4	6	5
	19	6	0.9	7	3.4		
	26	7	0.3			7	1.2
January	2			8	1.2	8	1.6
	10	8	0.4	9	2.2		
	16	9	0.2			9	1.9
	23			10	1.2	10	1.5
	30	10	0.3	11	2.0		
February	6	11	0.05			11	1.4
	13			12	1.0	12	1.1
	22	12	0.4	13	1.1		
March	1	13	0.3			13	0.5
	13	14	0.2	14	0.8	14	0.6
	20	15	0.3			15	0.5
	26			15	0.5	16	0.5
April	3	16	0.5	16	0.3		
	14	17	0.3	17	spoiled	17	0.5
	19	18	0.4	18	0.3	18	0.7
	28	19	0.3	19	0.3	19	0.8
May	5	20	0.8	20	0.4	20	0.7
	5			21	0.5		

Chaoborus was found in some of the samples but since it floated they were not included in the volumes above. It occurred as follows: None in Cottage Lake; in Star Lake sample 6 had two, sample 11 had one, sample 14 had one and sample 18 had two; in Muir Lake sample 8 had two, sample 9 had one, sample 10 approximately 15, sample 15 had one, sample 16 had one, sample 17 approximately 30, sample 18 had two, and sample 19 had approximately 15.

Table IX shows that the decrease in oxygen did not have a large effect upon the amount of zooplankton within the water. Phytoplankton, which is not included in the volumes of table IX, was markedly decreased during the first two months. This decrease, however, was probably due to a decrease in sunlight rather than an oxygen depletion.

Muir Lake showed a trend to a decrease in zooplankton population with a drop in oxygen. As the oxygen fell from 11.7 p.p.m. to 1.23 p.p.m. the plankton decreased from 12 to 0.5 cc. From March 1st to May 5th, no appreciable fluctuations occurred.

Star Lake had a curious history; when the oxygen content rose, early in the season, the zooplankton showed a marked decrease; however, as soon as the oxygen content started to fall the zooplankton increased in number and maintained a volume much the same as that of Muir Lake plankton. This increase was probably due to the increase in oxygen which had been caused by photosynthesis early in the season (see the discussion part one). On two occasions, January 10 and January 23, the plankton showed a slight increase. On these two dates the average oxygen content also rose slightly (Fig. 10). It is unexplainable why the plankton would

increase at these lower oxygen tensions while it had a lower population during the periods of higher oxygen tension earlier in the season.

Cottage Lake, which had a relatively high oxygen content compared to the other two lakes, had a very low plankton population. This level of plankton was maintained throughout the season with the exception of the period from November 21 to December 26. This period coincided with the period of supersaturation that took place in Muir Lake (see page 44).

These facts show that the oxygen content has some effect upon the zooplankton population. It is also apparent that there is a relationship between the plankton volume and the organic content of the ooze. If the total vulumes of plankton for the whole year are considered it is seen that Muir Lake had the largest volume and Cottage Lake the smalles. Correspondingly Muir Lake mud had the largest organic content and Cottage Lake the least organic material (see Table IV). It is not being suggested that all the organic material within the ooze is composed of plankton but the higher volume of plankton probably contributes to the organic richness of the mud. There is alwo a definite relationship between the volume of plankton and the B.O.D. of the water. It was shown (Table V) that Muir Lake had the highest B.O.D. and Cottage Lake the lowest. This fact is directly correlated with the amount of zooplankton present with Muir Lake having the most plankton and Cottage Lake the least. The greater the plankton the greater the organic richness of the water. When the organic material decomposes aerobically the oxygen is decreased. Thus when the volume of plankton is high the B.O.D. is

also correspondingly high.

When referring to Table XII it should be remembered that volumes of 0.5 cc. are insignificant in this method of random sampling.

VII DISCUSSION

1 Weather, Ice and Snow

The following excerpt from the Annual Meteorological Summary for Edmonton describes the general climate of the region as follows:

"The climate is described as a cold temperate climate but is not so severe as might be expected in a continental climate at 53 degrees N. The chinooks which modify the long winter just east of the Rockies do not usually reach as far east as Edmonton. However, their modifying influence does extend to Edmonton for brief spells nearly every winter. The frequency of the chinook is variable. Some winters will be quite mild with recurring chinooks. Other winters may witness only one or none. Average winter temperature is 13.7 degrees F. Low temperatures of -30 degrees F occur on the average of three or four times each winter. Extremely low temperatures of-40 degrees F or less, occur about once every three winters. Depth of snow on the ground averages seven inches by midwinter and seldom exceeds 14 inches in the city area".

The weather for the months of the research period is shown on Table X.

Table X: Edmonton region conditions recorded by the Weather Bureau (Annual Meteorological Summary 1956 and 1957).

	1956 Oct.	Nov.	Dec.	1957 Jan.	Feb.	Mar.	April
Mean temperature for the month (degrees F)	39.4	34.1	13.8	5.7	10.4	23.7	40.7
Normal mean temperature	40.9	24.2	13.2	6.0	11.2	22.8	39.8
Precipitation for the month (in inches of rain	0.50	0.46	1.27	0.56	0.73	0.64	0.76
Normal precipitation	0.75	0.84	0.85	0.93	0.73	1.62	0.99
Sunshine for month (in hours of bright sunlight)	173.2	144.3	62.3	111.2	142.4	171.6	232.8
Normal sunlight	170.2	97.9	76.9	82.8	115.5	165.5	218.9

From the observed official records it can be seen that the winter of this experiment experienced climatic conditions which came very close to the long time averages. The sunlight for this period was 148.2 hours, only 18.7 hours more than the long time mean. The average of the mean temperatures was 23.0 degrees F. only 1.3 degrees higher than the long time average mean for this particular part of the season. Thus it is reasonable to say that it was a normal season.

The ice existed on the lakes from November 1st to May 1st, a period of 182 days. This period coincided almost exactly to the period in which frost persisted. The period between the first and last light frosts lasted 240 days while the period between the first and last killing frosts lasted 211 days. The ice formed approximately three weeks after the first killing frost. From this it can be said that the lakes underwent a period of average ice cover in respect to depth of ice,

period of cover, and time between overturns.

2) Water Temperature

It was observed that a very abrupt drop in temperature occurred in the upper few of water, with a more gradual decline from there to the bottom. This temperature distribution remained constant throughout the winter despite the external environmental fluctuations of snow cover, temperatures, and the amount of solar radiant energy. Toward the end of the season the upper levels warmed while the lower levels held their original temperatures. The warming trend was due to the normal spring conditions but in particular to the inflow of the warmer run-off water which entered the lake through cracks in the rotting ice and along the free edges of the shore ice.

At no time throughout the season did the general mass of the water heat up. Greenbank (1945) mentioned such an occurrence and attributed it to an increase in the oxidation of organic matter and to the heat produced by the radiant energy of the sunlight. In our more northerly latitudes such an occurrence is less likely.

3) Dissolved Oxygen

The best single indicator of the conditions for fish life during winter is the dissolved oxygen.

During the course of the study a relatively large range of dissolved oxygen values was observed. As the season progressed it soon became evident that each lake behaved differently with regard to oxygen loss. Even though the external conditions were the same for all three lakes, they soon began to differ markedly in dissolved oxygen content. Data in Table XI outline the general trends.

Table XI: General data on dissolved oxygen content of Lakes Star, Cottage and Muir during the winter of 1956-57. (Oxygen in p.p.m.)

	Lakes		
Time	Star	Cottage	Muir
At fall overturn	9.5	10.0	13.0
Fall maximum	10.2 (Nov. 7)	12.0 (Nov. 12)	13.0 (October)
Average minimum	1.5 (March 8 to 13)	2.2 (April 3)	1.5x (March 1)

x average of 1.5 p.p.m. from Feb. 6 to March 10

From these figures (Table XI) it can be seen that Muir Lake lost the most oxygen (from 13.0 to 1.5 p.p.m., a total of 11.5 p.p.m. in 19 weeks) and remained at supposedly lethal levels for the longest period. In Star Lake the drop was slightly lower, 9.1 p.p.m. in 19 weeks; the drop began one week later than in Muir Lake. This could be accounted for by the fact that Star had an increase in oxygen probably due to the activity of plankton or to the oxygenated run-off water which at that time was still entering the lake. This run-off was not present at Muir Lake which had, instead, half an inch of snow cover.

