AUTUMNAL AND OVER-WINTER LIMNOLOGY
OF THREE SMALL EUTROPHIC LAKES WITH PARTICULAR
REFERENCE TO EXPERIMENTAL CIRCULATION AND TROUT MORTALITY

by

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ABSTRACT

Autumnal and over-winter limnological conditions in Marquette, Corbett and Courtney Lakes in British Columbia were followed monthly from autumn, 1961, to spring, 1964, and some additional data were collected in winter, 1965. Indices of productivity for summer and winter conditions suggest that Courtney Lake is most productive, Marquette Lake least productive and Corbett Lake intermediate. Although over-winter mortality of fishes would be expected to occur in Courtney Lake it has not been observed there whereas in Marquette and Corbett Lakes it frequently occurs.

Marquette and Corbett Lakes were sharply stratified in summer because local topography provided protection from wind action whereas stratification in the more exposed Courtney Lake was ill-defined. Average wind velocities on Courtney Lake were 4.3 times greater and more unidirectional than those on Corbett Lake. Marquette Lake was subject to wind action similar to that of Corbett Lake. To test the hypothesis that winter limnological differences between Courtney and Corbett Lakes were due to insufficient autumnal circulation, Corbett Lake was experimentally circulated.

Autumnal circulation in Courtney Lake was complete and resulted in over-winter survival of Salmo gairdneri and Richardsonius balteatus. Incomplete autumnal circulation and oxygenation in Corbett and Marquette Lakes resulted in

over-winter mortality of Salmo gairdneri and Salvelinus fontinalis.

In order to experimentally examine causes for the limnological differences between the lakes, Corbett Lake was artificially circulated. A compressed air "bubbler system" comprised of a submerged circle (circumference = 726 m) of plastic pipe and an air compressor was used to circulate Corbett Lake in the autumn of 1962 and 1963. The results of the experimental circulation of Corbett Lake compared to the limnological conditions in the "control" lakes, confirmed the original hypothesis.

Below average snow fall in 1962-63 resulted indirectly in anomalous dissolved oxygen values (supersaturation). Consequently the expected over-winter mortalities of fishes in Marquette Lake did not occur whereas the expected winter mortalities did occur in 1961-62 and 1963-64.

Winter light penetration and intensity in Corbett Lake was correlated with differences in snowfall between years. Light penetration and intensity differed considerably between lakes when snow and ice conditions were about equal (1965) because of differences in water quality.

TABLE OF CONTENTS

	Page
INTRODUCTION	1
DESCRIPTION OF THE STUDY AREA	2
BIOLOGICAL CHARACTERISTICS OF THE LAKES	6
METHODS AND MATERIALS	8
GENERAL LIMNOLOGY	8
EXPERIMENTAL CIRCULATION.	10
RESULTS	13
COMPARATIVE MORPHOMETRY	13
METEOROLOGY	15
OVER WINTER FISH MORTALITY.	19
PHYSICAL CHARACTERISTICS.	23
Transparency.	23
Temperature	23
(1) Summer Stagnation	27
(2) Autumnal Circulation.	28
(3) Winter Stagnation	29
(4) Vernal Circulation.	30
Stability	30
CHEMICAL CHARACTERISTICS.	31
Oxygen.	31
(1) Summer Stagnation	31
(2) Autumnal Circulation.	35
(3) Winter Stagnation	36
(4) Vernal Circulation.	37
Hydrogen Sulfide.	37
pH.	39
Alkalinity.	39
Total Dissolved Solids.	42
Conductivity.	42
INDICES OF PRODUCTIVITY	44
Physical.	44
Chemical.	44

	Page
EXPERIMENTAL CIRCULATION.	47
DISCUSSION	51
RELATIVE PRODUCTIVITY	51
TOPOGRAPHY AND WIND ACTION.	55
SNOW COVER AND WINTER LIMNOLOGY	58
WINTER OXYGEN DEMAND.	61
EXPERIMENTAL CIRCULATION.	63
SUMMARY	68
LITERATURE CITED	70

LIST OF TABLES

<u>Table</u>	Page
I. Morphometric parameters of Marquette, Corbett and Courtney Lakes.	14
II. Monthly snowfall as recorded by the Department of Transport Recording Station near the study area	20
III. Fish mortality (during study period) for Marquette, Corbett and Courtney Lakes	22
IV. Mean Secchi disk readings (m); calculated from data collected in all seasons except winter	23
V. Maximum and minimum bicarbonate and carbonate alkalinity (mg/l) recorded during the study period (August 28, 1961 - May 24, 1964)	41
VI. Mean concentration of total dissolved solids (mg/l). Calculated from data collected in August, October and December, 1961 and May, 1962, for Corbett and Courtney Lakes--June, 1962 for Marquette Lake.	42
VIIa. Morphometric indices of productivity (ranked).	45
b. Chemical indices of productivity	45
VIII. Summary of indices of productivity	55

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1.	Location at the study lakes with respect to relative proximity of surrounding topography (contours in meters).	3
2.	Hydrographic maps of the study lakes showing location of limnology Station I and wind recording stations (contours in meters). Limnology Station I is shown for Corbett Lake in Fig. 3.	4
3.	Layout of Corbett Lake experimental circulation system and sampling stations . .	11
4.	Average velocity of wind on immediate lake surface (June - November, 1962). The dotted line for Marquette Lake represents an estimate of average wind velocity	16
5.	Average wind direction on the immediate lake surfaces of Corbett and Courtney Lakes. See text for explanation of weekly average	18
6.	Average thickness of ice and snow depth for each winter of study (3 recordings 1962 and 1963; 4 recordings 1964).	21
7.	Light intensity and penetration through ice and snow cover (January 30, 1965 and January 31, 1965).	24
8.	Light intensity and penetration through ice and snow cover (January 25, 1964 and January 27, 1963).	25
9.	Seasonal isotherms ($^{\circ}\text{C}$) for Marquette, Corbett and Courtney Lakes for the duration of the study period 1961-64. Note duration of ice cover and periods of artificial circulation	26
10.	Seasonal differences in Schmidt's thermal stability.	32
11.	Dissolved oxygen isopleths (mg/l) for the duration of the study period (1961-64) . . .	34

Figure

Page

12.	Hydrogen sulfide - vertical series (Jan. 30, 1965)	38
13.	Vertical pH series (1961 and 1965)	40
14.	Summer and winter vertical specific conductivity values. Measurements taken <u>in situ</u>	43
15.	Daily changes in mean oxygen concen- tration and the vertical extent of dissolved oxygen effected by the experimental circulation of Corbett Lake, 1963 and 1962. (Note hours of experimental circulation and surface water temperature)	48

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INTRODUCTION

Over-winter mortality of fishes most often occurs in shallow eutrophic lakes that have three to four months of ice and snow cover (Greenbank, 1945; Welch, 1952; Hutchinson, 1957; Reid, 1961). This phenomenon is attributed mainly to oxidative demands of high productivity which results in severe oxygen depletion during the period that the ice cover effectively seals off the lake from atmospheric oxygen. Most eutrophic lakes are completely circulated in the autumn and are fully or nearly saturated with dissolved oxygen prior to ice formation.

The typical pattern wherein high productivity causes a severe reduction of an ample autumn oxygen supply is not applicable to at least two lakes, Marquette and Corbett, in the southwest interior of British Columbia. In Corbett Lake, over-winter mortality of fishes occurred six out of ten recorded years and in Marquette Lake, two out of three recorded years. Courtney Lake, a shallower nearby lake, has no recorded cases of over-winter fish mortalities.

In the autumn of 1961 studies were started to investigate the differences between Corbett and Courtney Lakes with respect to general autumn and winter limnology. In 1962 data from an ancillary investigation showed the value of Marquette Lake as an additional comparison. Data collected in 1961 and 1962 indicated that the principal reason for

different limnological conditions was due to incomplete autumnal circulation.

To test the hypothesis that differences between the lakes were due to lack of autumnal circulation in Marquette and Corbett Lakes, an experimental circulation of Corbett Lake was conducted first in the autumn of 1962 and was repeated in the fall of 1963.

DESCRIPTION OF THE STUDY AREA

Marquette, Corbett and Courtney Lakes are situated between latitude 50° and 53° N and longitude $120^{\circ} 39' 45''$ W and $120^{\circ} 35' 20''$ W.

The topography of the area surrounding the study lakes affords varying degrees of protection from wind action (Fig. 1). Marquette and Corbett Lakes (elevation 1036 metres) are closely surrounded by protective hills whereas Courtney Lake (elevation 975 metres) is more exposed to wind action. The orientation of the lake basins and the detailed hydrography are shown in Fig. 2.

