A COMPARISON OF WHOLE-LAKE, AND SEDIMENT OXYGEN CONSUMPTION IN TWO SUBARCTIC LAKES

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ABSTRACT

The rates of whole-lake oxygen depletion during summer 1978 and winter 1978/79 were measured in two lakes of different trophic status near Schefferville, Québec. Naturally eutrophic Elizabeth Lake consumed its hypolimnetic oxygen at a rate of 390.56 $mg \cdot m^{-2} \cdot day^{-1}$, about three times the rate predicted by Cornett and Rigler's (1979) empirical model (137.83 $mg \cdot m^{-2} \cdot day^{-1}$). Oligotrophic Dolly Lake did not stratify during the summer and remained saturated with oxygen. The rates of winter oxygen consumption, 97.49 $mg \cdot m^{-2} \cdot day^{-1}$ in Dolly and 204.08 $mg \cdot m^{-2} \cdot day^{-1}$ in Elizabeth, reflect the difference in trophic status during the previous summer, but do not agree with the relationship derived from temperate lakes in Ontario (Welch et al. 1976). An attempt to measure sediment "respiration" in the laboratory gave inconclusive results because of methodological problems. According to these estimates, sediment oxygen consumption could account for 50% to 100% of the loss of oxygen from each lake during winter.

RESUME

Les taux de désoxygénation estival et hivernal de deux lacs subarctiques près de Schefferville, Québec, furent mesurés de juin 1978 à juin 1979. Le lac Elizabeth, naturellement eutrophe, consommait son oxygène hypolimnique au taux de 390.56 $mg \cdot m^{-2} \cdot jour^{-1}$, soit trois fois plus rapidement que la prédiction du modèle empirique de Cornett et Rigler (1979) (137.83 $mg \cdot m^{-2} \cdot jour^{-1}$). Le lac Dolly, une étendue d'eau oligotrophe holomictique, est resté saturé d'oxygène dissous. Pendant l'hiver, le métabolisme lacustre reflète le niveau trophique de l'été précédent car le lac Elizabeth se désoxygène plus rapidement que le lac Dolly (204.08 $mg \cdot m^{-2} \cdot j.^{-1}$ contre 97.49 $mg \cdot m^{-2} \cdot j.^{-1}$). Le modèle de Welch et al. (1976), basé sur des lacs du sud de l'Ontario, ne s'applique pourtant pas à ces deux lacs subarctiques.

Des expériences en laboratoire, visant à mesurer la consommation d'oxygène par les sédiments, ne permettent pas d'évaluer avec précision leur contribution à la perte d'oxygène hivernale. Les résultats varient de 50% à 100% des taux lacustres sans différence significative entre ces deux lacs.

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INTRODUCTION

Dissolved oxygen is an essential requirement for a large and diverse range of aquatic life. One of the first seasonal chemical trends observed in lakes was the loss of dissolved oxygen in the hypolimnion during summer stratification (Alsterberg 1929), as well as from most of the entire body of water during the period of winter ice cover (Drown 1892, Thienemann 1927). In the latter case, this depletion may be severe enough to cause a massive "winter-kill" of the fish population, especially in shallow eutrophic lakes (Greenbank 1945). In addition, hypolimnetic (i.e. summer) oxygen depletion accelerates in response to higher nutrient loading (Edmondson et al. 1956, Dobson and Gilbertson 1971). Since Man is capable of influencing this important process in lakes, models to predict the quantitative effects of his actions are needed in order to make intelligent management decisions.

The first attempts to develop such models began with Strøm (1931) who, in refining Thienemann's (1928) idea that the hypolimnetic oxygen deficit reflects lake trophic status, argued that this deficit must be expressed per unit area of hypolimnetic surface to allow comparisons between lakes of different hypolimnetic thicknesses. Henceforth this loss of oxygen was to be designated the "Areal Hypolimnetic Oxygen Deficit" (AHOD), which is the rate of deoxygenation expressed per unit area of the plane at the top of the hypolimnion (typical units = $mgO_2 \cdot m^{-2} \cdot day^{-1}$).

Hutchinson (1938) went one step further when he found an empirical relationship between AHOD and dry weight of seston, an indicator of plankton production, in 4 Wisconsin lakes. Unfortunately, subsequent investigations in other areas failed to confirm this link (Riley 1939, Deevey 1940, Lasenby 1975). A recent model proposed by Cornett and Rigler (1979) casts further doubt on Hutchinson's (1938) assumptions, while providing a new empirical equation for predicting AHOD.

Areal Winter Oxygen Deficits (AWOD) have received far less attention. But considerable progress has been made with the publication of an empirical equation of AWOD for several Ontario lakes (Welch et al. 1976).

Since the predictive models for AHOD and AWOD arose from data on temperate lakes, applying them to subarctic lakes would be an ideal test of their generality. In thermal regime, at least, subarctic lakes are intermediate to temperate and arctic lakes. Thus, they can stratify during the summer long enough to develop a measurable AHOD and, in addition, undergo prolonged freeze-up leading to a large AWOD. A glance at maps of the Canadian Subarctic Zone reveals a plethora of possible research sites.

There are several reasons why Schefferville, Québec, was the chosen location for this project. Firstly, it lies within the Subarctic Zone as defined by Löve (1970).

Secondly, there was considerable logistic support available from the McGill Subarctic Research Station, where a five-year nutrient budget study on seven nearby lakes is in progress. Finally, twenty-five years of research at the station has produced good background data for the area (Adams et al. 1974, Granberg 1978), especially morphometric maps of several of the lakes under study (Bryan 1965). This simplified calculations of lake volumes and, consequently, of mass budgets.

Amongst the seven Schefferville lakes currently under examination (Dian, Dolly, Elizabeth, Hope, Lejeune, Maryjo and Ridge; see fig. 1), I decided to concentrate on the two, Dolly and Elizabeth, that contrasted the most in trophic status, based on values of transparency, total phosphorus and chlorophyll-a measured in 1977/1978 (table 2). Only Elizabeth stratified during the summer (fig. 7). Between-lake comparisons of oxygen depletion are possible during the winter when ice cover seals them for an average of 7.4 months (from Oct. 31st to June 10th; Adams and Shaw 1966). All of this allows me to ask the following three questions, which are important in forecasting the concentration of dissolved oxygen in lakes:

1) Does the Cornett-Rigler model (1979) predict AHOD's of subarctic lakes?
2) Does the model of Welch et al. (1976) predict AWOD's of subarctic lakes?
3) Does primary productivity of the previous summer affect the AWOD of subarctic lakes?

However this holistic approach, whatever its outcome, does not satisfy our need to understand oxygen depletion. Explaining why our predictions succeed or fail requires a reductionist strategy (Rigler 1975). The rate of oxygen consumption (the property or state variable) being measured results from the combined action of several compartments within the "respiring" lacustrine volume (the "black box"). Reductionism strives to quantify as many of these subsystems as possible. In this particular situation, we can recognize intuitively at least three: sediment oxygen uptake, open water consumption, transport of oxygen in or out of the entire system. To keep this project within manageable limits, I chose to tackle only one compartment.

Sediment oxygen uptake appears more tractable than the other two, if only because it is better documented. Furthermore, suggestions that the AWOD is related to production during the previous summer (Hargrave 1972, Welch 1974) tempts us to hypothesize that the difference lies in the activity of the sediments, because they are the ultimate repository of dead organic matter. I am assuming of course that oxygen is lost by the breakdown of autochthonous organic matter (Strøm 1931) and that there is very little production during the winter (Albrecht 1964, Wright 1964). Dolly and Elizabeth lakes have all the desired attributes to test this hypothesis.

To summarize, I will test two models of oxygen depletion on subarctic lakes and attempt to quantify one of the components of this process.

CHAPTER I

THE STUDY AREA

The town of Schefferville (lat. 54°49'N, longit. 66°50'W) is located at the Québec-Labrador border, 515 km due north of the Port of Sept-Iles (fig.1). It is situated on the Labrador Geosyncline, a belt of Proterozoic sediments stretching north-south through Labrador-Ungava for about 1100 km (Nicholson et al. 1975). Because of the presence of rich iron ore formations (Sokoman Formation, Ruth Slate), the area has been the site of extensive open-pit mining by the Iron Ore Company of Canada Ltd. since the early 1950's. The Labrador Trough appears to have undergone at least three cycles of orogeny and sedimentation, the ore bodies resulting from the leaching of silica by groundwater (ibid.).