Cottage Lake was much slower to lose its oxygen (10.8 p.p.m. drop in 21 weeks) although the total loss was greater. It is conceivable that fish may have been killed if the period of stagnation had been prolonged.

4) Relation of Dissolved Oxygen to Winter-kill

Some of these data have already been discussed. However, some material found in the work of other researchers has a bearing on the present study, although conclusions that have been reached are largely speculative. It is unquestionable that if the oxygen tension remains below

a minimum value for a considerable length of time, fish will die. However, it is also true that various noxious gases, such as hydrogen sulfide, ammonia, methane, and carbon dioxide, can be lethal (Scidmore 1955). Therefore, a conclusion that oxygen lack is the sole cause of death is not always justified. Carbon dioxide alone, if in high enought concentrations, can kill fish, even in the presence of abundant oxygen. It has been shown by Fry (1939) and others that the presence of large amounts of carbon dioxide greatly reduces the ability of fish to utilize oxygen at low tensions. That is to say, the toxicity is increased as the oxygen tension is decreased.

Unfortunately the literature on winter mortality has insufficient information on which to base any definite conclusions regarding the importance of these factors. At the same time no records were kept on the quantities of these gases present throughout the winter. Therefore, it will have to suffice to say that the very low oxygen concentrations were probably the primary cause of the death of the fish and that the effect of low oxygen may have been aided by the presence of the other gases.

5) The Oxygen Demand of the Lake Muds

Since the oxygen content is decreased by processes going on within the lake, under the ice seal, it is reasonable to suppose that the oxygen demand of the bottom mud contributes a great deal to this depletion. The fish and the live crustaceans do not deplete the oxygen to an important degree (Greenbank 1945).

The B.O.D. is the oxygen consumed in a certain period of

time, from a sample incubated in the dark at a fixed temperature. Theoretically the oxygen is consumed only by bacterial action, but also possibly by algae, protozoa, and microscopic metazoa. Actually a part of the demand, usually a small part, may come from purely chemical oxidation. Conventionally, if the limiting conditions are not indicated, it is understood that the time period is five days (120 hours) and the incubation temperature 20° C. In the present series of B.O.D. determinations, all the samples were incubated within the lake and thus experienced all the slight changes which the water around them underwent, except, of course, possible diffusion to the bottom mud. The period of so-called incubation varied from seven to thirty-nine days.

The B.O.D. gives a rather accurate picture of the relative organic richness of the water sample, and the likelihood of the depletion of its dissolved oxygen supply in a given time. When measured at the actual lake conditions (temperatures), the B.O.D. of a sample of water from an ice-covered lake provides a reasonably accurate indication of the probable behavior of all the water with respect to oxygen depletion. Tests of the B.O.D. early in a season might give a good picture of the future course of oxygen depletion of that particular lake during ice cover. This may be the case since it is possible that dead algae are completely oxidized before they settle to the bottom, so that the samples in the fall would give an accurate picture of the rate of oxygen loss. On the other hand it is just as possible that the early depletion (after freeze-up) could be due to dead algae still in suspension. These would settle out, leaving a lesser B.O.D. behind them. This second statement is only theory and the facts do not seem to fit it.

In this study the following observations were made. The B.O.D. of Cottage Lake was lower than that of the other two lakes (see Table V). The greatest single depletion in Cottage Lake was lower than that of the other two lakes (see Table V). The greatest single depletion in Cottage Lake was only 2.2.p.p.m. for a period of 39 days at an average temperature of approximately 1.5° C. The average of all the bottles from Cottage Lake showed a depletion of 1.98 p.p.m. of oxygen.

In Muir Lake the B.O.D. was higher than that of Cottage. The bottles were in the water for a period of only seven days. The oxygen decreased 1.0 p.p.m. in those seven days; using simple direct proportion, Muir Lake water would use an average of 5.57 p.p.m. in a period of 39 days. If correct, this indicates that the B.O.D. of Muir Lake is about two and one-half times as great as that of Cottage Lake. Star Lake, with an average B.O.D. of 2.56 p.p.m., was only 0.58 p.p.m. higher than Cottage Lake.

It is unfortunate that all the bottles could not have been left in the lakes for the same period of time. But by reducing the data to an average one-day period we find that the B.O.D.'s of Cottage, Star and Muir Lakes were 0.050, 0.066 and 0.143 p.p.m. respectively. These figures show that Star had a B.O.D. 32 percent higher than Cottage and Muir 186 percent higher than Cottage.

Even though the B.O.D. is a fairly reliable criterion from which to predict the future oxygen content of the lake, the bottom ooze, which composes the bulk of the mud, is just as important. This fact is revealed by the data in Table VII. As well as showing the B.O.D. of the lake water, the table also shows the total decrease of dissolved

oxygen in the water around the bottles during the same period of time. It is this decrease that indicates how seriously the mud depletes the oxygen. In Muir Lake, for instance, the bottled water depleted the oxygen by 1.0 p.p.m.. The total drop in the lake however, was 1.79 p.p.m. in the same seven days. This means that 0.79 p.p.m. of oxygen were used by something other than the lake water. This 'something' may very likely be the mud which would use the oxygen for the aerobic decomposition of the organic material in it. Since the organic content of the mud is fairly high, 0.5 g. of organic material per g. of dried mud, the reasoning above seems justified.

The bottled water of Star Lake used an average of 2.13 p.p.m. in 32 days. However, the water in the lake around the bottles depleted the oxygen by an average of only 1.41 p.p.m. for the same period. From these facts it would appear that the lake gained oxygen. This was not the case. It must be remembered that by this time of the winter the mud was almost isolated from the upper aerated water and thus little, if any, aerobic decomposition could be going on within the mud due to the very slow rate at which oxygen diffuses. However, the difference between the two figures above is only 0.72 p.p.m.. When average over the 32 days this means a difference of only 0.02 p.p.m. per day. This is a very small difference which could be an error in titration. Thus it may be said that the B.O.D. of the water was the only factor in depleting the oxygen and that the oxygen in the water in the sample bottles and the water in the lake were depleted to the same degree.

It is difficult to explain the situation in Cottage Lake. Although there is certainly evidence that oxygen was used by the bottom mud, the mud contained only 0.2279 gms. of organic material per g. of dry mud which is less than half that of Muir. But the Muir Lake mud, though

much richer organically, was isolated from the oxygenated water by a layer of water containing little or no oxygen; therefore it could have less effect on the oxygen content of the supernatant water than the less rich mud of Cottage Lake. In Cottage Lake, there was no layer of deoxygenated water near or at the bottom and thus the aerobic decomposition of organic material in the ooze played an important part in depleting the oxygen. The depletion in the water averaged during the 39 day period, a drop of 1.98 p.p.m.. The data in Table V show that the greatest oxygen depletions were near or at the bottom in all cases; the oxygen near the surface was depleted to a lesser extent. Another explanation of this increased oxygen depletion near the bottom in Cottage Lake may be that the organic material (dead summer plankton) present in the water settled to the bottom and in doing so increased the B.O.D. of the water near the bottom. But as this did not occur in the other two lakes it seems a less reasonable hypothesis. Star Lake showed a higher B.O.D. near the surface and Muir Lake showed a relatively even distribution of B.O.D. with only a slight tendency to increase at about the 15 to 20 foot depth.

The facts presented so far have proven the importance of the role played by the mud in the depletion of the oxygen in lakes under winter conditions.