Generally considered, the southwest interior of British Columbia has a mild, continental climate. Winters are cold and snow is present for most of December and January. Most of the annual precipitation is snow in December, January and February. Summer is generally bright and cloud-

Fig. 1. Location of the study lakes with respect to relative proximity of surrounding topography (contours in meters).

Fig. 2. Hydrographic maps of the study lakes showing location of limnology Station I and wind recording stations (contours in meters). Limnology Station I is shown for Corbett Lake in Fig. 3.

MARQUETTE LAKE

CORBETT LAKE

COURTNEY LAKE

less in contrast with cloudy winters. The uplands are cool in summer, cold in winter and have more precipitation than the valleys. "Air movements at the stations with records differ so much that little generalization is possible. In the valleys the wind almost always blows along the valley, that is in most cases from north or south....." (Kendrew and Kerr, 1955).

The nearest official meteorological observation station, Princeton, about 62.5 km south of the study area is subject to local variation in wind direction and velocity because of local topography. Consequently, the wind direction and/or velocity at Princeton is probably not indicative of meteorological events at the immediate study area. Wind direction and velocity was measured for Corbett and Courtney Lakes. Frequent visual observations of wind on Marquette Lake indicated a marked similarity to the records for Corbett Lake but Marquette Lake is probably subject to even less wind action.

The mean annual snow fall for the southwest interior of British Columbia is 101.6 cm (Kendrew and Kerr, 1955). A marked difference in snow fall between years, within the study period was recorded.

BIOLOGICAL CHARACTERISTICS OF THE LAKES

Phytoplankton samples taken in May, 1952, show representatives of Chrysophyta, Pyrrophyta, and Cyanophyta (March, 1963) in Marquette Lake, whereas Corbett Lake has representatives of Chlorophyta and Chrysophyta. Courtney Lake has representatives of Chlorophyta, Chrysophyta, Pyrrophyta and Cyanophyta. No marked blooms of phytoplankton were observed in the study lakes during spring, summer or autumn.

Common zooplankton of Marquette Lake include the Cladocerans Daphnia and Bosmina and amphipods Hyalella and Gammarus. Cyclopoid and Calanoid copepods and rotifers are also recorded. Commonly occurring zooplankton of Corbett Lake are noted by Teraguchi (1964) as Daphnia pulex and Daphnia rosea (dominant Cladocerans). The common copepod is Diaptomus leptopus whereas Diaptomus nudus and Diaptomus sicilis occur rarely. The most common species of Chaoborus larva is C. flavicans. C. nyblaei and C. americanus also occur. Rotifers are evident in plankton samples as well. Cladocerans, amphipods, copepods and rotifers are recorded for Courtney Lake plankton.

The littoral zone of Marquette Lake, like that of Corbett and Courtney is characterized by thick mats of Chara. Planorbis, Physa, Trichopteran larvae and numerous Hyalella and Gammarus are found in the littoral region. The

littoral zone of Corbett Lake harbours comparatively large numbers of aquatic insects and Gyraulus, a pulmonate snail of the family Planorbidae (Humphreys, 1964). Humphreys (1964) also found abundant Hyalella azteca and chironomid larvae. The Chara or littoral zone of Courtney Lake is characterized by large numbers of Hyalella azteca, Humphreys (1964).

Fishes found in Marquette Lake are rainbow trout (Salmo gairdneri) and brook trout (Salvelinus fontinalis). Corbett Lake has the same species and in both lakes they occur in about equal numbers. Rainbow trout (Salmo gairdneri) occur in Courtney Lake and large numbers of reidside shiners (Richardsonius balteatus) are also present. The three lakes have no natural spawning habitat for salmonids and consequently are regularly stocked by the B.C. Fish and Game Branch. Marquette Lake was stocked with 5,000 Salvelinus fontinalis and 5,000 Salmo gairdneri in the summers of 1962, 1963 and 1964. Corbett Lake was stocked in 1962 with 7,000 Salmo gairdneri and 5,000 Salvelinus fontinalis; in 1963 and 1964 with 5,000 each of Salvelinus fontinalis and Salmo gairdneri. Courtney Lake was stocked only with Salmo gairdneri; 5,400 in 1962, 3,400 in 1963 and 10,000 in 1964.

METHODS AND MATERIALS

GENERAL LIMNOLOGY

Contour maps for each lake were drawn from soundings taken with a Furuno 200 Kc., model F-701, recording echo sounder. Improved accuracy of outline maps was obtained by adjusting air interim series (B.C. Department of Lands and Forests) through the use of enlarged air photos of each lake. All morphometric data were then calculated from the maps.

Meteorological data were collected from two totalizing anemometers (Munro, London) and two wind direction recorders (Schmidt and Marshall, 1960). These instruments were mounted on rafts on Corbett and Courtney Lakes at about 0.5 metre above the lake surface (Fig. 2).

A sampling station was set up on each lake and permanently marked in 1962. Sampling was conducted more or less monthly.

Transparency was measured with a standard (20 cm diam.) Secchi disk using a glass viewing box. No Secchi disk readings were taken during ice cover. Some transparency measurements were made with a submarine photometer (Model 15-M-02/1-GM Manufacturing Company) equipped with Weston Photronic Photo-electric "deck" and "sea" cells.

Vertical temperature series were taken with a Tele-thermometer using a rapid responding thermistor (Yellow Springs Instrument Company, Inc., Model 44TB).

Dissolved oxygen determinations were made using the unmodified Winkler method. Water samples were taken with a standard Kemmerer bottle and water samples for oxygen determination were "fixed" in 300 m. B.O.D. bottles. In most cases the samples were titrated within 24 hours. During the experimental circulation of Corbett Lake, samples were titrated two to four hours after having been taken.

Hydrogen sulphide determinations were made using a colour comparator set (Hache Chemical Company, Ames, Iowa, Test Paper No. 393).

Measurements of pH were taken at the immediate time of sampling with a portable battery operated pH meter (Analytical Measurements Inc., N.J.)--probably accurate to about 0.3 pH units. Some additional pH readings were taken in 1965 with a Beckman N portable pH meter.

Total dissolved solids were determined by the evaporation method outlined in Standard Methods (American Public Health Association Inc., 1960) and modifications suggested by the B.C. Research Council (stream evaporating for one hour and dessicating for one hour) and by Rawson (drying at 110°C. Total dissolved solids determined in 1952

were done by the B.C. Research Council.

Phenolphthalein and Methyl Orange alkalinity were determined by the method outlined in Standard Methods (American Public Health Association Inc., 1960) with the exception that the titre was 0.10 N, H_2SO_4 .

In situ conductivity readings were taken with a model RB2-3341 Solu Bridge (Industrial Instruments, U.S.A.).

Plankton sampling was conducted with a standard (22.9 cm diam.) Wisconsin closing net with a net mesh size of 0.158 mm (109 meshes per inch).

Bottom samples were taken using a 15.24 cm (6 inch square Ekman dredge).

Monofilament nylon gill nets were used for fish sampling. In the winter nets were set under the ice by means of a prairie ice jigger. Observations on fish populations during the winter were also made through the use of SCUBA.

EXPERIMENTAL CIRCULATION

Experimental circulation of Corbett Lake was effected through the use of a 726 m (circumference) plastic pipe (inside diam. 2.5 cm) with 0.08 cm holes drilled every 3.7 meters (Fig. 3). An attempt was made to suspend the weighted pipe from surface rafts at a depth of about 12 -

Fig. 3. Layout of Corbett Lake experimental circulation system and sampling stations.

13 meters. Compressed air was supplied to the system by an Atlas Copco V.T. 4, 160 c.f.m. air compressor which was operated at 90 - 100 lbs/sq in. In 1962 the compressor was powered by a gasoline engine and in 1963 a diesel driven machine was utilized.

In addition to limnology Station I on Corbett Lake, seven other stations were established. Records of oxygen, temperature, and some readings of transparency, alkalinity and conductivity were taken daily at Station I. At Stations B and C oxygen and temperature were recorded daily. At Stations A and C to G daily vertical temperature records were taken. Measurements were not taken daily during the 1963 experiment. Oxygen and temperature samples were taken at the extreme "ends" of Corbett Lake, in 1962, on October 24 and 28, November 7, 9, 20 and 22. On November 23 and 25, 1962, vertical oxygen series were taken at Stations A and G.

Vertical temperature recordings at Stations A to G and additional oxygen determinations for Stations A and G and the extreme ends of the lake were taken to establish the extent of lateral effect of artificial circulation.