The presence of several large meltwater channels (Barr 1964) and extensive glacial deposits (Kirby 1960) bear witness to heavy glaciation during the Pleistocene. The numerous ridges around the town are oriented southeast to northwest. Radiocarbon dating of peat cores places the last deglaciation at around 5700 B.P. (Morrison 1970). Pollen analyses show that the present day vegetation differs little from when it was first established ca. 5200 B.P. (ibid.). Because of geological and physiographic variation, many types of vegetation are present,

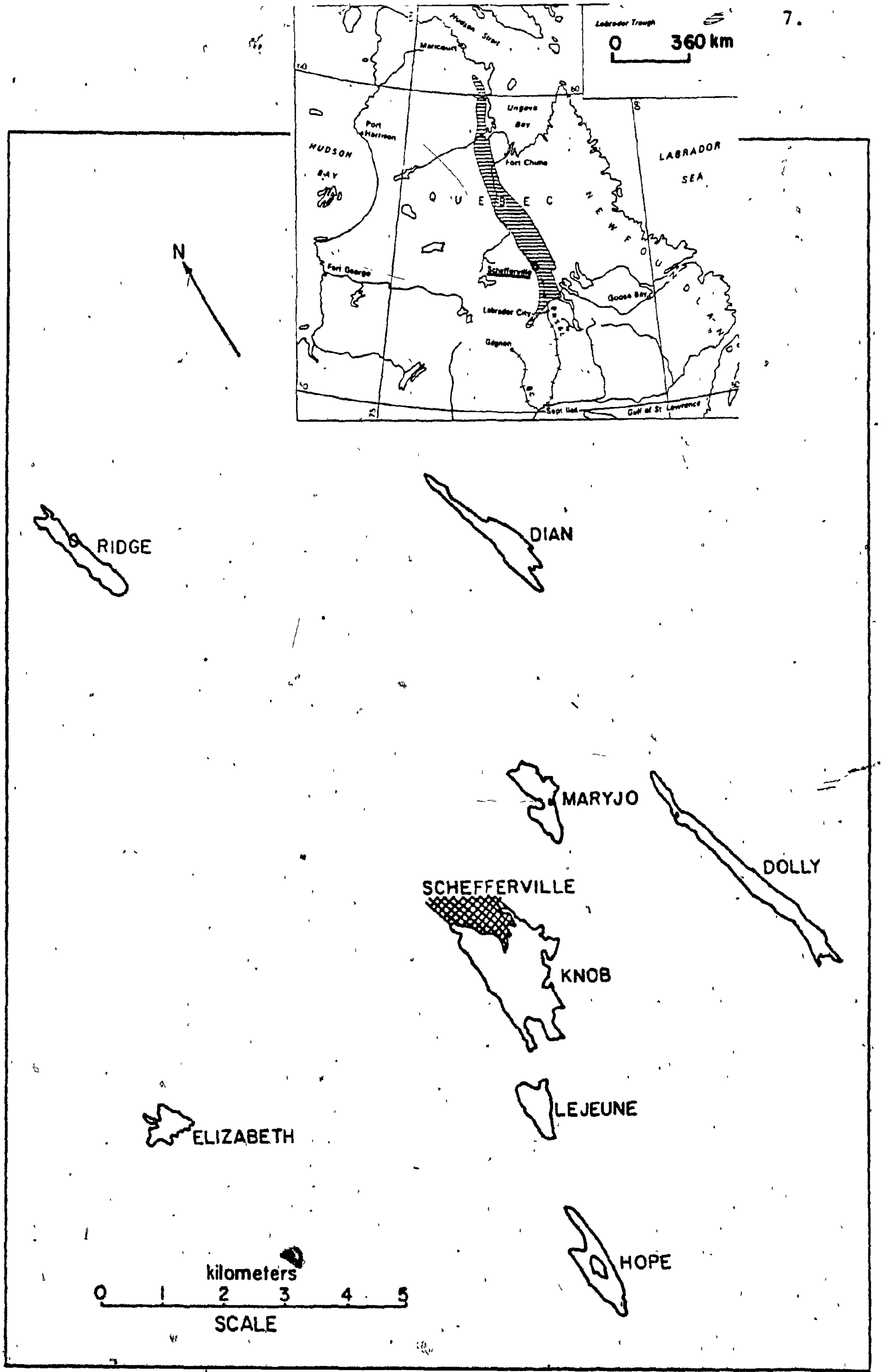


Fig. 1 - The study area.

from close canopy spruce forest or bog in the valley bottoms to open tundra on the exposed hill tops (Nicholson et al., op.cit.). Schefferville lies in the discontinuous permafrost zone (Annersten 1964). The active layer on average sites varies between 2 to 4 m, but no permafrost is found beneath wooded sites (Nicholson and Lewis 1976). The three most common species found in the lichen woodlands are caribou moss Cladina stellaris (known until recently as Cladonia alpestris), Picea glauca (white spruce) and Picea mariana (black spruce) (Fraser 1956). Dwarf birch (Betula glandulosa) is widespread in the more open areas. The treeline is encountered at about 600 m altitude above which the local climate becomes too harsh to support growth (Nicholson et al., op.cit.). The author observed numerous examples of Krummholz (stunted) growth forms of spruce and wind gaps (segments of tree trunks denuded by abrasion from wind-borne snow and ice crystals) at the treeline.

Table 1 lists some important climatic statistics for Schefferville. More detailed analyses are available in Tout (1964) and Lechowicz and Adams (1978).

Dolly, Elizabeth and the five other lakes being studied lie within an 8 km radius of the town (fig. 1) and are accessible by road during the summer and snowmobile during winter. Dolly Lake borders on Dolly Ridge (chiefly slate and siltstone) to the North-East, the Wishart Formation (mainly orthoquartzite and feldspathic quartzite) to the South-West, and on the Denault Formation (predominately dolomite) to the North-West (Harrison et al., 1972, fig. 10). Closed lichen woodland covers much of the shoreline. Elizabeth Lake is surrounded chiefly by the Fleming Formation (chert conglomerate and breccia, massive and bedded chert), with some contact with the Denault Formation on the North-West shore (ibid., fig.9). Closed lichen woodland, open lichen woodland and tundra are all present in the catchment.

Table 1 . Some important climatic statistics for Schefferville (means of 1955-1973 data). Source: Nicholson et al., 1975.

Mean yearly temperature	- 4.7°C
Range of monthly means	-21.7°C (Jan.) to +12.4°C (July)
Total Precipitation	735 mm
Rainfall	400 mm
Snowfall[1]	344 mm (water equivalent)
Evapotranspiration[2]	292 mm

1. The figure for snowfall is greater than the difference between total pptn and rainfall because of variations in the water equivalence of snow at different times during the winter.
2. Interpolated from the Hydrological Atlas of Canada 1978. The interpolated total precipitation is 708 mm.

Table 2 lists some basic data for both lakes. The total phosphorus concentrations in Dolly Lake are amongst the lowest recorded in the literature (F.H. Rigler, pers. comm.). Since neither body of water is cottaged, differences in nutrient loading are probably due to the geology of their respective catchments. Inflowing streams are either ephemeral (as in the case of a large meltwater inflow at Elizabeth) or very weak. Outflows, however, are strong and well defined. The Dolly Lake discharge

Table 2 . Some comparative data for Dolly and Elizabeth Lakes.

	DOLLY	ELIZABETH	SOURCE
Position	54°49'N, 66°46'W	54°46', 66°54'W	--
Altitude	525 m	616 m	Bryan (1965)
Map number (Nat'l. Topogr. Series 1:50,000)	23 J/15 (East & West halves)	23 J/15 (West half)	---
Area of catchment (A_d)	3.91 km^2	2.98 km^2	Courtesy F.H.Rigler
Lake area (A_o)	1.053 km^2	0.281 km^2	Bryan (1965)
A_d/A_o	0.27	0.09	---
Volume (V)	8.848 x 10^6 m^3	2.444 x 10^6 m^3	Bryan (1965)
Mean depth ($\bar{Z}$)	8.4 m	8.7 m	"
Maximum depth (Z_m)	23.7 m	27.1 m	"
Yearly discharge[1] (Q)	2.780 x 10^6 m^3	2.237 x 10^6 m^3	Courtesy F.H.Rigler
Areal water load[2] (q_s)	2.64 m	7.96 m	---
Flushing rate[3] (τ)	0.31 yr^{-1}	0.92 yr^{-1}	---
Summer thermal stratification?	No	Yes	This study
Mean Secchi depth[4]	11.5 ± 1.9 m	4.7 ± 0.6 m	Courtesy FH.Rigler
Mean total Phosphorus[5]	1.51 ± 0.48 ug.l^{-1}	12.38 ± 1.59 ug.l^{-1}	"
Mean chlorophyll a[5]	0.30 ± 0.17 ug.l^{-1}	3.81 ± 2.15 ug.l^{-1}	"

1. Mean of 1977/78 and 1978/79 water years.
2. $q_s = Q/A_o$
3. $\tau = Q/V$
4. Mean of values (± std. dev.) recorded from June 1977 to November 1977.
5. Mean of values (± std. dev.) recorded from June 1977 to May 1978.

is measurable throughout the year whereas the one at Elizabeth Lake dries up only from the third week of March to the third or fourth week of April.

CHAPTER II

MATERIALS AND METHODS FOR WHOLE-LAKE MEASUREMENTS.

Units

All data in this thesis are expressed in SI units. Some background information, most notably morphometric measurements, were converted to SI units according to the built-in equivalence factors of the Texas Instruments SR-51A electronic calculator. The abbreviations of units are preceded by a slash ("/") when they label axes of graphs or columns in data tables, in accordance with McGlashan (1968).

Sampling

All whole-lake measurements originate from one sampling station over the deepest point of each lake (figs. 2 , 3), selected according to the contour maps drawn by Bryan (1965). Temperature and transparency were measured on the spot whereas other parameters were analyzed in water brought back to the laboratory. Temperature, dissolved oxygen, and specific conductivity were evaluated at every meter; total phosphorus and chlorophyll-a were derived at every two meters. During both seasons, the surface of the water was considered to be depth zero.