6 Effect of Sunlight

It was mentioned previously that the high oxygen content of Star and Cottage Lakes at the start of the season was due mainly to run-off water. However, this increase may also be associated with the amount of sunlight during that period. It must be remembered that at the beginning of the winter the ice remained fairly thin for a comparatively long period and very little snow cover was present. These conditions are conducive to the production of oxygen by phytoplankton and other aquatic plants since the light rays can easily penetrate the ice (Greenbank, 1945). The oxygen produced during this period could not escape into the air, therefore the water would become supersaturated with oxygen or, at least, the oxygen depletion which was taking place would be less rapid. The following figures show daily records of hours of bright sunlight from October 28th to November 6th inclusive: 3.0. 7.6, 0.0, 8.7, 7.8, 7.1, 715, 4.9, 0.0, 2.9. During this period both Star and Cottage lakes gained oxygen under the ice. From November 16th to November 30th the following were the reported sunlight records: 5.3, 6.0, 1.0, 5.7, 5.6, 0.1, 7.7, 7.2, 7.0, 7.6, 7.5, 7.1, 6.3, 7.4, 6.8. In this period the oxygen in Cottage Lake rose markedly especially from November 21 to November 30th (the period of greatest sunlight). There was no rise in oxygen in Star Lake because of a cover of snow (which blew off Cottage Lake); in Muir Lake there was no increase in dissolved oxygen but there was a marked decrease in the rate of oxygen depletion. Cottage Lake suffered the same rate of oxygen depletion as the other two lakes and had it not been for this early winter period when the water became supersaturated, it would have declined to the same very low oxygen levels, by spring, as

the others did. The excess is readily seen if the oxygen is computed as percent saturation. From saturation tables given by Mortimer (1956) the following figures were obtained for Cottage Lake.

Date	Average Oxygen Content
October 17	98.2%
November 7	108.5%
November 14	110.0%
November 21	111.2%
November 28	120.6%
December 8	99.0%

In making these calculations the altitude of the lakes were taken as 2,000 feet above sea level and the appropriate corrections were made for water temperature.

From these facts it is seen that the amount of sunlight has an important effect on the dissolved oxygen in a lake when ice cover has formed. However, sunlight is effective only when the ice is thin (up to three inches) and the snow cover is not extensive. If the ice becomes thicker or the snow deeper the amount of light penetration becomes negligible and the photosynthetic production of oxygen is eliminated. But, as in Cottage Lake, if the ice remains thin for a realtively long period of time at the start of the winter season and the B.O.D. of the water is not very high, there is an increase in oxygen content that might mean the difference between life and death to the fishes.

VIII SUMMARY

1) Three lakes in the Edmonton area, Starr, Muir, and Cottage, were chosen for a study of winter conditions, particularly dissolved oxygen.

2) The depths of the lakes were measured to establish sampling stations (see 4 below).

3) The thickness of the ice and the amount of snow cover were noted from time to time.

4) Sampling stations were established at the 5, 10, 15-foot and deepest depths. They were numbered 1, 2, 3 and 4, respectively.

5) Water samples were taken with a Kemmerer bottle as follows:

Station No.	
1	surface and five feet (bottom).
2	5 feet and 10 feet (bottom).
3	5 feet, 10 feet and 15 feet (bottom).
4	surface, 5 feet, 10 feet, 15 feet, 20 feet and bottom.

Samples were taken twice in every three weeks from each lake during the period October 17, 1956 to May 5, 1957.

6) The temperature of the water was taken at every level at the same time that a water sample was taken.

7) The dissolved oxygen content of the water samples was determined by the unmodified Winkler method.

8) The oxygen demand of samples of the water was determined in sealed bottles suspended in the lake below the ice.

9) Plankton hauls were taken at Station 4 each time a lake was visited.

10) Samples of the muds were dried and the amounts of organic material they contained estimated by measuring the loss in weight on incineration.

11) Nets were set to see if there was a correlation between oxygen

depletion and any fish mortality that might occur.

12) Oxygen was depleted from all three lakes to the point where fish would be expected to asphyxiate. Only in Star Lake was a partial winter mortality observed.

13) The three lakes lost their oxygen at about the same rate.

14) The oxygen demand of the water was the greatest factor in the depletion of the oxygen; almost as large a factor was the aerobic decomposition of organic materials within the mud.

15) The photosynthetic production of oxygen by phytoplankton while the ice cover was thin and snow-free at the start of winter probably greatly decreased the period of oxygen depletion, thus helping to keep the oxygen at or just above the lethal levels for trout.

16) The water at or near the bottom, especially at the deepest stations, lost oxygen most rapidly. This depletion is believed to have been caused by the mud. The rate of oxygen depletion at this level decreased as the mud became separated from the upper oxygenated water by a layer of deoxygenated water.

17) The lethal oxygen level for trout acclimatized to winter conditions is shown to be about 1.25 p.p.m.. Fish acclimatized to these conditions appear to cease moving as none were caught in nets or by angling.

18) The winter of 1956-57 was an average one for this region; the ice-cover lasted for 182 days. The maximum depth of ice formed during

this period was four feet but for most of the season the average depth was about two-and-one-half feet.

19) The water temperature did not fluctuate greatly. Immediately under the ice the temperature was close to 1.0° C.; from here down the temperature gradually increased to close to 4° C. at the bottom.

IX CONCLUSIONS

1) Much too little research in this field has been done.

2) A winter mortality of fish is an always present probability in eutrophic lakes like the ones studied.

3) As yet no suitable method of predicting the probability of a winter mortality has been established. This fact was shown by the observations on Muir and Star Lakes. At the beginning of the season it was predicted that Muir Lake was the most likely to produce a winter-kill. However, an unforeseen occurrence, a sudden rise of oxygen followed by a very rapid decrease in Star Lake, showed that to base a prediction on few isolated facts at the beginning of the season is foolish. Not until all the facts are obtained can one draw any reasonable conclusions as to what actually occurred. However, a very thorough study of a lake during the start of the season can give some indication of the probable course of oxygen depletion within the lake if it is remembered that many things may change during the season.

4) Rainbow trout (*Salmo gairdneri*) can withstand low oxygen tensions for a considerable period of time. An example of this is provided by Muir Lake where the trout survived oxygen tensions below 2 p.p.m. for six weeks. This is believed to have been due to a) an acclimatization

to the low oxygen levels, b) a greater affinity of the fish haemoglobin for oxygen at the low temperatures, c) less activity by the fish, and d) a lower oxygen requirement due to a lower metabolic rate brought on by inactivity and low temperatures.

5) The organic richness of the water at the start of winter is very important. If the oxygen demand is high the rate of oxygen depletion is also rapid. The rapid decrease of the oxygen at the start of the season means that the lethal level is reached more rapidly and therefore the possibility of a winter-kill is much greater.

6) The organic richness of the mud plays an important role in the initial decrease in oxygen. As long as there is oxygen present at or near the mud, aerobic decomposition of organic material occurs. However, as the oxygen is eliminated from the water just above the mud, the decomposition ceases and the mud no longer contributes to oxygen depletion. This cessation of oxygen depletion may aid greatly in keeping the oxygen tension above the lethal level if the stagnation period is prolonged. This is what probably happened in Muir Lake.

7) If a period of sunny weather is experienced at the beginning of the season, when the ice is thin, oxygen is produced by higher plants and phytoplankton. The oxygen so produced cannot escape due to the ice cover. This additional oxygen could enrich the water sufficiently to prevent any winter mortality. It does so by shortening the period during which the oxygen is depleted.

8) The oxygen lack in a lake may not be the only factor in the winter mortality of the fish but it is the primary one. Noxious gases may play an important role. However, the individual action of these gases on fishes, or their possible indirect action by interference with the oxygen-combining capacity of the haemoglobin have not yet been evaluated.

X RECOMMENDATIONS

1) More studies of this type should be done if small lake management is to become completely successful.

2) If such work is done, particular emphasis should be placed on the oxygen consuming powers of the mud and of the water, individually; and on the amount of sunlight that penetrates the ice.

3) A lake in which trout stocking is planned should be examined as to size and shape as well as the three points mentioned above. Such an examination should last at least one season and preferably two.