RESULTS

COMPARATIVE MORPHOMETRY

Courtney Lake is large and shallow whereas Marquette and Corbett Lakes are relatively small and deep (Table I). Consequently Courtney Lake has the smallest mean depth (4.9 m), Corbett Lake the greatest (7.0 m) and that of Marquette Lake is intermediate at 5.9 meters. The maximum effective length is defined by Welch (1948) as the axis along which the prevailing wind blows. Courtney Lake has the longest maximum effective length; those of Corbett and Marquette Lakes are considerably smaller. In each case the maximum effective length differs considerably from the maximum length of the lakes.

The shore line development of Corbett and Courtney Lakes does not differ significantly whereas that of Marquette Lake is somewhat lower.

The basin of Corbett Lake has a mean depth to maximum depth ratio of 0.36 and thus departs very little from that of a true cone (0.33). Marquette Lake basin (0.64) departs markedly from the conical shape and is more U-shaped whereas Courtney Lake basin is relatively saucer-shaped as is indicated by a small maximum to mean depth ration of 0.29.

Another indication of basin shape is given by relative depth (Hutchinson, 1957). Relative depth values

show the same general trend between lakes with regard to basin shape as the maximum depth to mean depth ratio (Fig. 2). (Marquette Lake and Corbett Lake basins are relatively U-shaped compared to the saucer-shaped basin of Courtney Lake.)

Table I. Morphometric parameters of Marquette, Corbett and Courtney Lakes.

	Marquette Lake	Corbett Lake	Courtney Lake
Area (hectares)	5.3	24.2	71.6
Maximum Depth (m)	9.2	19.5	17.0
Mean Depth (m)	5.9	7.0	4.9
Maximum Effective Length (m)	141.7*	244.3*	946.0
Maximum Length (m)	372.9	990.0	1637.4
Volume ($\times 10^4 \text{m}^3$)	31.1	168.9	351.2
Shore Line Development	1.2	1.6	1.5
Ratio Mean Depth to Maximum Depth	0.6	0.4	0.3
Relative Depth (%)	3.5	3.5	1.8
Mean Slope of Basin (Degrees)	7°55'	6°9'	3°13'
Littoral Development (%)	8.5	46.4	60.3

* Maximum effective length is equal to mean width because winds on Marquette and Corbett Lakes are prevailing variable in direction.

The mean slope of the basin of Marquette Lake, 7°55', indicates a relatively steep-sided basin similar to

that of Corbett Lake which is $6^{\circ}9'$. The mean slope of the basin of Courtney Lake has the least grade ($3^{\circ}13'$) of the three lakes.

Littoral development is defined by Rawson (1939) as the area of the littoral zone expressed as a percentage of the total area. The littoral zone, for purposes of this study, is determined by the extent of the Chara growth. SCUBA observations and enlarged aerial photographs show the offshore boundary of Chara to be very distinct. The Chara zone of Marquette Lake extends to a depth of 2 meters with a consequent small "littoral development" of 8.5% but the littoral zone of Corbett Lake extends to a depth of 4 meters which results in a larger "littoral development" (46.4%). The largest "littoral development" is 60.3% (Courtney Lake) and the littoral zone extends to a depth of 4.5 meters.

METEOROLOGY

The average wind velocity on Courtney Lake (199 cm/sec) is, on the average, 4.3 times greater than the average wind velocity on Corbett Lake - 46.2 cm/sec (Fig. 4). Frequent visual observations and some spot measurements of wind velocity on Marquette Lake show it to be most like that of Corbett Lake but to a lesser degree.

Wind direction, like wind velocity, was recorded on the immediate lake surface. The wind direction recorders

Fig. 4. Average velocity of wind on immediate lake surface (June - November, 1962). The dotted line for Marquette Lake represents an estimate of average wind velocity.

used on Corbett and Courtney Lakes were designed to record the four cardinal compass points (N.S.E.W.) plus the four principal intermediate compass points. In addition, periods of calm and periods that show wind to be highly variable in direction are easily discernible on the recording charts. If the wind were entirely random in direction the expected average number of hours per week (Fig. 5) in any direction would be equal to the total average number of recorded hours per week divided by the number of recorded directions and/or quadrants. Difficulty was encountered in mounting the wind direction recorders on rafts and during the period of recording the rafts were subject to some movement (about 10 - 30°). Consequently, the directions that were readable on the recording charts were only those shown in Fig. 5. For the study period the average number of hours per week of recordable time in Corbett Lake was 165.1 and the mean number of hours per week that was actually readable from the recording charts was 107.3 while the respective averages for Courtney and Corbett Lakes were 166.2 hours and 103.1 hours. This amounts to the wind direction on Corbett Lake being measured for 64.9% of the recorded study period and that of Courtney Lake, 62.1%.

A prevailing wind direction does not exist for Corbett Lake (predominant direction is variable) whereas on Courtney Lake a prevailing wind is very evident and blows along a 180 - 225° (S.S.W.) axis (Fig. 5). In all

Fig. 5. Average wind direction on the immediate lake surfaces of Corbett and Courtney Lakes. See text for explanation of expected weekly average.

WIND DIRECTION (DEGREES)

--- EXPECTED WEEKLY AVERAGE

probability the prevailing wind direction on Marquette Lake is also variable. It is also pertinent to note that the prevailing wind direction on Courtney Lake is the same as the long axis of the valley to the south of the lake (Fig. 1).

Snowfall is recorded by an official recording station near to the study area and is summarized in Table II. Striking differences between the monthly snowfall for the winter of 1962-63 and that for the winters of 1961-62 and 1963-64 are evident. Fig. 6 shows that snow fall on the immediate ice surface of the respective lakes was virtually nil in 1962-63 and considerably greater in 1961-62 and 1963-64.

OVER-WINTER FISH MORTALITY

In the winter of 1961-62 a complete over-winter mortality of fishes occurred in Corbett Lake (Table III) whereas no such phenomenon was recorded or observed in Courtney Lake. In the winter of 1962-63 over-winter mortality of fishes did not occur in any of the study lakes but in 1963-64 a complete mortality of trout occurred in Marquette Lake. In all probability this would have occurred in Corbett Lake as well if the oxygen concentration had not been increased by experimental circulation.

Table II. Monthly snowfall (cm) at the official recording station nearest the study area (Craigmont Mines, Merritt).

	Snowfall in cm	No. of Days With Measurable Snow		Snow on Ground at End of Month
1961 Nov.	29.21	No Record	10	12.70
1961 Dec.	65.79		20	30.48
1962 Jan.				
1962 Feb.				
1962 Mar.	7.62		3	0
1962 Apr.	---		0	0
Total	95.00		33	43.18
1962 Nov.	2.79		3	
1962 Dec.	12.19		4	
1963 Jan.	1.27		2	0
1963 Feb.	4.57		1	0
1963 Mar.	5.08		2	0
1963 Apr.	0		0	0
Total	25.9		12	0
1963 Nov.	12.70		5	0
1963 Dec.	40.89		11	1.62
1964 Jan.	86.61		18	33.0
1964 Feb.	2.54		2	0
1964 Mar.	14.73		5	0
1964 Apr.	5.08		1	0
Total	162.55		42	34.62

Mean annual snowfall for study area = 101.6 cm (Kendrew and Kerr, 1955).

Fig. 6. Average thickness of ice and snow depth for each winter of study (3 recordings 1962 and 1963; 4 recordings 1964).

Table III. Record of over-winter fish mortality in Marquette, Corbett and Courtney Lakes (1961 - 1964) - (Artificial aeration in Corbett Lake during the autumn of 1962 and 1963.)

Date of Sampling	Marquette Lake	Corbett Lake	Courtney Lake
1961 Sep. 30		+ N	+ N
1961 Oct. 28,29		+ N	+ N
1962 Jan. 30		-*D,N	+ N
1962 Mar. 14			+ N
1962 May 3			+ N,A
1962 Jun. 28	- N		
1962 Aug.		+ N	+ N
1962 Nov. 22-26		+ N	
1962 Dec. 21	+ N		
1963 Jan. 26		+ N	
1963 Mar. 4- 8	+ D,N	+ N	+ N
1963 May	+ N	+ A	+ A
1963 Oct. 29	+ N		
1964 May 2- 3	- N	+ A,N	+ N

D - Dead fish retrieved through use of SCUBA.
A - Presence of live fish indicated by angling.
N - Presence of live fish indicated by gill net.
Fish were stocked in Corbett and Marquette
Lakes in the summer of 1962 and 1963.

+ - Presence of live fish.
- - Absence of live fish.
* - Dead fish retrieved from under the
ice.

PHYSICAL CHARACTERISTICS

Transparency

Secchi disk readings averaged for all seasons except winter show that light transmission is greatest in Corbett Lake (5.48 m) intermediate in Courtney Lake (5.0 m) and least in Marquette Lake (3.0 m) (Table IV).