I used a Van Dorn bottle during the summer but switched in winter to a cast aluminium sampler consisting of a cylindrical jacket held up by a spring-loaded clip;

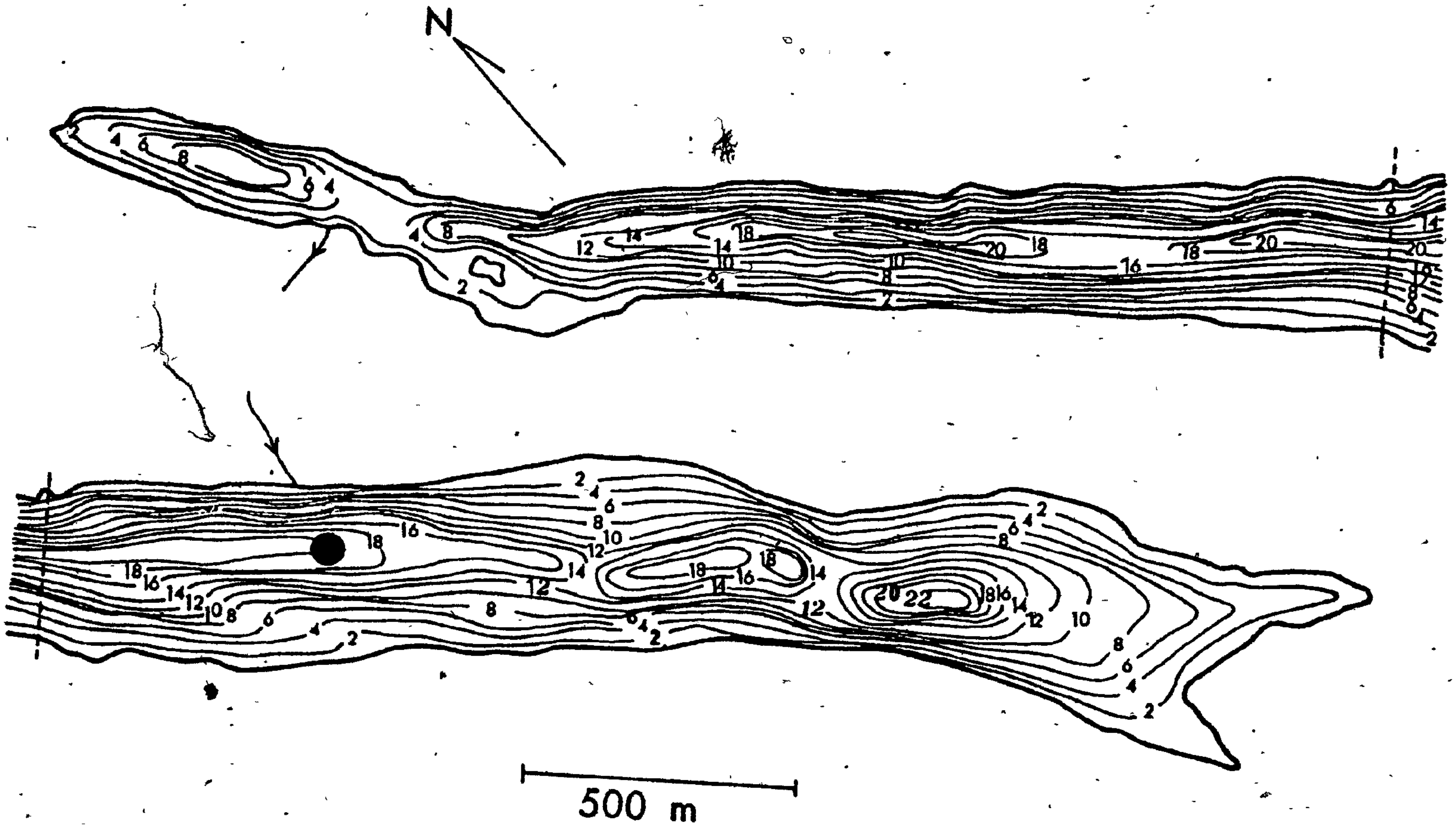
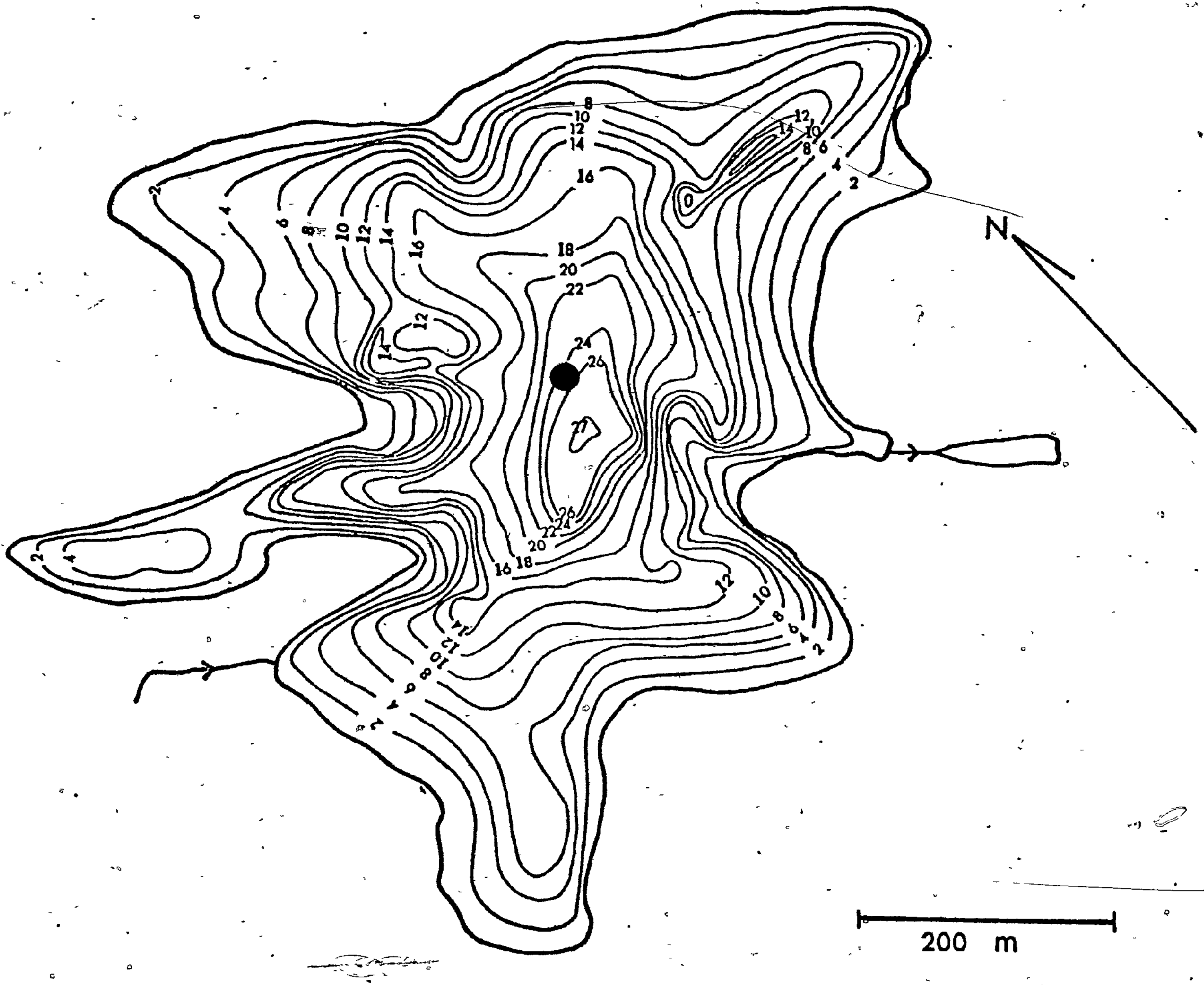


Fig. 2 - Contour map of Dolly Lake, from Bryan (1965), converted to metric depths. The dot marks the position of the sampling station.


N
200 m
0
2
4
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18
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22
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27

when the messenger strikes, the jacket releases and slides down along the axis of the bottle to seal against a bottom plate. Although prone to accidental triggering, it proved the easiest to use and the most reliable in the cold. The lines attached to either sampler were marked at one-meter intervals beginning at the top of the bottle. The sampling hole through the ice was drilled by hand with a Snabb spoon drill (blade width = 17.8 cm or 7 in.). It was far better than the standard helicoidal ice auger. The frequency of sampling varied from once a week during summer to once every three or four weeks during the middle of winter.

I could not sample to the maximum depths reported by Bryan (table 2) because consistent contamination from sediments occured beyond 18 meters in Dolly and 24 meters in Elizabeth (23 meters during the winter). The vertical series stopped at these depths.

Morphometry

The calculations of areas and volumes are entirely based on the maps and figures compiled by Bryan (1965). Although he gives the hypsographic curves for both lakes, he does not list the point coordinates used to plot them. His maps were planimetered anew and the curves redrawn. I relabeled the depth axis in meters to convert from English to SI units. The fraction of A_o (i.e. area at Z=0 meters) at any given depth is interpolated linearly between the two closest points of known position. The area at any depth is the product of A_o and the fraction of A_o at that depth. The volume (V) of a particular stratum approximates that of a conical frustrum of top area A, bottom area a, and depth h such that

$$V = h/3\ (A+a+(Aa)^{1/2})$$

Since we sample at every meter, h = 1. I used my computed volumes for all the mass balance calculations, ignoring the discrepancy between their summation and the total lake volumes given by Bryan (1965). Appen~~dix A~~ contains the results. The difference represents 2.8% of the entire water mass of Dolly and a surprising 19.9% of the volume in Elizabeth Lake.