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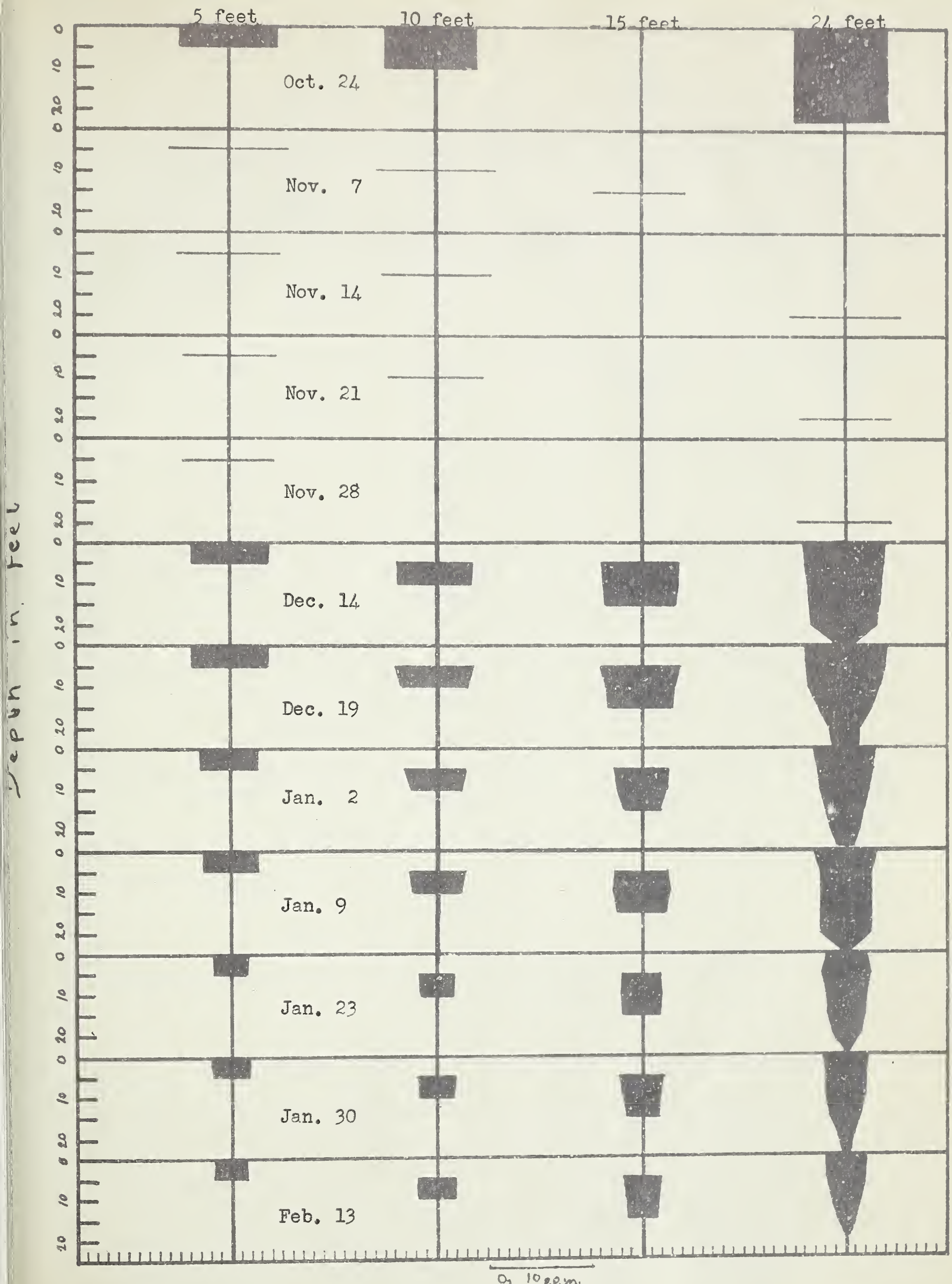
APPENDIX

Figure 4 Oxygen Content of Star Lake



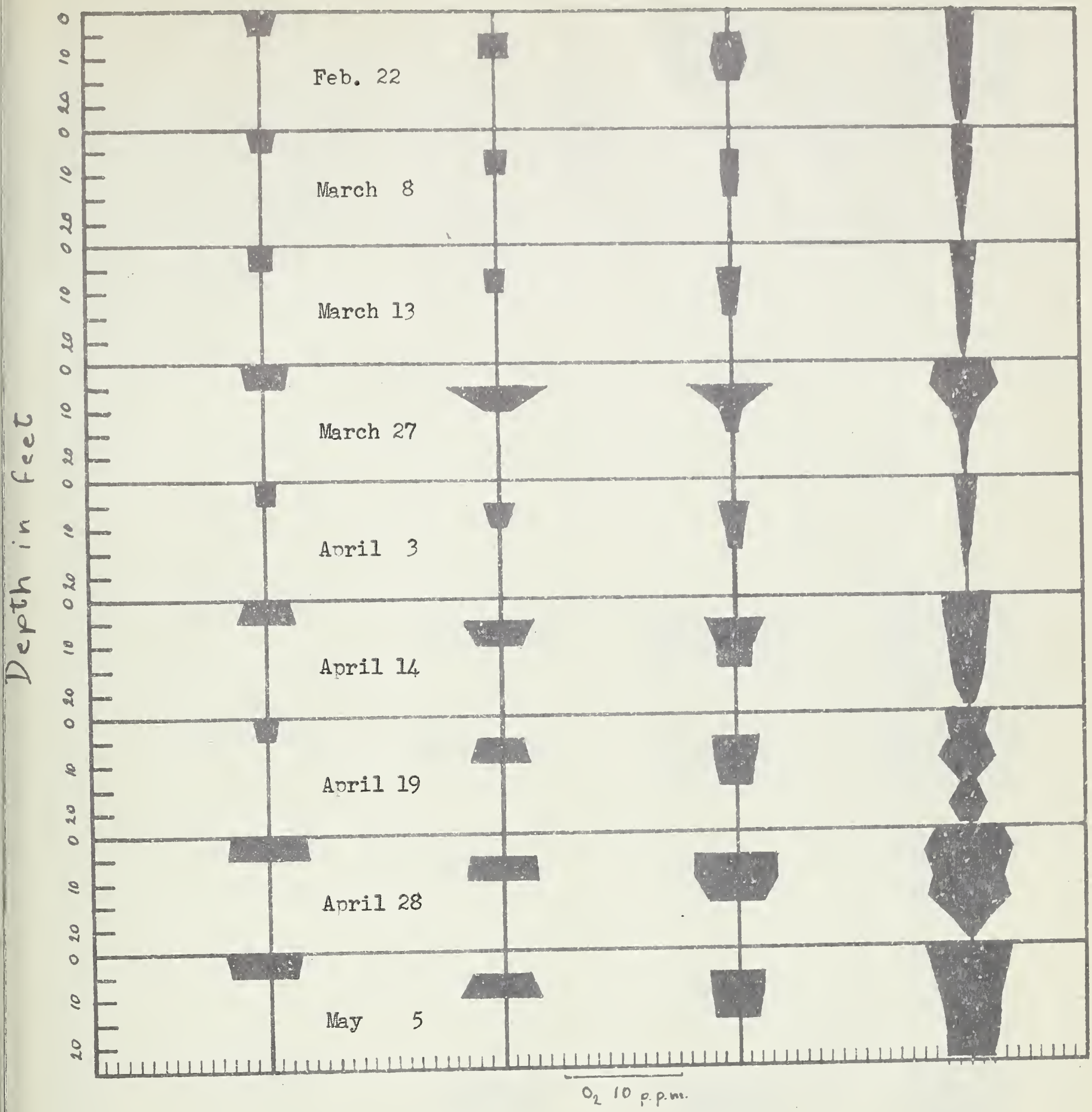

Depth in feet
0
10
20
Feb. 22
March 8
March 13
March 27
April 3
April 14
April 19
April 28
May 5
O_2 10 p.p.m.