Table IV. Mean Secchi disk readings (m); calculated from data collected in all seasons except winter.

Marquette Lake	Corbett Lake	Courtney Lake
3.0	5.48	5.0
(4 recordings)	(12 recordings)	(10 recordings)

Light intensity and penetration through ice and snow shows the same relative relationship as that for Secchi disk readings (Fig. 7). In Corbett Lake light penetration and intensity is considerably greater in 1963 than in 1964 (Fig. 8). In 1963 recordable light penetrates to 19 meters at an intensity of 2.9 lux whereas in 1964 an intensity of 2.9 lux reaches only the 6 meter depth, even though the mean incident light (6568 lux) is considerably higher than in 1963 (4320 lux).

Temperature

The thermal record of Marquette, Corbett and Courtney Lakes is shown for the study period 1961-64 in Fig. 9.

Fig. 7. Light intensity and penetration through ice and snow cover
(January 30, 1965, and January 31, 1965).

Fig. 8. Light intensity and penetration through ice and snow cover
(January 25, 1964 and January 27, 1963).

Fig. 9. Seasonal isotherms ($^{\circ}\text{C}$) for Marquette, Corbett and Courtney Lakes for the duration of the study period 1961-64. Note duration of ice cover and periods of artificial circulation.

Gross characteristics of the seasonal thermal cycle are obvious and only salient features will be discussed in detail.

(1) Summer Stagnation

On August 31, 1962, the marked stratification of Corbett Lake is evident from the closeness of the isotherms in the 4 - 5 meter stratum. Courtney Lake, however, is not as sharply stratified (the isotherms are more widely spaced) and has an ill-defined thermocline between 6 - 8 meters. The difference between lakes with respect to summer thermal stratification is best shown in Fig. 9 by data for the summer of 1962. Corbett and Marquette Lake isotherms are parallel and very close together compared to those of Courtney Lake which are not parallel and are well spaced. This is a reflection of sharp thermal stratification in Marquette and Corbett Lakes (little or no circulation) whereas Courtney Lake is virtually unstratified and well circulated.

The difference in surface to bottom temperature (August 7 - 9, 1962) for Marquette Lake is 13°C and is similar to the difference in Corbett Lake (13.6°C) but in Courtney Lake the difference is much less (5.6°C). Consequently Courtney Lake is much warmer than either Marquette or Corbett Lake. The sharp depression in isotherms between August 9 to 31, 1962, in Courtney Lake and to a lesser degree between August 19 to 31, 1962, in Corbett Lake should

be noted. Attendant with the depression in isotherms is a reduction in the difference between surface and bottom temperatures, particularly in Courtney Lake (2.8°C); Corbett Lake - 13.4°C . The thermal stratification of Corbett Lake during the summer of 1963 is almost identical to that of 1962. The characteristic feature of summer stagnation in Marquette and Corbett Lakes is that of well defined stratification and stability whereas Courtney Lake is characterized by ill-defined stratification and instability as a result of mixing.

(2) Autumnal Circulation

Natural autumn circulation occurs in all three study lakes during the study period only in the fall of 1961 (Fig. 9). Homothermal conditions exist at about the same time and temperature (5.6°C) in both Corbett and Courtney Lakes as shown by data for October 28, 1961. On October 28 and 29 of 1962 homothermy is recorded for Courtney Lake at 8.9°C and Marquette Lake is almost homothermal at 7.2°C --a reflection of circulation from top to bottom in both lakes. Corbett Lake at this time is very nearly homothermal at 7.2°C but this condition is a result largely of experimental circulation. Data for 1963 show Courtney Lake to be isothermal on October 20 whereas Marquette Lake is well stratified and Corbett Lake, even after some experimental circulation, is still sharply stratified.

Autumn circulation as reflected in isotherms of Fig. 9, generally show that Marquette and Corbett Lakes become isothermal at a later date than does Courtney Lake. This is a reflection of greater autumnal circulation in Courtney Lake than in Marquette and Corbett Lakes.

(3) Winter Stagnation

Typical, winter inverse temperature stratification is shown by under-ice isotherms for the three study lakes (Fig. 9). In addition, differences in temperature exist. Courtney Lake is somewhat warmer--5°C is recorded for Courtney Lake but not for Corbett Lake (1961-62). Some cooling does occur immediately under the ice in both Corbett and Courtney Lakes (1961-62). The depth of 1°C is depressed from about 0.1 meter to 1.5 meters in Corbett Lake and to 1 meter in Courtney Lake. Concurrent with this cooling, the 4° isotherm in Courtney Lake rises to 3 meters thus reflecting an increase in temperature of the bottom waters. Similar heating is recorded by Ökland (1964).

Under-ice thermal features are similar in 1962-63 to those of 1961-62 except that anomolous warming occurs in a well-defined stratum in each lake (Fig. 9, March 7 - 8, 1963). Both Corbett and Courtney Lakes are colder in 1962-63 and Marquette Lake is similar to Corbett Lake in this respect.

The winter thermal stratification of 1963-64 is almost identical to that of 1962-63. No anomalous warming occurs in 1963-64.

(4) Vernal Circulation

Complete vernal circulation does not occur in Corbett Lake whereas Courtney Lake is fully circulated in the spring (Fig. 9, May 3, 1962). Similarly, for May 13, 1964, temperature data shows that Marquette and Corbett Lakes are not completely circulated but Courtney Lake is well mixed. Vernal circulation occurs about two weeks later in 1964 because of an extended period of ice cover. The same phenomenon of respective incomplete and complete mixing for Marquette, Corbett and Courtney Lakes occurs in the spring of 1964 (Fig. 9).

Stability

Stability is the amount of work needed to mix the entire body of water to uniform temperature without changing its mean temperature (Eckel, 1950 quotes Schmidt, 1928). Formulae for the calculated stability (Eckel, 1950) show that the computations take into account both the density changes imparted by thermal stratification and the morphometric features of the lake basin. In the study lakes, density changes resulting from chemical stratification are probably minimal. Thus, a quantitative statement of the amount of work necessary for full circulation of each lake

can be made.

Corbett Lake is much more stable than is Courtney Lake (Fig. 10). The stability of Marquette Lake is intermediate to the other two lakes. Based on thermal stratification alone, one would expect Marquette Lake to be as stable as Corbett Lake. It can be safely assumed, considering the second factor that contributes to stability--morphometry--that the difference is due largely to basin size and shape. The relatively low stability values for Courtney Lake are primarily the result of ill-defined stratification which in turn is the result of greater wind action on the lake.

CHEMICAL CHARACTERISTICS

Oxygen

(1) Summer Stagnation

Corbett Lake is much more stagnant than is Courtney Lake (Fig. 11, August 28, 1961). Dissolved oxygen isopleths of Fig. 9 show that the epilimnion of Corbett Lake extends to a depth of 3 meters whereas that of Courtney Lake reaches a depth of 9 meters. With respect to oxygen then, Corbett Lake (1961) is sharply stratified and the concentration per unit volume is relatively low compared to a higher mean concentration in Courtney Lake and a less well defined stratification. A complete summer stagnation period is

Fig. 10. Seasonal differences in Schmidt's thermal stability.

recorded in Fig. 11 for 1962. Absolute oxygen concentration is generally higher in Courtney Lake, lower in Corbett Lake and lower still in Marquette Lake. The zero mg/l isopleth oxygen value is recorded for the duration of the summer in Corbett Lake and probably also in Marquette Lake. In Courtney Lake, however, the zero mg/l oxygen value is recorded only for the latter part of the summer. Consequently, a relatively large portion (or the whole) of the hypolimnion of Corbett Lake is deoxygenated but the hypolimnion of Courtney Lake is relatively well oxygenated. The closely spaced and parallel isopleths of Corbett Lake reflect the sharp stratification and relative stability opposed to the widely separated isopleths of Courtney Lake which are dissimilar in aspect and therefore reflect a greater amount of mixing. Data available for Marquette Lake suggests a condition similar to that of Corbett Lake.

The very sudden depression of 0 - 8 mg/l oxygen concentrations in Courtney Lake on August 25, 1962, are the result of a very strong wind. Courtney Lake was subject to an unseasonable, complete mixing on August 25, 1962; (Fig. 11) but Corbett Lake and probably Marquette Lake remain sharply stratified.

The effects of experimental circulation on oxygen concentration and distribution within the lake will be discussed in a later section.

The stratification of oxygen in Corbett Lake for 1963 (Fig. 11) is almost identical to that for 1962. Summer data are lacking for Marquette and Courtney Lakes but if Corbett Lake data are so similar to the preceding summer, it is likely that the oxygen features of Courtney and Marquette Lakes would be the same as those of the preceding summer.