Temperature

A YSI Model 54 Temperature and Oxygen Meter supplied the readings until August 15th, 1978 (absolute error = $\pm$ 0.5°C). Because rain short-circuited the instrument I adopted another device, the Fenwal Type GB32P2 glass probe thermistor connected to a Data Precision Model 245 digital multimeter. It had already been used successfully to record ground temperatures in the area (Nicholson and Granberg 1973, Nicholson 1976). The absolute accuracy is $\pm$ 0.01°C (Nicholson 1976), the digital readout stabilizes very quickly and the multimeter can be easily shielded from the rain because of its small size.

The resistance (R) of this type of thermistor increases by roughly 3.9% (at 25°C) for each degree Celsius drop in temperature (T). The response curve takes the form

$$R = Ae^{(B/(T+C))} \quad \text{or} \quad T = (B/(\ln R-\ln A)) - C$$

Table 3 - Specifications of Fenwal GB32P2 thermistors used for measuring lakewater temperatures.

Dates used	Number on master list	Temperature range* /°C	ln A	B	C	Resist. @ 0.01°C /ohms
30/06/78**	6610 ("No Cable")	+0.075 to +10.140	-6.13725	4897.05	330.060	6004
18/08/78 to 8/12/78	10052 ("Cable 25")	-0.129 to + 9.737	-5.70013	4463.79	314.073	4982
		+4.551 to +14.795	-6.10408	4727.04	323.410	
8/12/78 to 14/06/79	10029 ("No Cable")	-4.355 to + 4.376	-5.75318	4647.22	320.374	6312
		+0.457 to + 8.810	-5.39186	4416.89	312.273	

* Temperature estimates using each set of constants over the common temperature range agree to within ± 0.002°C.

** Elizabeth Lake only. Damaged after use and discarded.

where R is in ohms, T in degrees Celsius; A, B and C are calibration constants obtained from a master list of values for all GB32P2 thermistors used for permafrost studies at the McGill Subarctic Research Station. The Geological Survey of Canada in Ottawa calibrated them against a standard platinum resistance thermometer and calculated the values of A, B and C by semilogarithmic regression. Three thermistors were used during this study; their specifications appear in table 3 . I adopted the constants of the listed thermistor whose resistance is closest to the field device at the triple point of distilled water (0.01°C). The response curves of two closely matched thermistors are essentially parallel over the short range of expected lakewater temperatures (0 to 15°C). One can measure R at 0.01°C by immersing the glass bead just below the surface of an agitated bath of distilled water and crushed ice held in a thermos flask (the thermistor passes through a small hole in the cap). Lakewater measurements are listed in Appendix A .

Dissolved oxygen

I followed the azide modification of the Winkler technique to determine dissolved oxygen concentrations (APHA 1976). Table 4 gives the composition of the reagents. Preparation of the sodium thiosulphate ($Na_2S_2O_3$) and potassium iodate (KIO_3) standard solutions followed Carpenter's (1965) method. The iodate standardization technique was easier to use than the dichromate

Table 4 - Composition of reagents used for dissolved oxygen analysis.

SOLUTION	FORMULA	VOLUME PREPARED /ml	MASS TO BE ADDED /g	REFERENCE
Manganous sulfate	$MnSO_4\cdot H_2O$	1000	363.7	APHA 1976
	or...$MnSO_4\cdot 4H_2O$	1000	480	
Alkaline-iodide-azide	$NaOH$*	1000	500	APHA 1976
	NaI *		135	
	NaN_3**	40	10	
Sulfuric acid 18M	H_2SO_4	1000 (sp.grav.1.84)	--	APHA 1976
Sodium thiosulphate 0.05N	$Na_2S_2O_3$	1000‡	7.95	Carpenter 1965
	or...$Na_2S_2O_3\cdot 5H_2O$§	1000‡	12.50	
Starch§§	---	1000	5.0 to 6.0	APHA 1976
Potassium iodate 0.10N	KIO_3	1000	3.5670	Carpenter 1965

* Combined in 1000 ml of water.

** Dissolved separately in 40 ml of water then added to NaOH-NaI solution.

‡ Use 5 ml of chloroform as a preservative and store in a dark bottle.

§ Incorrectly reported by Carpenter (1965) as $Na_2S_2O_3\cdot H_2O$.

§§ Store in a dark bottle. Add a few drops of toluene as a preservative instead of salicylic acid which dissolves poorly.

or biniodate procedures (APHA 1976) and gave very reproducible results.

Water samples were collected in 140 ml Pyrex glass bottles with ground glass stoppers. Because there was only one bottle for each meter sampled, great care was taken to prevent the trapping of air bubbles by allowing overflow. Each bottle received 1 ml of manganous sulphate ($MnSO_4$) solution and 1 ml of alkaline-iodide-azide ($NaOH$-NaI-NaN_3) reagent. After letting the precipitate settle twice, 1 ml of concentrated sulfuric acid (H_2SO_4) was added. Acidification was done in the field during the summer; in winter, the fixed samples were brought back to the laboratory in a heated insulated box before acidification. Hot water bottles made of rubber provided just enough warmth to prevent freezing. The reagents were dispensed from Nalgene® brand volumetric dispenser bottles which remained reproducible to ± 1%, provided that they were thoroughly washed after each sampling trip. They were easy to use, prevented accidental spillage or splashing, and did not clog in the cold like pipettes or syringes.

All samples were titrated, the following day at the latest, with 0.05N sodium thiosulphate solution dispensed from a Gilmont micropipette-burette (barrel volume = 2.0 ml; accuracy = ± 0.001 ml). Each bottle yielded two 50 ml aliquots measured by graduated cylinder (all samples were allowed to reach room temperature first).

Since 1 ml of 0.025N titrant corresponds to 1 $mgO_2 \cdot l^{-1}$ in a 200 ml aliquot (APHA 1976), the equivalence of my titrant solution is

$$\frac{0.050\ N}{0.025\ N} \times \frac{200\ ml}{50\ ml} = 8\ mg\ O_2 \cdot l^{-1} \cdot ml^{-1} \text{ of } Na_2S_2O_3$$

Before and after each batch of titrations, the thiosulphate is standardized by titrating five 50 ml aliquots of a potassium iodate standard solution prepared as follows:

1. Pipette 1.0 ml of KIO_3 0.10 N solution in a bottle or flask reserved for this purpose. All my standards were prepared in a 271.3 ml glass reagent bottle with a ground glass stopper.
2. Add distilled water up to the level of the bottom of the stopper (total volume in bottle is now 267.3 ml).
3. Add 2 ml of sulfuric acid followed by 2 ml of alkaline-iodide-azide. Stopper the bottle and shake thoroughly. The loss of 1.47% of the standard's volume ((4 ml/271.3) x 100) is compensated by adjusting the titers upward by the same fraction.

Each ml of titrant neutralized the same volume of KIO_3 standard solution if their normalities are equal (Fox and Wingfield 1935). The theoretical titer is:

$$\frac{V_{std}}{V_b} \times \frac{N_{std}}{N_{thio}} \times V_{al} = \frac{1}{271.3} \times \frac{0.10}{0.05} \times 50 = 0.369\ ml$$

where V_{std} = volume of iodate solution added to the bottle (in mls).
V_b = volume of bottle (in mls).
N_{std} = normality of iodate solution added to the bottle.
N_{thio} = apparent normality of the thiosulphate solution.
V_{al} = volume of standard solution titrated (in mls).

The actual normality of the thiosulphate ($N'_{thio.}$) is:

$$N'_{thio.} = N_{thio.} \times \frac{0.369}{\overline{std.}}$$

where $\overline{std.}$ = mean standardization titer (in mls); ten are performed for each batch of samples.

Consequently, each titer of 0.05 N sodium thiosulphate (in mls) converts to dissolved oxygen (in $mg \cdot l^{-1}$) according to the equation

$$[O_2] = V_t \times 8 \times (0.369/\overline{std.})$$

where V_t = volume of titer (in mls).

All the aliquots, including the standards, were titrated in 50 ml erlenmeyer flasks directly illuminated by a fluorescent tube, and stirred continuously by a magnetic stirring bar. A white background provided high contrast. One ml of starch solution was added to indicate the end-point.

The overall mean standardization titer for all dates (corrected for the loss of volume during preparation) was 0.386 ml (n = 57, std. dev. = 0.008). All sample titers were converted to oxygen concentrations using this value. Each concentration listed in Appendix A is the mean of two aliquots. The average difference between these is 0.09 $mgO_2 \cdot l^{-1}$ (n = 1146, std. dev. = 0.03) and represents the relative error of titration.