Figure 5 Oxygen Content of Cottage Lake

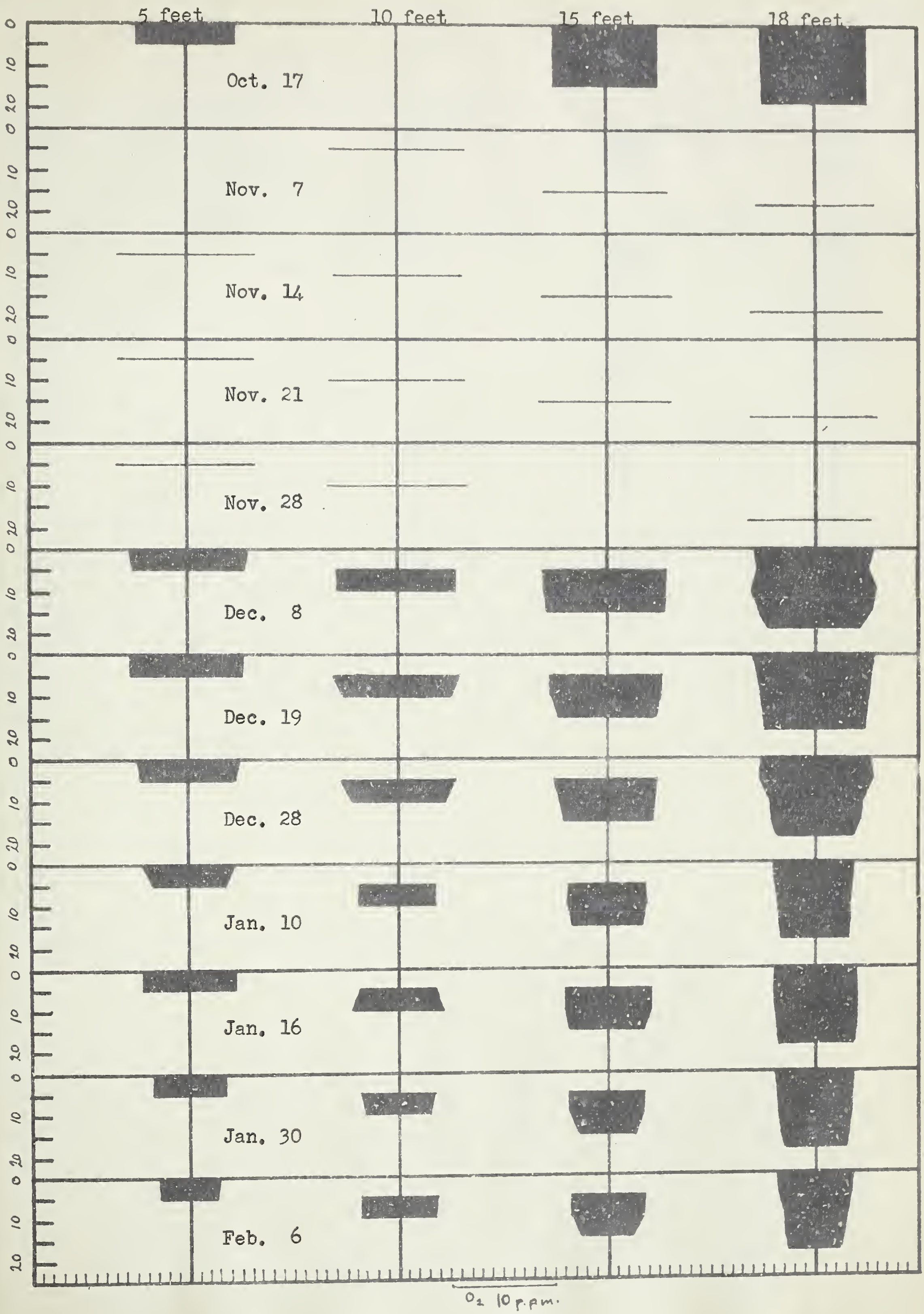


Figure 5 Continued

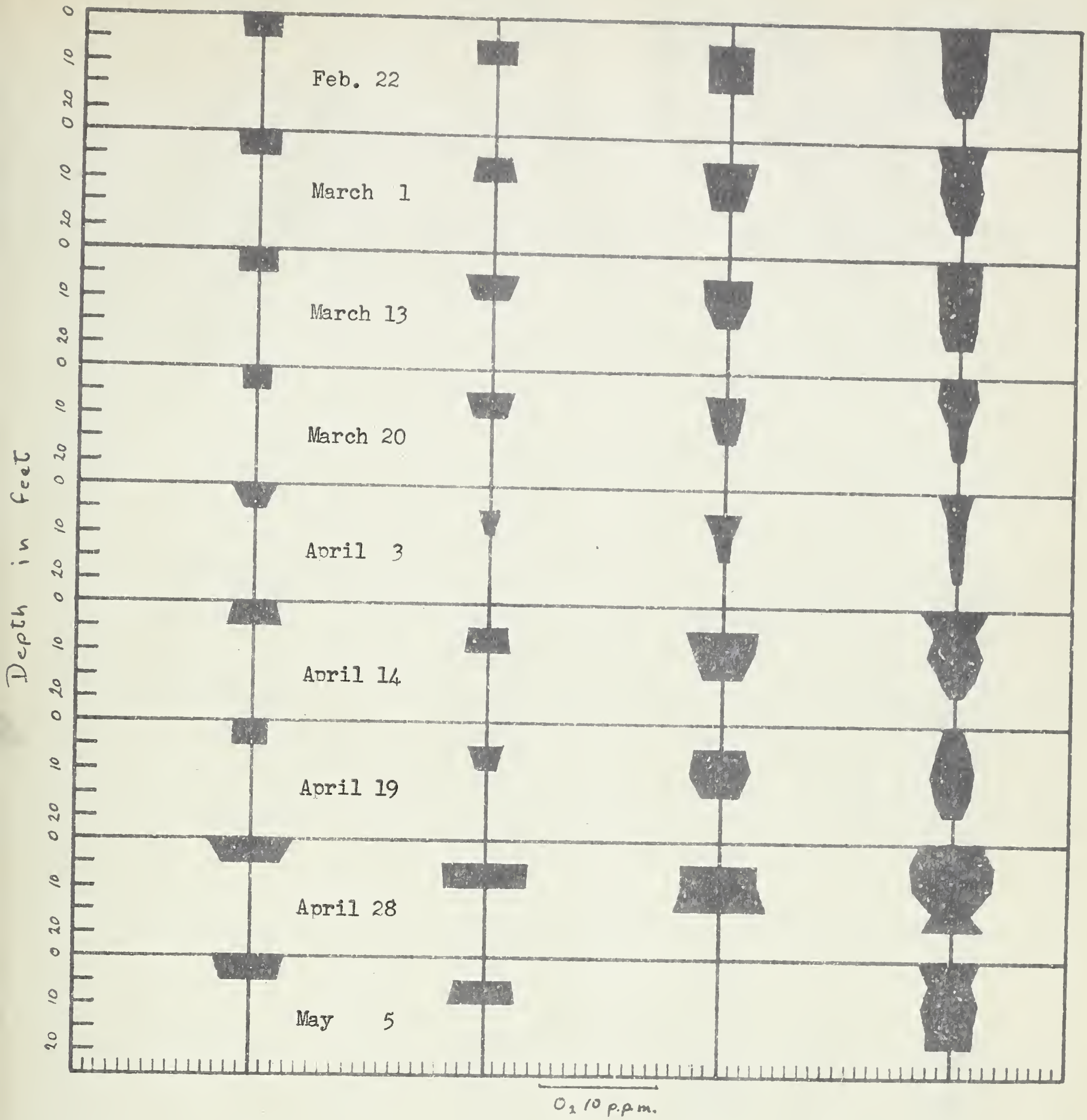
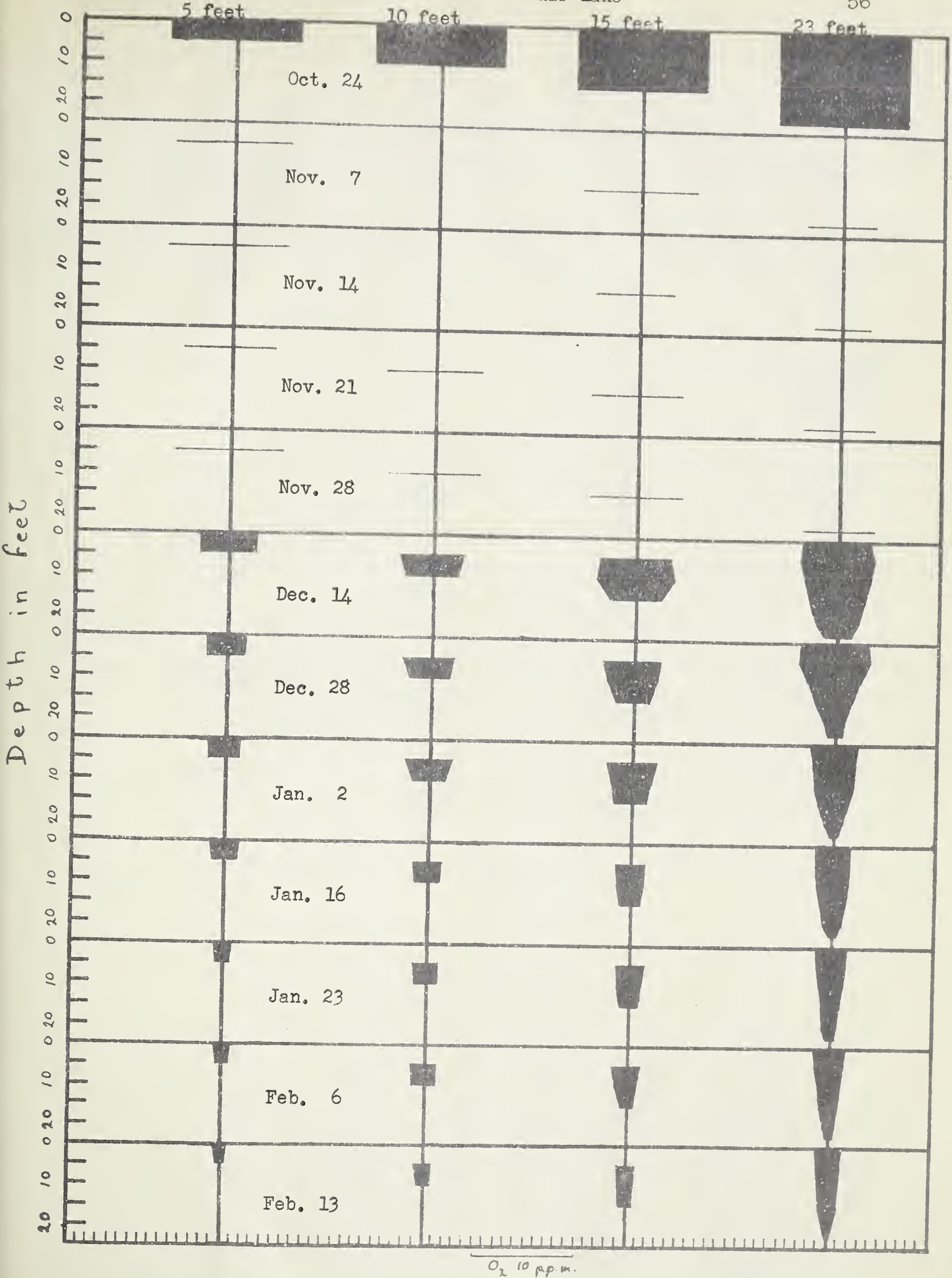