(2) Autumnal Circulation

Natural circulation is recorded for both Corbett and Courtney Lakes only in the autumn of 1961 (Fig. 11). Corbett Lake is incompletely oxygenated and/or circulated and surface oxygen concentration is very low compared to the complete circulation and relatively high surface concentration of Courtney Lake (Fig. 11, October 31, 1961).

Autumnal circulation of Corbett Lake in 1963 and 1964 is artificial. The 1962 autumn circulation of Courtney Lake occurred prematurely on August 25 and relatively slight stratification occurred before the ice formation (October 31). Marquette Lake does circulate completely but dissolved oxygen concentrations are much lower than those of Courtney Lake. Autumnal circulation is similarly effective in 1963--Courtney Lake being oxygenated and Marquette Lake relatively poor in oxygen (Fig. 11, November 9, 1963).

(3) Winter Stagnation

After natural autumn circulation (1961) in Corbett Lake, winter stagnation is severe. Virtually no oxygen is present in Corbett Lake by mid-March, 1962, whereas the vertical extent and concentration of oxygen in Courtney Lake is relatively great.

The under-ice oxygen features are unusual in Marquette and Courtney Lakes for the winter 1962-63. A well defined stratum of supersaturation of oxygen is recorded in both lakes (Fig. 11, March 7 and 8, 1963). This stratum of supersaturation corresponds exactly with the layer in which increased temperature is recorded for the same date (Physical Characteristics - Temperature). The under-ice oxygen content of Courtney Lake is somewhat higher in 1962-63 than in the previous winter. Similarly Corbett Lake has a higher oxygen content.

Marquette Lake is almost completely depleted of oxygen by March 6, 1964, whereas Corbett and Courtney Lakes have much higher mean concentrations of oxygen.

The slope of oxygen isopleths under the ice drawn for Corbett Lake is much greater than the slope of oxygen isopleths drawn for Courtney Lake (Fig. 11). Oxygen isopleths recorded for Courtney Lake show an initial steep slope immediately after ice cover but for the remaining ice-

covered period they are relatively parallel. The slope of isopleths for Marquette Lake, similar to Corbett Lake, are greater than those of Courtney Lake. Thus, during winter stagnation there is a more rapid consumption (depletion) of oxygen in Marquette and Corbett Lakes compared to Courtney Lake and under the normal natural circumstances this would result in nearly complete oxygen depletion in Marquette and Corbett Lakes but not in Courtney Lake.

(4) Vernal Circulation

Vernal circulation in Corbett Lake is incomplete whereas Courtney Lake is completely mixed at spring turn-over (Fig. 11, April 30, 1962). Data recorded at a later date (June 24, 1962) for Marquette Lake are good evidence for a spring circulation similar to that of Corbett Lake. Data collected on Marquette Lake at an earlier date in 1963 (May 13) support this conclusion. The relative effectiveness and extent of vernal circulation is well illustrated by data collected two days after ice break-up in 1964 (Fig. 11). Surface concentration in Marquette and Corbett Lakes is low compared to that of Courtney Lake.

Hydrogen Sulfide

The presence of hydrogen sulfide in Corbett Lake is restricted to the hypolimnion (Fig. 12). Some overlap in the presence of hydrogen sulfide and oxygen is evident

Fig. 12. Hydrogen sulfide - vertical series (January 30, 1965).

at about the 12 meter level. Corbett Lake was experimentally circulated again in the autumn of 1964 sufficient to provide a mean concentration, top to bottom, of oxygen of about 10 mg/l prior to ice cover. Thus, the presence of hydrogen sulfide at the 17 meter level, in excess of 5 mg/l must be considered a relatively high concentration and higher concentrations likely occur under natural conditions without artificial autumnal circulation.

pH

Summer (August 28, 1961) pH readings show a gradation from surface to bottom for both Corbett and Courtney Lakes and (Fig. 13) vertical changes in pH generally parallel temperature and oxygen stratification. pH readings taken during fall turn-over (October 28, 1961) reflect the change in chemical and physical stratification that occurs with autumnal circulation. Courtney Lake is generally more alkaline than Corbett Lake and Marquette Lake is relatively acidic compared to Corbett and Courtney Lakes (Fig. 13).

Alkalinity

Absolute values of bicarbonate alkalinity in Marquette, Corbett and Courtney Lakes are rather similar (Table V). Carbonate alkalinity occurs only in Courtney Lake. Minimum surface values for carbonate alkalinity occur in the winter and are probably a result of the freeze-out

Fig. 13. Vertical pH series (1961 and 1965).

Table V. Maximum and minimum bicarbonate and carbonate alkalinity (mg/l) recorded during the study period (August 28, 1961 - May 24, 1964).

	Marquette Lake		Corbett Lake		Courtney Lake	
Bicarbonate Alkalinity						
Depth (m)	0	7.6-8.5	0	10.7-18.3	0	8.5-10.7
Maximum	300 (Jun.24/62)	365 (Mar.4/63)	350 (Aug.28/61)	349 (Aug. 8/62)	329 (Mar.14/62)	329 (Mar.14/62)
Minimum	150 (Mar. 4/63)	345 (Aug.9/62)	35 (Jan.31/62)	310 (Sep.30/62)	20 (Mar. 7/63)	285 (Oct. 1/62)
Carbonate Alkalinity						
Maximum	Nil	Nil	Nil	Nil	80 (May 20/62)	74 (May 20/62)
Minimum	Nil	Nil	Nil	Nil	32 (May 13/62)	0

phenomenon (Welch, 1952; Anderson, 1958a; Krumholz and Cole, 1959).

Total Dissolved Solids

Courtney Lake has the highest mean concentration of total dissolved solids (406 mg/l) and Marquette Lake has least (352 mg/l). Corbett Lake has an intermediate value of 361 mg/l (Table VI). In each lake the surface concentration is lower than that of the bottom.

Table VI. Mean concentration of total dissolved solids (mg/l). (Calculated from data collected in August, October and December, 1961, and May, 1962, for Corbett and Courtney Lakes--June, 1962, for Marquette Lake.

	Marquette Lake		Corbett Lake		Courtney Lake	
Depth in Meters	0	8.5	0	13.1-16.7	0	7.9-9.7
Mean Concentration	294	410	345	377	287	426
Mean Concentration for Whole Lake	352		361		406	

Specific Conductivity

Selected, typical summer and winter specific conductivity readings (in situ vertical series) are presented in Fig. 14. Autumn (data not shown) recordings are intermediate to summer and winter values but vernal recordings for Marquette and Courtney Lakes are slightly higher than summer readings whereas spring records for Corbett Lake are

Fig. 14. Summer and winter vertical specific conductivity values. Measurements taken in situ.

similar to those of summer.

INDICES OF PRODUCTIVITY

Physical

Ranked morphometric indices of productivity show that Courtney Lake is most productive (total of 19). Corbett Lake is intermediate (14) and Marquette Lake is least productive (total 10) (Table VII). In order to further establish the relative productivity of each lake winter areal oxygen deficits were calculated (Hutchinson, 1957, planimetric method).

Chemical

Hypolimnetic areal oxygen deficits are used as an index of productivity in stratified lakes because it is assumed that organic seston from the trophogenic layer, "raining" down (into the tropholytic zone) will use oxygen in the same proportion to the amount of production in the trophogenic zone. Thus a measure of oxygen consumed in unit time per unit area is a measure of productivity. Courtney Lake is not sharply stratified in the summer, therefore the method could not be used on a comparative basis. In Corbett Lake, during the winters of 1961-62, 1962-63 and 1963-64, there is no evidence for an increase in dissolved oxygen after ice cover and therefore the total lake area (T) is used in calculating oxygen deficits (Table VII). In Courtney Lake,

Table VIIa. Morphometric indices of productivity (ranked).

	Marquette Lake	Corbett Lake	Courtney Lake
Mean Depth	2	1	3
Maximum Effective Length	1	2	3
Shoreline Development	2	3	1
Ratio Mean Depth to Maximum Depth	1	2	3
Relative Depth	2	2	3
Mean Slope of Basin	1	2	3
Littoral Development	1	2	3
Total	10	14	19

Table VIIb. Chemical indices of productivity.

	Marquette Lake	Corbett Lake	Courtney Lake
Oxygen Deficits mg/cm ² /day			
Oct.28-Mar. 15, 1961-62	No data	0.0165(T)	0.0282
Dec.21, 1962 (Theoretical)	0.0077	0.0469(T)	0.1315
Nov.24, 1963 (Theoretical)	0.0163	0.0965(T)	0.1339

(Theoretical) - see text for explanation.