Specific conductivity

The samples for specific conductivity measurement were collected in 50 ml plastic vials or 140 ml plastic bottles. Containers are rinsed with distilled water between uses and with lake water just before filling. In the laboratory, the samples are warmed to between 20°C and 30°C in a water bath. I used an Industrial Instruments Model RC16B2 bridge coupled to a YSI probe. The latter was calibrated against a 0.01 N KCl solution (0.7459 g KCl dissolved in 1 liter of distilled water). Its constant was 1.13. The temperature of each sample was taken with a mercury thermometer (accurate to ± 0.1°C) just before reading the conductivity. The results were expressed at 25°C according to the equation

$$C_{25} = \frac{KMC_t}{1 + (0.025\ (t-25))}$$

where C_{25} = specific conductivity in $\mu S \cdot cm^{-1}$ @ 25°C.
K = probe constant = 1.13 cm^{-1}.
M = scale multiplication factor at which the bridge is set when the reading is taken (usually, $M = 0.10$).
C_t = conductivity reading on the scale (in μS).
t = temperature of the sample in °C.

The apparatus was precise to ± 0.14 $\mu S \cdot cm^{-1}$ @ 25°C when tested on 47 samples of distilled water. The results are listed in Appendix A .

Transparency

The transparency readings were taken with a Secchi disk of 21 cm in diameter lowered from the shaded side of the boat. Two measurements were obtained; one upon disappearance and the other upon reappearance. Their mean represents the Secchi depth. The average difference between "down" (disappearance) and "up" (reappearance) depths was 37 cm ($n=23$, std. dev. = 21 cm). The data are given in Appendix A .

A Chipman light meter was employed on a few occasions to estimate light extinction coefficients. I used the calibration curves already provided by F.H. Rigler to obtain light intensities, and semilogarithmic regression to find the extinction coefficient. These results are found alongside the Secchi depths in Appendix A .

Snow, ice, and hydrostatic water level

Snow and white ice thicknesses were measured directly at the sampling site with an Atmospheric Environment Service standard snow ruler (graduated in units of 2 mm). Because of considerable variations of lake cover even in the immediate area around the hole, the assumed accuracy of measurement for snow and ice is estimated at ± 2.5 cm (Adams and Brunger 1975). The white ice thickness is measured from the surface of the ice to the white-black ice interface which is clearly visible. Black ice thickness is calculated by subtracting white ice from total ice. The latter is determined by jamming the edge of the drill blade against the underside of the ice and measuring the length of shaft between the blade and the top of the ice. The hydrostatic water level is the head of water expressed with reference to the ice surface (Adams and Brunger 1975). A positive value indicates flooding. See Appendix A for the measurements. The following parameters were not measured by the author but their mention in this thesis requires a brief outline of the methods followed to obtain them. Although I participated in the sampling, the analyses were performed by the staff of the Schefferville Limnology Project.

Total phosphorus

The method is a modification of Menzel and Corwin's (1965) persulphate digestion. The details are given in Appendix B . The reproducibility is ± 10%.

Chlorophyll-a

The pigment was extracted from glass fibre filters (Whatman GF/C 47 mm) using 96% ethanol without grinding. Appendix C outlines the procedure. Phaeophytins were not measured.

Streamflow

The figure for outflow discharge at any date is the mean of a direct determination by dye dilution and an indirect estimate from a stream level gauge. A solution of Lissamine Red is injected at a constant rate (measured prior to each run) by a peristaltic pump; eight consecutive water samples are collected downstream every 20 seconds beginning 8 minutes after the start of injection. Trial runs in the field had shown that this was the time necessary for the dye concentration to reach a plateau. These concentrations were subsequently read in the laboratory on a Turner fluorometer. The flow rate Q is given by the equation

$$Q = q\,(C_d/C_s)$$

where q = dye injection rate (in $ml \cdot min^{-1}$).
C_d = concentration of injected dye (in $g \cdot l^{-1}$).
C_s = concentration of dye in stream, at the plateau phase (in $g \cdot l^{-1}$).

Q is subsequently converted to $m^3 \cdot day^{-1}$.

The level gauge is a meter stick attached to an iron post sunk into the stream bed. The rating curves relating height of water to discharge of each outflow were based on comparative data collected during the preceding summer (1977) and winter (1977/78).

CHAPTER III

MATERIALS AND METHODS FOR MEASURING SEDIMENT OXYGEN UPTAKE

In order to improve clarity, this chapter merely describes the methods I used to measure "Sediment Oxygen Consumption" (SOC) in the laboratory. A discussion of the advantages and shortcomings of the experimental procedure accompanies the results in Chapter VI.

A series of experiments was performed in Schefferville during the winter of 1978/1979. Numerous difficulties encountered there inspired another series of experiments performed in Montreal between November 1979 and February 1980.

Sampling

All the mud was collected with a 6-inch (15 cm) Birge-Ekman grab (Sly 1969). The sampling stations were chosen at random on each lake. A special effort was made to grab the top 5 to 10 cm of sediment. Any hauls showing washout were discarded. The sampler operated well on these muddy bottoms and the lake ice provided a very stable platform from which to work.

The grab was emptied into a large plastic bucket, the contents of which were immediately poured into glass jars with screw-cap lids. The containers were carried back to the laboratory in an insulated soft-drink cooler. Rubber hot water bottles provided just enough heat to prevent freezing. Samples were stored in a refrigerator at between 4°C and 5°C until the contents had settled. This took from 2 to 5 days. The overlying water was then decanted so that filling of the incubators could begin.

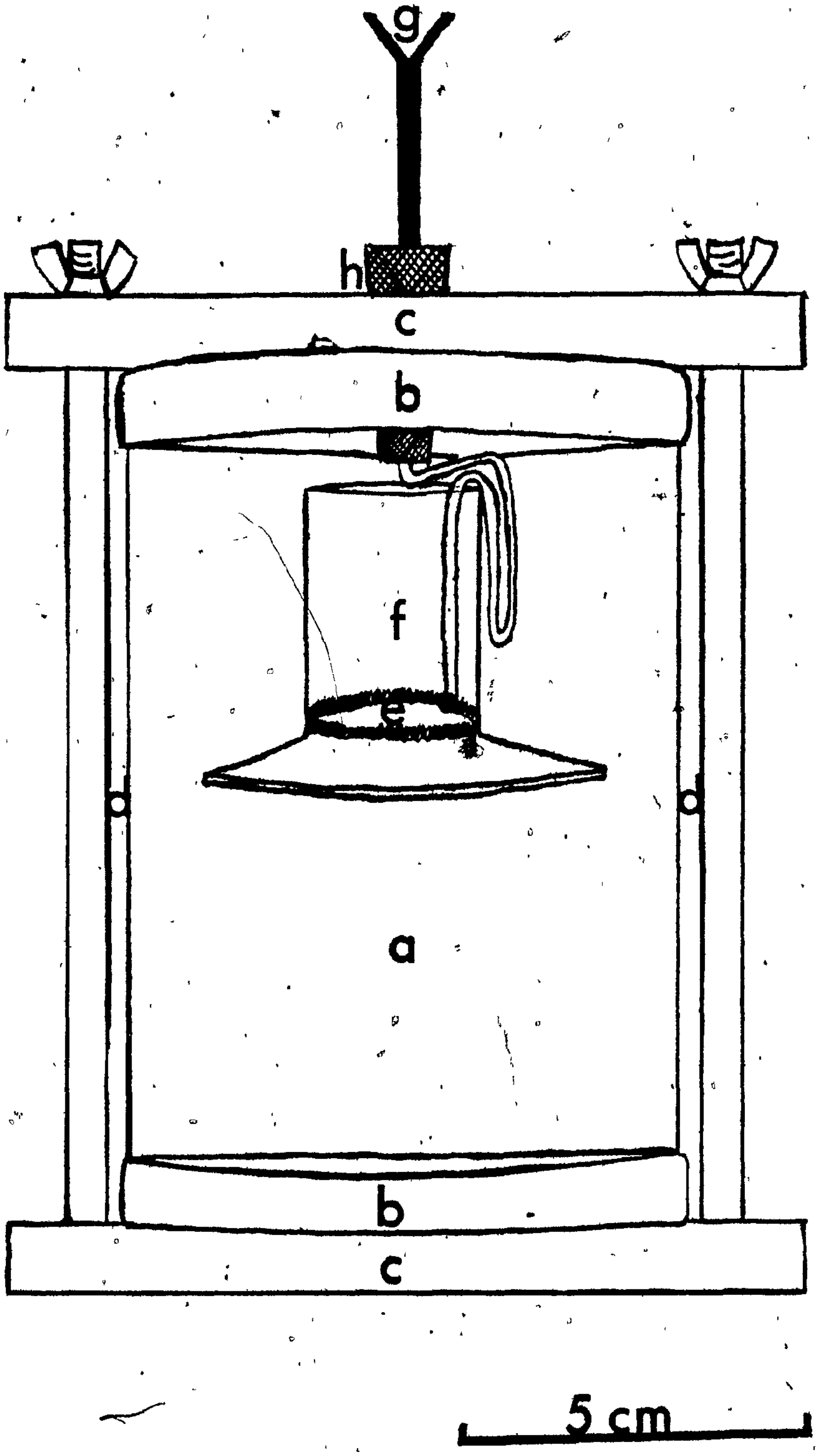
Incubation experiments in Schefferville

The sediment chambers used in Schefferville (fig. 4) were largely inspired by McDonnell and Hall's (1969) design, although I used glass and aluminium instead of Plexiglas in order to avoid diffusion of oxygen through the walls (Pamatmat and Banse 1969, Granéli 1977). About half of each incubator was filled with the mud, which had a slight gel-like consistency (mud depth = 5 cm, volume = 220 ml, area = 44.2 cm^2). Lake water, collected at the same time as the sediment, and stored at the same temperature, was siphoned into the chambers through a Tygon tube (inner diameter = 6.3 mm) at a rate of roughly 160 $ml \cdot min^{-1}$. There was slight resuspension of sediment but the mud-water interface could be seen at all times. Each set of 10 incubators had 2 controls filled with lakewater only. Care was taken to maintain water and mud as close as possible to 4°C during the entire filling process. All containers were held in a water bath placed in a refrigerator. Before beginning to incubate, the water overlying the sediments was slowly flushed (rate = 1.4 $ml \cdot min^{-1}$, renewal time = approx. 3 hours) with lakewater siphoned in through very fine polyethylene tubing (inner diameter = 0.76 mm) from a single common reservoir. This was to get rid of any suspended matter which might interfere with oxygen analysis

Fig. 4 - Sediment incubator used in Schefferville, drawn to scale.
(a) Glass tube, (b) Aluminium lid with recessed rubber "O" ring, (c) Aluminium and brass clamping bar, (d) Clamping rod, (e) Nichrome heating element, (f) Heating element support, (g) Insulated copper leads, (h) Rubber stopper. N.B. A sampling port (6mm diam.) is present in the top lid. It is sealed with a small cork.