Figure 6 Oxygen Content of Muir Lake



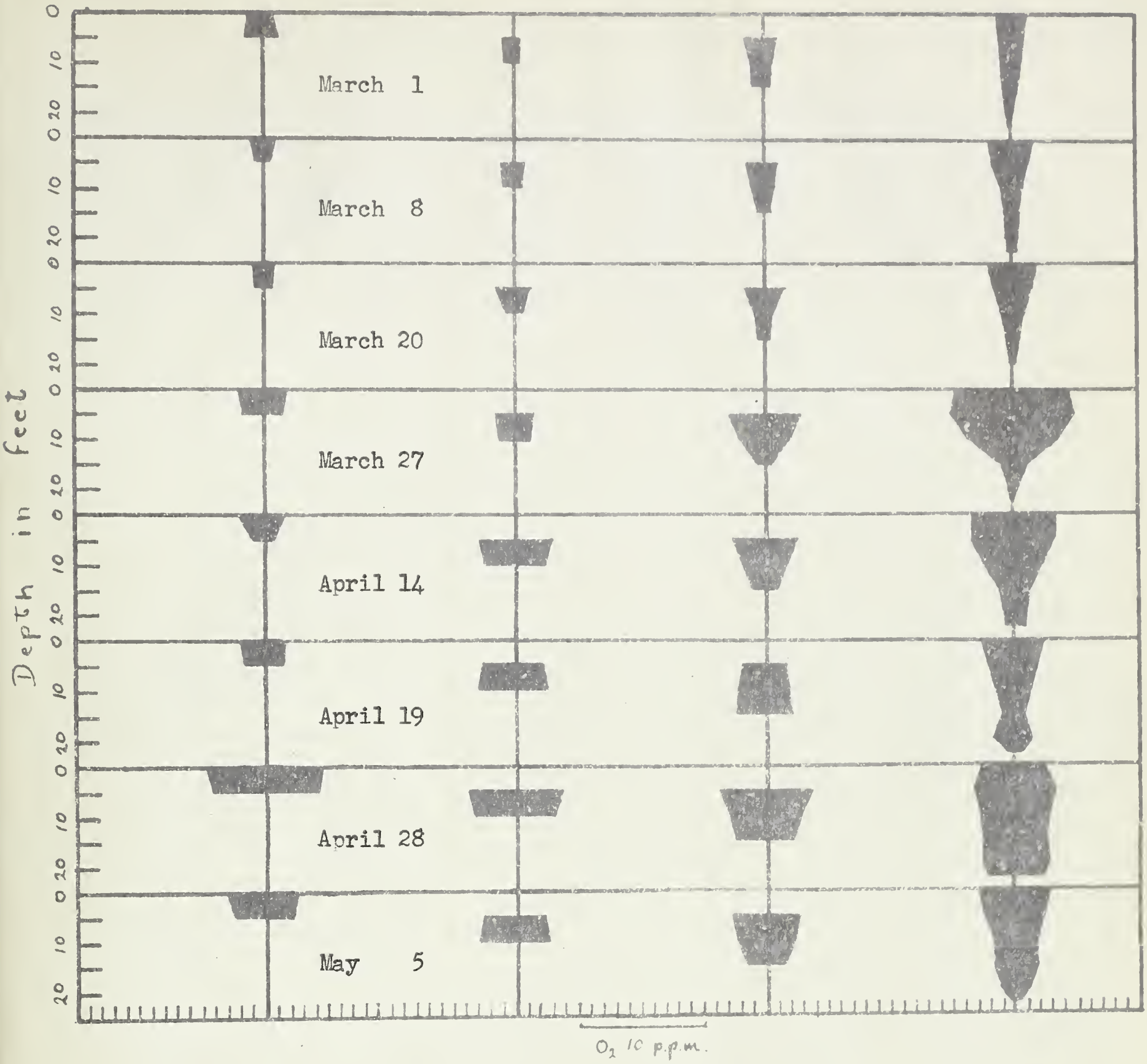
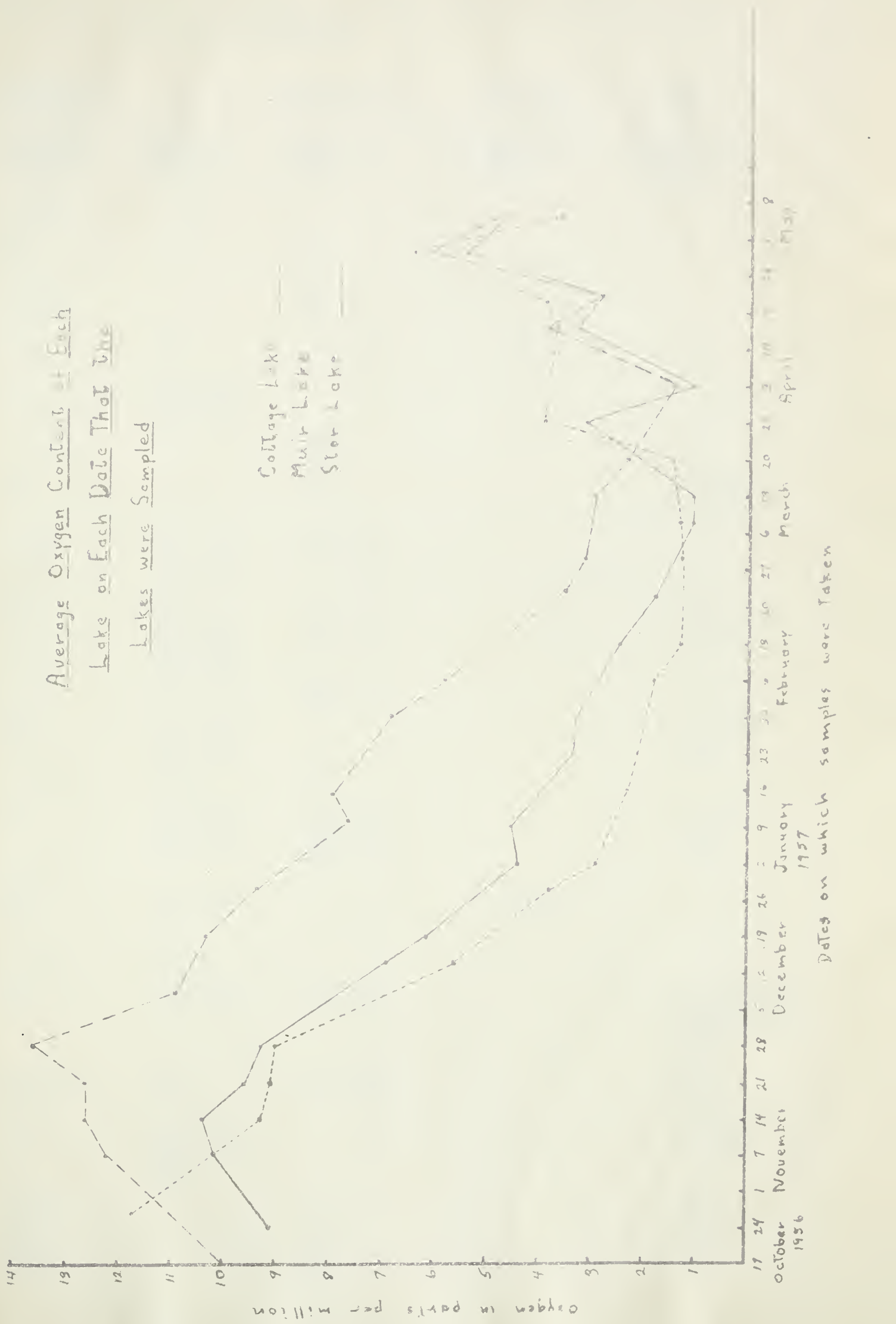