(T) - Total lake area utilized in calculating deficit (see text).

however, there is evidence for an increase in dissolved oxygen after ice cover and consequently the area of the hypolimnion, for purposes of computing areal oxygen deficit, is determined by the depth at which no increase in oxygen concentration over the previous reading is recorded.

"Theoretical" oxygen deficits are calculated because there is a slight difference in freeze-over time for each lake and the rate of oxygen consumption in each lake is greatest immediately after ice cover (Fig. 11). Therefore, if oxygen deficits were calculated for each lake, say two weeks after freeze-over, a meaningful comparison could not be made. In order to make reliable comparisons of oxygen deficits between lakes, the surface oxygen concentration recorded on December 21 and November 24 of 1962 and 1963 respectively was assumed to be the top to bottom concentration for each lake at the time of freeze-over. Areal oxygen deficits were calculated on the difference of this "theoretical" value and those values actually recorded on the above-mentioned dates.

Each winter areal oxygen deficit in Table VII shows that Courtney Lake is more productive than Corbett Lake and that Marquette Lake is the least productive.

Preliminary C^{14} investigations were begun on January 30, 1965. Water samples were collected at 0, 1 and 2 meters from Marquette, Corbett and Courtney Lakes and

incubated, without ice and snow cover, in Corbett Lake at the same depths of collection. Replicates varied considerably and consequently the data are not too reliable. The general trend, however, showed that Courtney Lake was the most productive of the three.

EXPERIMENTAL CIRCULATION

Experimental circulation is evidenced in depressed isotherms and depressed and altered dissolved oxygen isopleths (Figs. 9 & 11). In 1962 (Fig. 9) the first nine days of experimental circulation depressed the 6°C isotherm 3.25 meters. In 1963 during the first eight hours of artificial circulation the 8°C isotherm is depressed 2.5 meters.

Oxygen isopleths show sharp changes similar to those of isotherms, during experimental circulation.

The initial effect of experimental circulation is to reduce the mean concentration of oxygen (Fig. 15). (Mean concentration of oxygen is determined planimetrically on the concentration--depth curve.) A second immediate effect of artificial circulation is a strong odour of hydrogen sulfide which persisted in 1962 from October 17 (circulation started) and decreased gradually until November 23.

Fig. 15 shows the initial reduction in the mean

Fig. 15. Daily changes in mean oxygen concentration and the vertical extent of dissolved oxygen effected by the experimental circulation of Corbett Lake, 1963 and 1962. (Note hours of experimental circulation and surface water temperature.)

concentration of oxygen from 6.39 mg/l to 5.62 mg/l in the first four hours of circulation (October 17, 1962). After 18 hours of artificial circulation a minimum of 4.70 mg/l was reached (October 18, 1962). The accompanying changes in vertical penetration of oxygen were from 10.7 meters to 12.2 meters in the first four hours and from 12.2 meters to 13.7 meters in 18 hours of circulation (Fig. 15).

Little increase in mean concentration of oxygen was shown (October 17 - 19) during the first period of experimental circulation. From October 18 to 25 there was greatest increase in depth penetration of oxygen (13.7 to 17.5 meters), whereas the greatest increase in mean concentration (October 25 to 28) was attendant with the smallest increase in vertical extent of oxygen (17.5 to 18.3 meters).

From October 29 to November 7, 1962, Corbett Lake was not circulated experimentally and the mean concentration of oxygen dropped from 5.50 mg/l to 4.85 mg/l (surface water temperature was still relatively high, Fig. 15). Artificial circulation was again initiated from November 7 to 8 and a substantial increase in mean oxygen concentration was evident (4.85 to 5.63 mg/l). It is pertinent to note that the lake was oxygenated from surface to bottom on October 28. Although the oxygen concentration decreased from October 29 to November 7 there was no oxygen deficit at the bottom of the lake, for that period. Accompanying changes in surface

water temperature (Fig. 16) are doubtless correlated with the rate of solution of oxygen.

Artificial circulation again ceases from November 10 to 18 but the mean concentration of oxygen increases and is probably the result of natural circulations coupled with decreased surface water temperature.

From November 18 to 26 the rate of increase in mean oxygen concentration is much increased and a maximum of 8.28 mg/l is reached on November 26 after 359.2 hours of experimental circulation.

A similar trend in change of mean oxygen concentration and a gradual penetration of dissolved oxygen from surface to bottom is evident for the period of experimental circulation in 1963--the mean concentration of oxygen at the end of the experiment being 6.80 mg/l--a result of 180 hours of experimental circulation.

The lateral extent of experimental circulation was assessed by periodic and daily temperature and oxygen readings at Stations A to G (Fig. 3). Daily vertical temperature records at Stations A to G show that artificial circulation does indeed affect Corbett Lake at its extreme ends. However, there is a time-lag between the changes effected at Station 1 and the more distant stations.

Water samples taken at Stations A and G on the

25th of November, 1962, have a mean concentration of 8.2 mg/l and 8.7 respectively. From these data it is deduced that experimental circulation effectively increased the mean concentration of oxygen in the entire lake volume. Oxygen determinations at Stations A and G, however, may be affected by oxygen produced photosynthetically in the littoral zone. Oxygen pulses measured in the littoral zone at the extreme "ends" of Corbett Lake on November 20 - November 21 and November 22 to 23, 1962, showed 12 hour differences as great as 2.5 mg/l and as small as 1.9 mg/l. However, in Corbett Lake the contribution of oxygen from a photosynthetic source is probably small and the large changes in mean oxygen concentration and vertical penetration are doubtless the result of experimental circulation.

DISCUSSION

RELATIVE PRODUCTIVITY

Lakes that are subject to over-winter mortality of trout populations are generally shallow and highly productive. Courtney Lake is shallower and more productive than Corbett Lake. Consequently one would expect that Courtney Lake, rather than Corbett Lake, would be subject to winter mortality of fishes. Therefore, an examination of the productivity of the lakes should help to explain the expected differences with respect to winter mortality of fishes.

Morphometric parameters are frequently employed by limnologists as indices of productivity (Rawson, 1939, 1955, 1961; Northcote and Larkin, 1956; Larkin and Northcote, 1958).

Limnologists are generally agreed that no single parameter serves alone as an index of productivity and that the inter-relationships of the effects of different parameters are complex. Rawson (1939) classified the factors influencing lake productivity into three groups: morphometric, edaphic, and climatic. Rawson (1939) states that edaphic and climatic factors cause over-riding deviations from the correlations between morphometry and productivity. In this study, morphometric and local climatic differences are largely responsible for differences in productivity.

Rawson (1939, 1952, 1955 and 1961) correlated low mean depth with relatively high productivity in large Canadian lakes. Larkin (1964) maintains that mean depth is a valuable indicator for capacity of biological production within limited areas. Small lakes are treated by Hayes and Anthony (1964) who find that there is good correlation between high "Productivity Index" and low mean depths (1.4-11.6 m). On the basis of mean depth, Courtney Lake (4.9 m) is most productive, Marquette Lake (5.8 m) next most productive and Corbett Lake (6.9 m) is least productive of all three.

"A lake with a gradually sloping basin or with broad shoals could normally be expected to be more productive biologically than a deep lake with steep sides.", (Reid, 1961). Basin shape is indicated by the ratio of mean depth to maximum depth and mean slope. Shoal area is indicated by "littoral development". The contribution of each index of productivity (above) to the relative productivity of each lake results in the same inter-lake relationship--Courtney Lake is most productive, Marquette Lake is least productive and Corbett Lake is intermediate. Northcote and Larkin (1956) cite a case, similar to this study, wherein two basins with similar altitude, climate, substrate and area differ because one has a greater productivity which is due to ".....the more productive of the two having extensive shoal areas....."

Probably the most significant morphometric parameter in this limnological comparison is maximum effective length. Larkin (1964) maintained that climatic and edaphic factors are responsible for over-riding the relationship between morphometry and productivity. The maximum effective length of Marquette, Corbett and Courtney Lakes (141.68, 244.30 and 946.0 meters respectively) demonstrates the dramatic differences in wind action on the lakes.

The effect of wind action on productivity is considered by several investigators (Larkin, 1964; Murphy, 1962; Patalas 1960b; Rawson, 1961; Larkin and Northcote,

1958). All are agreed that increased mixing of a lake does indeed increase production. Courtney Lake on the average is subject to 4.3 times as much wind as Corbett Lake and Marquette Lake receives less wind on the average than does Corbett Lake.

C¹⁴ data collected on January 30, 1965, further support, in part, the above conclusions regarding the productivity of the three lakes (Fig. 15). Replications of C¹⁴ determinations vary considerably and thus the data are probably not too dependable. They do show, however, that Courtney Lake is the most productive of the three study lakes.