Specifications:

Height of chamber = 10 cm
Inner diameter = 7.5 cm
Cross-sectional area = 44.18 cm^2.
Capacity (with heater and support) = 420 ml ± 5 ml.


g
h
c
b
f
e
d
d
a
b
c
5 cm

and to insure similar oxygen concentrations in each chamber at the start of the experiment. The controls remained sealed throughout this operation. At the beginning of the incubation, and at intervals thereafter, a volume of water was withdrawn from each chamber for oxygen analysis and replaced with the same volume of lakewater of known oxygen content.

Originally, I intended to use 10 ml glass syringes and apply the Winkler azide technique (APHA 1976) by adding the reagents directly to the syringes. This proved too difficult because air bubbles were invariably trapped at one stage or another. I resorted to using 60 ml glass bottles (with ground glass stoppers), filling them by siphoning water from the chambers, which were immediately refilled in the same way. I added 0.5 ml of each reagent to a sample bottle and titrated 2 aliquots of 25 ml apiece, following the same procedure as described in Chapter II for the measurement of whole-lake oxygen. The equation converting titer (V_t) to O_2 concentration was modified to take the smaller aliquot volume into account:

$$[O_2] = V_t \times 16 \times (0.369/\overline{\text{std.}}) \qquad \text{Eq.1}$$

Six of the twelve chambers (i.e. 1 water-filled control, 5 with mud) were subjected to convective mixing for the entire duration of the experiment to prevent the formation of a boundary layer at the sediment surface. I chose "thermal" instead of mechanical stirring for two reasons: fear that mechanical agitation in such a small volume of water (approx. 220 ml) might stir up the mud and the belief that the much slower mixing achieved this way better represents the situation at the lake bottom during the winter. The heaters (fig. 4) were made of a small length of nichrome wire (resistance = 1 ohm) pasted onto the inside wall of an inverted glass "funnel" by a generous coating of liquid polystyrene (a good adhesive and an excellent electrical insulator). The heaters were connected in series to a 6-Volt DC power supply so that each element put out roughly 1 Watt. A qualitative test with fluorescein dye showed that this was the power needed to create a visible convection current without a measurable increase of temperature inside the chamber.

The rate of SOC for a particular chamber, corrected for water "respiration", over an incubation period of T is given by the equation

$$\text{SOC} = \frac{(\text{Change in mass of } O_2 \text{ in chamber}) - (O_2 \text{ consumed by water})}{(\text{Sediment area}) \times (\text{Incubation time})} \qquad \text{Eq.2a}$$

$$= \frac{\Delta O_2 - W}{AT} \qquad \text{Eq.2b}$$

where SOC is in mg $O_2 \cdot m^{-2} \cdot day^{-1}$
ΔO_2 and W are in mgO_2
A = 4.42×10^{-3} m^2
T is in days

The terms of the numerator in eq. 2b break downas follows:

$$O_2 = (\text{Initial mass of } O_2) - (\text{Final mass of } O_2) \qquad \text{Eq.3a}$$

$$= \left[O_2^* \, (V^*)\right] + \left[{}_iO_2 \, (V-V^*)\right] - \left[{}_fO_2 \, (V)\right] \qquad \text{Eq.3b}$$

where O_2^* = O_2 concentration of added water (in $mg \cdot l^{-1}$)
V^* = volume of added water = 0.060 l (when sampling from time zero, $V^* = 0$)
${}_iO_2$ = O_2 concentration of water before adding V^* (in $mg \cdot l^{-1}$)
V = total volume of water overlying the mud (in l)
${}_fO_2$ = O_2 concentration at the end of the incubation period (in $mg \cdot l^{-1}$; ${}_fO_2 = {}_iO_2$ of the following incubation period).

and...

$$W = (\text{Change of } O_2 \text{ mass in incubator}) \times \frac{(\text{Volume of incubator water})}{(\text{Volume of control water})} \qquad \text{(Eq.4a}$$

$$= \left\{\left[O_2^* \,(V^*)\right] + \left[{}_iO_2' \,(V'-V^*)\right] - \left[{}_fO_2' \,(V')\right]\right\} (V/V') \qquad \text{Eq.4b}$$

where ${}_iO_2'$ = O_2 concentration of control water before adding V^* (in $mg \cdot l^{-1}$)
V' = total volume of water in control chamber (in l)
${}_fO_2'$ = O_2 concentration of control water at the end of the incubation period (in $mg \cdot l^{-1}$; ${}_fO_2' = {}_iO_2'$ of following incubation period).

All the chambers, mixed or unmixed, were used with their heaters installed; the unmixed ones were simply unconnected to the power source.

Incubation experiments in Montreal

To overcome the great variability of results obtained in the Schefferville experiments (see Chapter VI), I attempted some new experiments in Montreal between November 1979 and February 1980. The mud was collected with the Birge-Ekman grab from one station on each of the lakes in early November after freeze-up. A total of 16 liters of sediment was stored for 3 days in a refrigerator at 4°C before being shipped by air freight to Montreal. It was picked up the same day and held in a cold room at 4°C. The incubators were 24 Mason Jars (volume of each approx. 530 ml; fig. 5), filled with well mixed mud and allowed to settle in a large bath of water from Lac Hertel, a small naturally eutrophic lake near Montreal. This equilibration lasted for 66 days in order to recreate a well defined mud-water system with an oxidized surface layer as one expects to find in a lake. The bath water was bubbled with air continuously but no mixing was carried out in the jars themselves which remained open and under water. All work on the incubators proceeded in the cold room at 4°C.

After such a long equilibration time, it was necessary to clean the chamber walls which had a visible coating of organic matter. A length of bent glass tubing connected to a vacuum pump worked rather well. The water in the incubators was also renewed by suction through a Pasteur pipette, the tip of which was bent upwards, and held about 1 cm above the sediment surface. Because these chambers could be sealed under water no air bubbles were trapped inside. In this way they were superior to the incubators used at Schefferville.

Every incubation trial lasted only 24 hours. The water was collected at beginning and end with a 50-ml glass syringe. Any bubbles that were trapped in the syringe were squirted out with the water sampled in excess of 50 mls.

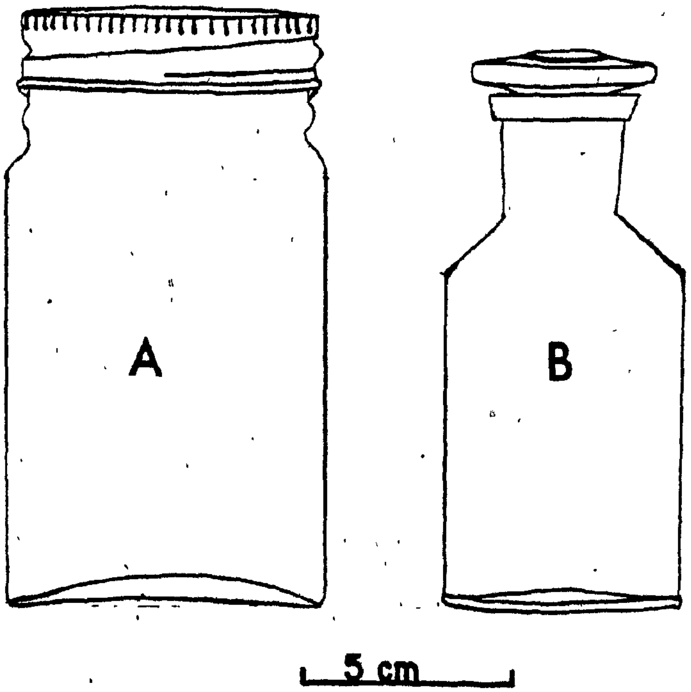


Fig. 5 - Apparatus used for sediment incubation in Montreal, drawn to scale.
a) Mason jar.
b) Control bottle.