Depth in feet
0
10
20
March 1
March 8
March 20
March 27
April 14
April 19
April 28
May 5
O2 10 p.p.m.

Figure 7



Average Oxygen Content at Each Lake on Each Date That the Lakes were Sampled
Cottage Lake
Muir Lake
Star Lake
oxygen in parts per million
October 1956
November
December
January 1957
February
March
April
May
Dates on which samples were taken

Table XII Lengths and weights of trout caught in Star Lake during the winter of 1956-57.

January 14		February 4	March 10	May 5
Length in inches	Weight in grams	Weight in grams	Weight in grams	Weight in grams
7 5/8	90			
8½	124	125		
8 5/8		140		
8¾	147	125 140	140	140
9	155 162 166 137			
9 1/8		140		172
9¼		153		180 180 172 180
93/8	154 174 170 155 172	155 162		
9½	170 178 196 165 182 198	172 174 168		185
9 5/8	182 182	165 172 174		
9¾	200 188 158 190			200 170 192
9 7/8	202	180		
10	194 195 215 194	178 190 200 194		205 178 208
10 1/8		195		
10¼	210 221		200 200	
10 3/8	192			
10½	247 250	270 214		226 170 260 235 200 238 228
10 5/8	245	210 260		212
10¾	248 240 210			245 240
11	266			
11 1/8				250
11 3/8		323		
11½				318
11 7/8		358		

Table XII continued

January 14

Length in inches	Weight in grams
13½	530 550
15	725
15 1/8	780
15½	875 790
15¾	910
16 1/8	1025
18¼	1235

Table XIII: Lengths and weights of trout caught in Muir Lake during the winter of 1956-57.

January 13		January 20	February 4	May 3
Length in inches	Weight in grams	Weight in grams	Weight in grams	Weight in grams
8				100
8¼	121			
8 5/8	115			
8 7/8	226			
9	278			145
9¼				158
9½	184 240 282			
9 5/8	209 180	184		
9¾	200 188		173	190
9 7/8	190			
10	218			190
10 1/8	205 196 218			
10¼	219 196	226		214 220
10 3/8				235

Table XIII continued

January 13		January 20	February 4	May 3
Length in inches	Weight in grams	Weight in grams	Weight in grams	Weight in grams
$10\frac{1}{2}$	239	245		
10 5/8	246			
$10\ \frac{3}{4}$		252 260 294		
10 7/8	242 248			
11	255 283 251	291		262 258
11 1/8	310	295 304		
$11\frac{1}{4}$	312			
$11\frac{1}{2}$	292 320 292			315
11 5/8		313		
$11\frac{3}{4}$	332			
11 7/8	468			320
12 1/8	400			
$12\frac{3}{4}$	476			

Table XIV: Oxygen content in p.p.m. of each sample taken in Star, Muir and Cottage Lakes during the winter of 1956-57.

Date	Station	Depth in feet	Star Lake oxygen	Muir Lake oxygen	Cottage Lake oxygen
Oct. 17		0			9.30
		15			10.00
		18			10.78
Oct. 24		5	9.40	12.20	
		10	9.08	12.10	
		15		12.00	
		23	8.82	12.10	
Nov. 7		5	10.80	12.72	
		10	10.40		12.70
		15	9.34	12.96	11.76
		18			11.90
		23		13.03	
Nov. 14		5	10.35	13.23	13.08
		10	10.30		12.75
		15		12.65	12.20
		18			12.35
		23	10.28	12.10	
Nov. 21		5	9.80	9.70	12.73
		10	9.70	9.70	13.08
		15		9.60	12.33
		18	9.34		12.20
		22		8.10	
Nov. 28		5	9.42	10.00	13.70
		10		9.60	13.74
		15		9.50	
		18			13.38
		23	9.14	7.60	
Dec. 8	1	0			10.78
		5			10.70
	2	5			11.20
		10			11.05
	3	5			11.20
		10			11.40
		15			11.40
	4	0			10.70
		5			10.79
		10			11.40
		15			10.60
		18			9.12

Table XIV continued

Date	Station	Depth in feet	Star Lake oxygen	Muir Lake oxygen	Cottage Lake oxygen
Dec. 14	1	0	7.75	5.35	
		5	7.28	5.40	
	2	5	7.75	6.08	
		10	7.25	5.45	
	3	5	7.68	6.60	
		10	7.25	6.85	
		15	6.92	5.30	
	4	0	7.85	6.60	
		5	7.68	6.80	
		10	7.28	6.45	
		15	6.75	5.30	
		20	6.19	4.31	
		23	1.96	2.75	
Dec. 19	1	0	6.88		10.50
		5	6.70		10.25
	2	5	6.90		10.50
		10	6.70		10.30
	3	5	6.95		10.45
		10	6.63		10.40
		15	6.30		9.80
	4	0	7.55		11.00
		5	7.00		10.78
		10	6.53		10.20
		15	5.30		9.80
		18			9.80
		20	3.35		
		24	3.13		
Dec. 28	1	0		2.75	9.65
		5		2.75	9.47
	2	5		4.15	10.25
		10		3.78	8.92
	3	5		5.28	10.30
		10		4.16	9.30
		15		3.48	8.72
	4	0		6.15	10.50
		5		6.15	10.22
		10		4.65	9.45
		15		3.58	8.50
		18			7.94
		20		1.20	
		23		1.33	