Any single index of productivity discussed above may not alone be conclusive demonstration of the productivity of the respective lakes. However, ranked morphometric indices of productivity, the relative amounts of wind action and the respective winter oxygen deficits all show that Courtney Lake is more productive than Corbett Lake which is more productive than Marquette Lake (Table VIII). In addition, preliminary C¹⁴ data show Courtney Lake to be the most productive of the three lakes.

The original premise states that: productive shallow lakes are more likely to be subject to over-winter mortality of fish populations than are less productive, deeper lakes. The data in Table VIII demonstrate the

productivity of each lake in relation to its neighbours and on this basis one would expect Courtney Lake to be subject to frequent over-winter mortalities of fishes and that Corbett and Marquette Lakes would not. However, records of winter fish mortalities show that Marquette and Corbett Lakes are subject to this phenomenon and Courtney Lake is not.

Table VIII. Summary of indices of productivity.

	Marquette Lake	Corbett Lake	Courtney Lake
Ranked Morphometric Indices of Productivity (Summed) (Table VII)	10	14	19
Ratio of Average Wind Velocity (Fig. 4)	1	1.3	5.7
Ratio of Oxygen Deficits	1	6	12.6

TOPOGRAPHY AND WIND ACTION

Marquette and Corbett Lakes are closely bordered by high rising hills parallel to the long axis of the lakes (Fig. 1). Courtney Lake, on the other hand, is not as closely bounded by protective hills and is consequently well exposed to the prevailing winds.

As a result of exposure the mean total wind recorded for Courtney Lake is 4.3 times greater than that recorded for Corbett Lake. Marquette Lake being even more

surrounded by shielding hills, is probably subject to even less wind action. Total wind action on Courtney Lake is not only greater, on the average, than that of Corbett and Marquette Lakes, but it is predominantly unidirectional. The major portion of total wind action on Corbett Lake and probably on Marquette Lake is variable in direction.

A strong prevailing wind will produce agitation and waves on a lake surface whereas a weak wind, variable in direction, will produce little surface agitation. Breaking waves were rarely seen on Corbett Lake, never on Marquette Lake but frequently on Courtney Lake. In this instance, wave action is of paramount importance in oxygenation (pers. comm. Dr. R.W. Stewart). Thus, wind acting on Courtney Lake in a prevailing direction produces breaking waves which are largely responsible for complete mixing and a higher mean oxygen concentration than is found in Marquette or Corbett Lakes. Conversely, lower winter oxygen concentration and incomplete autumnal mixing of Marquette and Corbett Lakes are the result of insufficient and variable winds that do not produce breaking waves and consequent high oxygen concentrations.

An excellent example of the difference in wind action that the exposure of the three lakes affords is provided by an unusually strong wind on August 25, 1962. Weekly totalizing anemometer readings for both Corbett and

Courtney Lakes for the week August 15-22 and 22-29 are higher than the weekly average for the period of recording. The effect of the strong wind was to completely mix Courtney Lake (Fig. 11) whereas Corbett Lake was relatively undisturbed and Marquette Lake was probably equally unaffected.

A consideration of Schmidt's stability values (Fig. 10), or the amount of work necessary to circulate a lake, explains in part, the differential effect of the above mentioned wind. The amount of work necessary to circulate Corbett Lake (August 7, 1962) is much greater than the amount necessary to mix Marquette Lake, which in turn is greater than the quantity necessary for Courtney Lake. Consequently, if each lake did receive the same amount of wind on August 25, 1962, Courtney Lake would be most likely to have mixed followed by Marquette Lake and Corbett Lake would probably be least affected. The drop in stability of Courtney and Corbett Lakes between August 7 and 19 respectively and the end of August is probably due to the increased wind action. This differential effect of circulation and oxygenation is critical at the time of autumnal circulation (Fig. 11 - Autumn, 1961, 1962 and 1963).

The consequence of incomplete autumnal circulation was low oxygen concentration prior to ice-cover which resulted in a complete over-winter mortality of fish in Corbett Lake (1961-62). Similarly, incomplete autumnal circulation of

Marquette Lake resulted in total over-winter fish mortality in 1963-64 and in all probability the same phenomenon would have occurred under ice cover in 1962-63 except for unusually light snow fall that winter. Because of differences in autumnal circulation, fishes in Corbett and Marquette Lakes were subject to over-winter mortality and those of Courtney Lake were not. Winter mortalities of fishes in Corbett Lake were prevented in 1963-64 and 1962-63 by experimental circulation.

SNOW COVER AND WINTER LIMNOLOGY

Anomalous physical and chemical limnological conditions recorded during the winter of 1962-63 are principally the result of a below-average snow fall.

The effect of snow and ice cover, and especially snow cover, on photosynthetic oxygen production and the corresponding effect on fish survival has been documented (Greenbank, 1945; Cooper and Washburn, 1946; Foster, 1960; Woods, 1961; Carufel, 1962). In all instances, complete, severe or partial mortalities of fish populations are correlated with heavy snow cover and survival of the respective fish populations is correlated with the absence, periodic, or light snow cover.

In particular, Greenbank (1945), Woods (1961) and Carufel (1962) find fluctuations of dissolved oxygen concentrations correlated with fluctuation of snow cover, in

shallow lakes, within one winter. Little such fluctuation is recorded for this study within one winter but similar correlations of winter oxygen concentrations and degree of snow cover are evident between winters.

Relatively high snow fall (Fig. 6) in 1961-62 and 1963-64 resulted in rapid depletion of oxygen in Corbett Lake (1961-62) and Marquette Lake (1963-64) with consequent complete mortalities of the respective fish populations. In 1962-63 the snow fall was almost nil, and as a result oxygen levels in Marquette Lake were unexpectedly high. Consequently, no fish mortality occurred from oxygen depletion. Over-winter fish mortalities were not expected to occur in Corbett Lake because of the effects of experimental circulation but probably would not have occurred regardless of this because of the light snow fall. Snow cover effectively reduces the amount of light that enters the lake.

There are significant differences, between winters, in light transmission through ice and snow cover on Corbett Lake (Fig. 8). In addition to snow cover, cloudy ice also reduces light transmission but snow cover is the most important factor (Croxtton, et al., 1937; Greenbank, 1945; Woods, 1961; Wright, 1964). Reduced light transmission through snow and ice results in reduced oxygen of a photosynthetic origin (Woods, 1961).

Supersaturation of oxygen was recorded in Marquette and Courtney Lakes for March 7 and 8, 1963 (Fig. 11)

(Increased temperature at the same respective depths was recorded for Marquette and Courtney Lakes and to a much less degree for Corbett Lake). Greenbank (1945) also recorded under-ice supersaturation of oxygen that was similarly correlated with low snow fall and relatively high light transmission. Greenbank (1945) did not report any positive evidence of the presence of phytoplankton. Wright (1964) recorded maximum numbers of phytoplankters in an ice covered lake during a snow-free period. Rhode (1955) similarly shows highest numbers of phytoplankton immediately under the ice where light intensity was highest. A well-defined layer of phytoplankton was observed through the use of SCUBA immediately below the ice and extended to a depth of about 1.5 meters in Marquette Lake on March 8, 1963. Trout were observed in this layer of oxygen supersaturation.

The difference in depth distribution of the supersaturated oxygen layer in Marquette and Courtney Lakes is probably the result of photosynthetic inhibition and selection of optimum light intensities by phytoplankters (Wright, 1964).

The supersaturation of oxygen is probably a result of the phytoplankton layer in Marquette Lake and also in Courtney Lake. The light snow fall of 1962-63 resulting in relatively high light penetration with the consequent increase in photosynthetically produced oxygen is the reason

for the prevention of winter mortality of fishes in Marquette Lake. In at least three other lakes in south central B.C., that are subject to frequent winter mortalities of the respective fish populations, none occurred in winter of 1962-63. However, in 1963-64 with greater snow fall reports received and some data were collected that indicated complete winter mortality of fish populations.