SPECIFICATIONS:

Mean volume of Mason jars = 533 ml

Width of Mason jar = 6.9 cm

Cross sectional area of jar = 47.61 cm^2

Mean volume of control bottle = 147 ml

The syringes were sealed with a 3 way plastic stopcock through which the Winkler reagents could be added. A preliminary experiment showed that a considerable vertical gradient of O_2 concentration occurred during incubation of sealed chambers. Consequently, I mixed the water just before taking the final sample from each jar; a coverslip glued to the end of a glass rod was moved up and down gently without disturbing the sediments. There was no continuous mixing during incubation experiments. The controls for water "respiration" were 140 ml glass bottles allowed to stand under water for a few days prior to each run. They were also sealed for 24 hours, but were not cleaned or flushed at the start. These controls had roughly the same surface to volume ratio as the portion of the jars occupied by water.

Addition of the Winkler reagents (azide modification: APHA 1976) proved tedious but possible. The syringes were brought back to the laboratory in a water bath. They were held upright in spring loaded clips during fixation and acidification. I introduced 0.5 ml of $MnSO_4$ and alkaline-iodide azide solutions followed immediately by 1.0 ml of H_2SO_4 10N. The stopcocks had to be well rinsed with distilled water and filled with the appropriate reagent before injection from a 1 ml disposable plastic syringe.

Two 25-ml subsamples were titrated with 0.025N sodium thiosulphate standardized with 0.5 ml of KIO_3 0.10N made up to 25 ml in a volumetric flask (by adding 2.0 ml

H_2SO_4 10N, 1.0 ml alkaline-iodide-azide and 22.5 ml distilled water). The theoretical standardization titer is 2.003 ml.

Instead of pouring out or pipetting 25 ml aliquots, I used a Mettler H40-T digital balance with automatic taring to mass an unknown volume of samples and to calculate the volume, knowing the mass of a 25 ml aliquot which is:

$$M_{25} = (V_w D_w + 0.5 D_{ms} + 0.5 D_{alk} + D_{sa})\ V/V_t \qquad \text{Eq.5a}$$

where M_{25} = mass of a 25 ml aliquot in g.
V_w = volume of water sampled = 50 ml.
D_w = density of (bath) water in $g \cdot ml^{-1}$.
D_{ms} = " " $MnSO_4$ solution in $g \cdot ml^{-1}$.
D_{alk} = " " alkaline-iodide-azide in $g \cdot ml^{-1}$.
D_{sa} = " " H_2SO_4 10N in $g \cdot ml^{-1}$.
V = volume of aliquot desired = 25 ml.
V_t = total volume of liquid in syringe = $50 + 0.5 + 0.5 + 1.0 = 52$ ml.

$$\text{or} \quad M_{25} = 0.481\ (50 D_w + 0.5\ (D_{ms} + D_{alk}) + D_{sa}) \qquad \text{Eq.5b}$$

Using eq.5b, I calculated what the titer of a sample of known mass would be if it was 25 ml:

$$T_{25} = T\ (M_{25}/M) \qquad \text{Eq.6}$$

where T_{25} = titer of 25 mls of that sample (in mls of $Na_2S_2O_3$).
M = mass of the aliquot of that sample (in g).

Similarly, I computed the standardization titer equivalent to that of 0.5 ml of KIO_3 0.10N solution:

$$T^*_{std} = T_{std}\ (M_{std}/M) = T_{std}\ (0.4999/M) \qquad \text{Eq.7}$$

where T^*_{std} = standardization titer of 0.5 ml of KIO_3 (in mls of $Na_2S_2O_3$).

T_{std} = standardization titer of prepared standard (in mls of $Na_2S_2O_3$).
M_{std} = mass of KIO_3 in 0.5 ml of a 0.10N solution (in g).
M = mass of KIO_3 used (in g).

Finally, knowing that 1 ml of $Na_2S_2O_3$ 0.025N corresponds to 16 $mgO_2 \cdot l^{-1}$ when titrating a 25 ml aliquot, I can combine eqs. 6 and 7 to convert any titer adjusted to 25 ml into $mgO_2 \cdot l^{-1}$:

$$[O_2] = 16T_{25}\ (\bar{T}^*_{std}\ /2.003) = 7.988T_{25}\bar{T}^*_{std} \qquad \text{Eq.8}$$

where $[O_2]$ = O_2 concentration in $mg \cdot l^{-1}$
$\bar{T}^*_{25}$ = mean adjusted standardization titer (in mls $Na_2S_2O_3$).

Now that O_2 can be determined, I estimated SOC in the chambers in analogous fashion to the Schefferville experiments. The calculations are simplified because there is no repeated addition of water at the end of an incubation period.

Thus:

$$SOC = \frac{(\text{Change of } O_2 \text{ mass in chamber}) - (O_2 \text{ consumed by water})}{(\text{Sediment area}) \times (\text{Incubation time})} \qquad \text{Eq.9a}$$

$$= \frac{\Delta O_2 - W}{AT} \qquad \text{Eq.9b}$$

where SOC is in $mgO_2 \cdot m^{-2} \cdot day^{-1}$
ΔO_2 and W are in mgO_2
$A = 4.761 \times 10^{-3} m^2$
T = incubation time in days; T = 1 day for all these experiments.

The terms of the numerator in eq. 9b break down as follows:

$$\Delta O_2 = ({}_iO_2 - {}_fO_2)\ (533 - (6.9)^2H) \times 10^{-3} \qquad \text{Eq.10}$$

where ${}_iO_2$ = initial oxygen concentration (in $mg \cdot l^{-1}$).
${}_fO_2$ = final " " (" " ").
H = thickness of the sediment in the jar (in cm)
533 = total volume of the jar (in ml).
6.9 = width of jar (in cm).
10^{-3} = number of mls per liter.

and...

$$W = (\text{Change of } O_2 \text{ mass in control bottle}) \times \frac{(\text{Vol. incubator } H_2O)}{(\text{Vol. control } H_2O)} \qquad \text{Eq.11a}$$

Taking into account the dimensions of the Mason jars and control bottles in fig. 5 , equation 11a becomes:

$$W = ({}_iO_2' - {}_fO_2')\ V'\ \frac{(533 - (6.9)^2H) \times 10^{-3}}{V'} \qquad \text{Eq.11b}$$

$$= ({}_iO_2' - {}_fO_2')\ (533 - (6.9)^2H) \times 10^{-3} \qquad \text{Eq.11c}$$

where ${}_iO_2'$ = initial oxygen concentration in the control bottle (in $mg \cdot l^{-1}$).
${}_fO_2'$ = final oxygen concentration in the control bottle (in $mg \cdot l^{-1}$).
V' = volume of control bottle.

Substituting equations 10 and 11c into equation 9b gives the expression for SOC as a function of oxygen change in chamber and in controls:

$$SOC = \frac{({}_iO_2 - {}_fO_2 - {}_iO_2' + {}_fO_2')\ (533 - (6.9)^2H) \times 10^{-3}}{AT} \qquad \text{Eq.12}$$