Table XIV continued

Date	Station	Depth in feet	Star Lake oxygen	Muir Lake oxygen	Cottage Lake oxygen
Jan. 2	1	0	5.35	2.35	
		5	5.70	2.70	
	2	5	5.82	4.15	
		10	4.73	3.45	
	3	5	4.92	4.35	
		10	4.50	3.95	
		15	3.66	2.63	
	4	0	5.80	4.15	
		5	5.70	3.60	
		10	4.55	3.57	
		15	3.63	2.55	
		20	2.80	0.58	
		23	1.51	0.24	
Jan. 10	1	0	5.00		8.15
		5	5.25		6.95
	2	5	5.10		7.50
		10	4.61		7.84
	3	5	5.10		7.65
		10	5.10		7.65
		15	4.87		7.25
	4	0	5.15		7.75
		5	4.65		7.65
		10	4.85		7.55
		15	4.65		7.55
		18			7.45
		20	4.40		
		24	0.57		
Jan. 16	1	0		2.65	8.45
		5		2.08	8.32
	2	5		2.40	7.94
		10		2.35	8.09
	3	5		2.65	7.94
		10		2.45	7.95
		15		2.05	7.58
	4	0		2.85	7.84
		5		2.90	7.80
		10		2.74	7.84
		15		2.24	7.80
		18			7.65
		20		1.70	
		23		0.90	

Table XIV continued

Date	Station	Depth in feet	Star Lake oxygen	Muir Lake oxygen	Cottage Lake oxygen
Jan. 23	1	0	3.76	1.85	
		5	3.75	1.55	
	2	5	3.62	2.11	
		10	3.58	2.10	
	3	5	3.82	2.13	
		10	3.82	2.00	
		15	3.25	1.80	
	4	0	3.92	2.20	
		5	4.06	2.14	
		10	3.75	1.96	
		15	3.40	1.51	
		20	2.40	0.74	
		23	0.00	0.78	
Jan. 30	1	0	3.80		6.95
		5	3.68		6.90
	2	5	3.92		7.05
		10	3.55		6.75
	3	5	4.00		7.25
		10	3.73		6.86
		15	3.47		5.85
	4	0	4.00		7.15
		5	3.92		7.05
		10	3.48		6.87
		15	3.24		6.50
		18			5.80
		20	1.65		
		24	0.15		
Feb. 6	1	0		1.96	5.55
		5		1.62	5.57
	2	5		2.25	6.58
		10		2.35	6.18
	3	5		2.38	6.50
		10		1.90	6.30
		15		1.30	4.90
	4	0		2.45	6.30
		5		2.15	6.25
		10		1.96	5.92
		15		1.80	5.40
		18			5.10
		20		1.02	
		23		0.56	

Table XIV continued

Date	Station	Depth in feet	Star Lake oxygen	Muir Lake oxygen	Cottage Lake oxygen
Feb. 13	1	0	2.94	1.25	
		5	2.88	0.80	
	2	5	3.48	1.65	
		10	3.44	1.75	
	3	5	3.28	1.85	
		10	2.77	1.90	
		15	2.70	0.98	
	4	0	2.94	2.10	
		5	3.03	1.98	
		10	2.40	1.50	
		15	1.75	0.78	
		20	0.00	0.54	
		23	0.00	0.00	
Feb. 22	1	0	2.54		3.38
		5	1.75		3.08
	2	5	2.35		3.04
		10	2.15		3.58
	3	5	2.00		3.82
		10	2.88		3.82
		15	1.96		2.62
	4	0	1.96		4.05
		5	1.96		3.58
		10	1.50		3.58
		15	1.50		3.04
		18			1.70
		20	1.25		
		24	0.88		
March 1	1	0		2.18	3.04
		5		2.28	3.13
	2	5		1.80	3.38
		10		0.88	3.28
	3	5		2.08	4.20
		10		0.93	3.58
		15		0.78	2.17
	4	0		1.45	3.48
		5		1.55	3.08
		10		1.25	3.58
		15		0.54	2.52
		18			1.90
		20		0.38	
		23		0.23	

Table XIV continued

Date	Station	Depth in feet	Star Lake oxygen	Muir Lake oxygen	Cottage Lake oxygen
March 8	1	0	2.00	1.30	
		5	1.55	1.08	
	2	5	1.80	1.70	
		10	1.35	1.34	
	3	5	1.40	2.00	
		10	1.32	0.79	
		15	1.16	0.78	
	4	0	1.40	2.83	
		5	1.33	2.18	
		10	1.15	1.35	
		15	0.98	0.44	
		20	0.00	0.48	
		23	0.00	0.67	
March 13	1	0	1.70		2.48
		5	1.64		2.60
	2	5	1.60		4.15
		10	1.45		2.73
	3	5	1.80		4.00
		10	1.50		3.44
		15	0.72		1.40
	4	0	1.50		3.62
		5	1.50		3.48
		10	1.06		3.08
		15	0.75		2.68
		18			2.14
		20	0.20		
		24	0.00		
March 20	1	0		1.26	2.18
		5		1.20	2.10
	2	5		2.39	3.98
		10		0.93	2.50
	3	5		2.38	3.10
		10		0.92	2.44
		15		0.83	1.10
	4	0		3.50	3.17
		5		3.25	3.24
		10		1.88	1.96
		15		0.35	1.45
		18			0.42
		20		0.19	
		23		0.00	

Table XIV continued

Date	Station	Depth in feet	Star Lake oxygen	Muir Lake oxygen	Cottage Lake oxygen
March 27	1	0	3.78	3.16	
		5	3.23	3.23	
	2	5	9.08	2.68	
		10	2.00	2.25	
	3	5	6.70	5.50	
		10	1.96	4.05	
		15	0.71	1.15	
	4	0	4.35	9.25	
		5	4.81	9.62	
		10	2.55	7.20	
		15	0.60	1.92	
		20	0.36	0.70	
		23	0.00	0.00	
April 3	1	0	1.80		3.48
		5	1.61		1.70
	2	5	2.25		1.58
		10	0.93		0.43
	3	5	2.03		2.73
		10	0.90		1.05
		15	0.48		0.38
	4	0	1.61		2.52
		5	1.20		1.45
		10	0.93		0.90
		15	0.23		0.68
		18			0.32
		20	0.18		
		24	0.00		
April 14	1	0	3.67	3.92	3.25
		5	4.40	1.15	4.40
	2	5	5.71	5.95	3.25
		10	3.84	5.10	3.50
	3	5	4.62	4.98	6.00
		10	2.80	3.86	5.20
		15	2.09	1.80	3.64
	4	0	3.70	6.20	4.60
		5	3.67	6.20	3.67
		10	2.88	4.85	4.00
		15	2.75	2.88	2.44
		18			1.96
		20	2.14	0.99	
		23	0.00	0.44	

Table XIV continued

Date	Station	Depth in feet	Star Lake oxygen	Muir Lake oxygen	Cottage Lake oxygen
April 19	1	0	1.65	2.63	2.55
		5	1.30	3.08	2.26
	2	5	3.87	4.61	3.15
		10	4.25	5.40	1.68
	3	5	3.87	3.10	4.30
		10	2.94	3.75	4.40
		15	2.70	3.81	3.47
	4	0	3.87	4.40	1.20
		5	2.67	3.57	2.25
		10	4.23	2.40	3.68
		15	0.74	1.80	3.13
		18			1.80
		20	2.24	2.18	
		23	2.17	1.96	
April 28	1	0	6.10	7.40	7.45
		5	6.70	6.05	4.80
	2	5	5.47	4.50	7.05
		10	5.88	5.90	6.95
	3	5	6.63	6.01	6.25
		10	6.86	4.91	6.26
		15	4.35	2.12	6.90
	4	0	5.95	6.10	5.70
		5	7.50	6.41	7.50
		10	6.09	5.40	6.20
		15	6.70	4.10	3.12
		18			5.15
		20	2.34	1.90	
		23	0.00	1.75	
May 5	1	0	5.30	5.38	5.60
		5	5.50	5.30	5.50
	2	5	4.90	4.65	4.47
		10	6.40	4.75	5.70
	3	5	4.10	4.95	
		10	4.10	4.23	
		15	3.78	3.08	
	4	0	7.25		5.55
		5	6.15	4.45	3.81
		10	5.20	3.78	4.30
		15	4.81	3.25	3.95
		18			4.10
		20	2.80	2.68	
		23	2.50	0.82	

Zero depth designates the surface samples. January 10 for Star Lake should read January 9. All depths of Star Lake which now read 23 feet should be 24 feet.