WINTER OXYGEN DEMAND

The differences in oxygen consumption or oxygen deficit between the winters 1961-62, 1962-63 and 1963-64 are evidenced in the concentration of dissolved oxygen represented by the duration and depth of, and the slope of individual oxygen isopleths (Fig. 11). The slopes and depths of oxygen isopleths 0, 2, 4 and 6 mg/l in Courtney Lake, for the winters 1961-62, 1962-63 and 1963-64 suggest a rather low oxygen consumption rate except that the 0 oxygen isopleth for the winter of 1961-62 and 1963-64 is rapidly established as are 0, 2, 4 and 6 mg/l isopleths. This suggests an initially large O_2 consumption (usually up to about December 22) and then a fairly stable situation until the ice goes off the lake. The winter of 1962-63 follows this general pattern but the initial decline of oxygen is not so rapid and larger quantities of O_2 are present due to photosynthetically produced oxygen. In contrast, the slope of the oxygen isopleths for Corbett Lake in any given winter are much greater than those of Courtney

Lake which suggests a greater oxygen consumption for Corbett Lake than that for Courtney Lake. As in Courtney Lake the initial period of greatest oxygen consumption is between freeze-over and about December 22. The slope of oxygen isopleths 0, 2, 4 and 6 mg/l for Corbett Lake, for 1963-64 more closely approximates the slopes of isopleths 0 and 2 mg/l isolines for 1961-62 than those for 1962-63 which is probably a reflection of the effect of greater photosynthesis in 1962-63 due to a much lighter snow fall. The degree of oxygen depletion in Marquette Lake is similar to that of Corbett Lake but is somewhat more severe which is probably due to the poor light transmitting qualities of Marquette Lake water (Fig. 7). In addition to dissolved oxygen, another environmental parameter is worth consideration--temperature.

Moore (1942), in a field study of the summer and winter lethal low-oxygen levels, found that the oxygen threshold is considerably depressed at winter temperatures (about 4-5°C). Similarly, Lindeman (1942) found experimentally that invertebrate organisms are more resistant to extended anaerobiosis at 0 and 5°C than at 10°C. Fig. 9 shows that in any winter Corbett Lake is colder than Courtney Lake. Artificial circulation may well provide a means of building up the oxygen concentration and at the same time lowering the water temperature. Both factors are an obvious advantage to fish survival in ice covered lakes.

EXPERIMENTAL CIRCULATION

Experimental circulation of Corbett Lake was conducted to test the hypothesis that the difference in survival of the respective fish populations and differences in physical-chemical characteristics between Corbett and Courtney Lakes and Corbett and Marquette Lakes is a direct result of the lack of sufficient autumn circulation and oxygenation in Corbett Lake. Thus, if artificial circulation of Corbett Lake could build up a dissolved oxygen reserve sufficient to maintain the fish population for the period during which it would normally be eliminated, the hypothesis would be confirmed.

Marquette and Courtney Lakes serve as experimental controls for the artificial circulation of Corbett Lake. Except for area the morphometric parameters of Marquette Lake are similar to those of Corbett Lake and Marquette Lake is likewise protected from wind action. Consequently it would be expected that the limnology of Marquette Lake would be affected by climate in a like manner to that of Corbett Lake. Courtney Lake on the other hand, being well exposed to wind action, would be expected to show limnological differences caused by normal climatic effects. Thus, the effects of experimental circulation in Corbett Lake can be compared to complete, autumn circulation in Courtney Lake and to incomplete autumnal circulation in Marquette Lake.

The method of artificial circulation employed in this experiment is not new. Puke (1949), Schmitz and Hasler (1958), Burdick (1959), Schmitz (1959), Foster (1960), Rassmussen (1960), Patriarche (1961), Woods (1961), Carufel (1962) all either suggest or report on its use and application. The time of such application is in this study, however, unique. In the above citations the compressed air system is usually employed after the permanent ice cover has been formed. Consequently, the primary object in such operations is to remove the ice cover so that atmospheric oxygen will be available for solution. The object of the application of the compressed air method of artificial circulation, in this study, was to build up a reserve of dissolved oxygen, before the permanent ice cover formed, such that the respiratory needs of the fish population would be met for the period of ice cover. The direct comparison of this experiment with any other published data is therefore precluded. Many effects of experimental circulation by compressed air are, however, comparable to this experiment.

Fig. 15 shows the results of changes in mean oxygen concentration and increase penetrations of dissolved oxygen, along with the accumulated hours of pumping and the surface water temperature for the respective periods of artificial circulation.

One of the initial effects of experiment circulation where the air outlet pipe(s) is located in the

hypolimnion is the sharp depression of the thermocline which is shown by sharply depressed isotherms. Schmitz and Hasler (1958) and Gilson (1962) note identical effects. Patriarche (1961) shows depressed isotherms for winter artificial circulation. This is caused by the rising bubbles lifting colder water from the hypolimnion to the epilimnion and thus depressing the thermocline until the lake is homothermal. Hooper, Ball and Tanner (1952) report identical results using a somewhat different method of circulation.

Fig. 16 shows the change in mean oxygen concentration immediately after the initiation of artificial circulation. The initial effect is a decrease in mean oxygen concentration. Patriarche (1961) suggests that the lowered oxygen values immediately following the initiation of artificial circulation are the result of upwelling bottom water that has a high B.O.D. However, Greenbank (1945) found that water samples taken from near the surface of shallow lakes usually had a higher B.O.D. than those taken near the bottom. In addition, Greenbank (1945) comments on the effect of H_2S in reducing the amount of dissolved oxygen. Similarly, Puke (1949) warns against the danger of artificially introducing large amounts of H_2S into an epilimnion already undersaturated with oxygen. H_2S and oxygen are mutually exclusive except in the absence of heavy metals (Waldichuck, 1964, pers. comm.). In Corbett Lake a very strong odour of H_2S was evident immediately at the onset of

experimental circulation. The H_2S odour continued strong until October 20 (in the 1962-63 experiment) and gradually decreased until October 23 when it was no longer detectable. In all probability, the considerable amount of H_2S in the epilimnion of Corbett Lake played a significant part in the initial reduction of dissolved oxygen at the onset of experimental circulation--a similar trend in the mean concentration of dissolved oxygen is noted for the 1963-64 experiments and is probably caused by the same events: (1) an introduction of hypolimnion deoxygenated water containing oxidizable organic matter into the oxygenated epilimnion and (2) the introduction of quantities of dissolved H_2S into the oxygenated epilimnion. It is significant to note (Fig. 12) that the mean concentration of oxygen starts to make substantial increases after October 22--the day before H_2S odour was last detected--a gradual increase in mean concentration of O_2 during artificial circulation is evident after October 23, 1962.

Artificial circulation was again initiated on November 7 - 10 and an increase in mean oxygen concentration was achieved. The lower surface water temperature, plus the fact that the lake, at this point, has a uniform concentration of oxygen, is significant. From November 10 to November 18 the mean concentration of oxygen increased without the assistance of experimental circulation. Some natural circulation was obviously taking place and a much lowered surface

water temperature assisted the solution of atmospheric oxygen at this time. The rate of solution for this period, judging by the slope of the line (Fig. 12) was not as great as the rate of solution for the final period of experimental circulation--from November 18 to November 26, 1962. The increased rate of solution of oxygen which was reflected in the increased mean oxygen concentrations for this period was probably the effect of a much lower surface water temperature.

Experimental circulation of Corbett Lake resulted in a mean concentration of oxygen sufficiently high to provide for the oxygen requirements of the fish population during the winters of 1962-63 and 1963-64. In the winter of 1961-62 the natural autumnal circulation resulted in low oxygen concentrations and consequent complete over-winter mortality of the fish population. Snow conditions in 1961-62 were similar to those of 1963-64. In the winter of 1963-64 no over-winter mortality of fishes occurred in the control lake, Courtney (complete natural autumnal circulation) whereas in the other control lake, Marquette (incomplete natural autumnal circulation) over-winter mortality of the fish population did occur. Over-winter mortality did not occur in Corbett Lake because experimental circulation provided an oxygen concentration high enough to prevent it. Thus, the experimental circulation of Corbett Lake confirms the original hypothesis.

SUMMARY

1. A comparison of indices of productivity showed that Courtney Lake is most productive, that Marquette Lake is least productive and that Corbett Lake is intermediate.
2. Measurement of average wind velocity and wind direction showed that Courtney Lake is subject to 4.3 times as much wind, as is Corbett Lake and that this wind is a prevailing wind whereas the wind acting on Corbett Lake is predominantly variable in direction. The difference in wind action on the respective lakes was found to be due to different topographical location.
3. Differences in snow cover during the study winters caused anomalous differences in dissolved oxygen in Marquette and Courtney Lakes which favourably affected fish survival in 1962-63.
4. The winter oxygen depletion was found to be greatest in Marquette and Corbett Lakes respectively and least in Courtney Lake.
5. Experimental autumnal circulation of Corbett Lake provided a mean dissolved oxygen concentration sufficient to prevent over-winter mortality of fishes. This affirmed the hypothesis that the differences in survival of the respective fish populations and differences in

physical-chemical characteristics between Corbett and Courtney Lakes and Corbett and Marquette Lakes were a direct result of the lack of sufficient autumnal circulation and oxygenation in Corbett Lake.

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