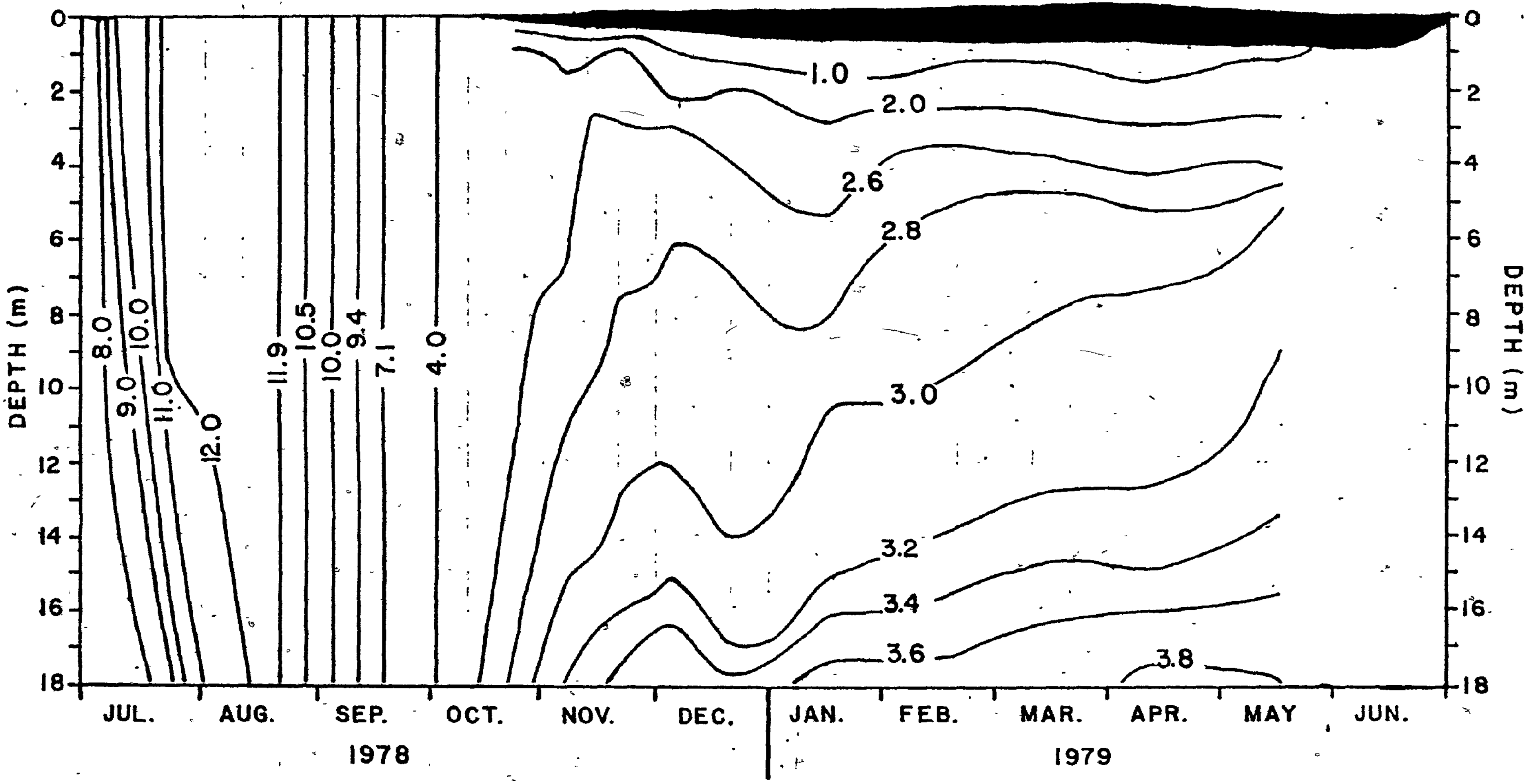
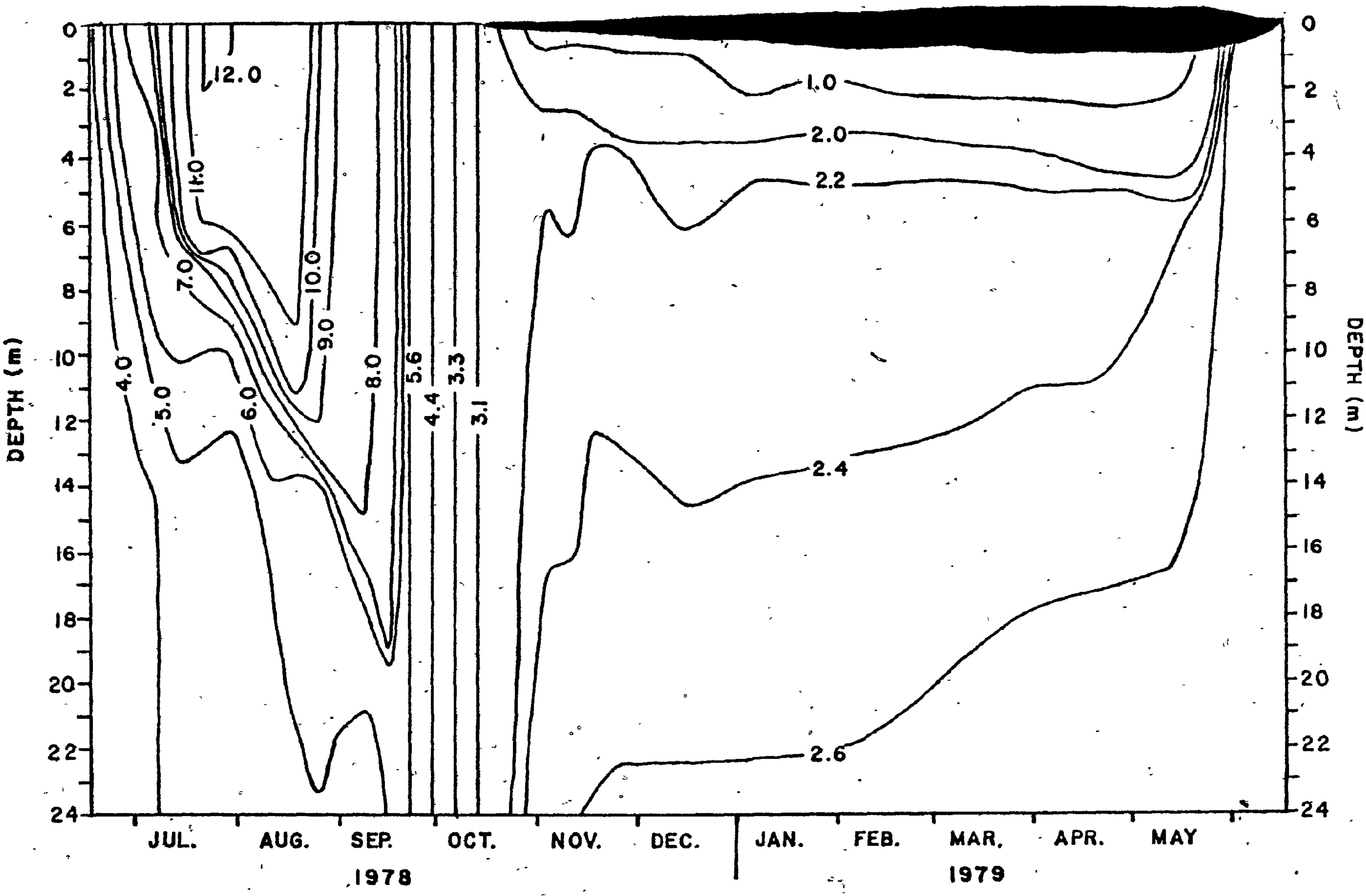


Fig. 6 - Depth-time diagram of temperature in Dolly Lake, Summer 1978 and Winter 1978/79. Ice cover drawn to scale. Temperatures in °C.

Fig. 7 - Depth-time diagram of temperature in Elizabeth Lake, Summer 1978 and Winter 1978/79. Ice cover drawn to scale. Temperatures in ^{o}C.


DEPTH (m)
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18
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24
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5.0
4.0
5.6
4.4
3.3
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1.0
2.0
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JUL.
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MAR.
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MAY
1978
1979
DEPTH (m)

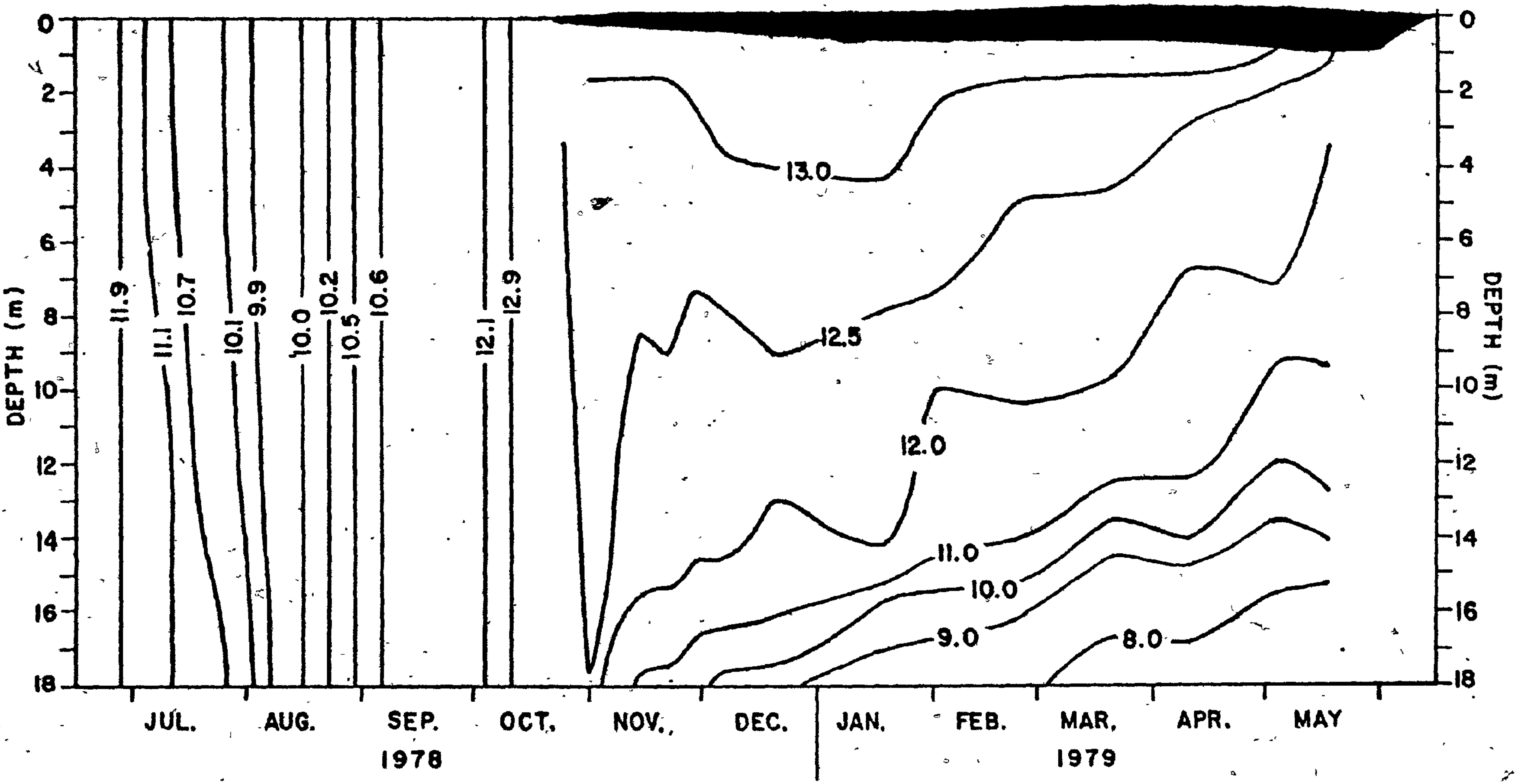
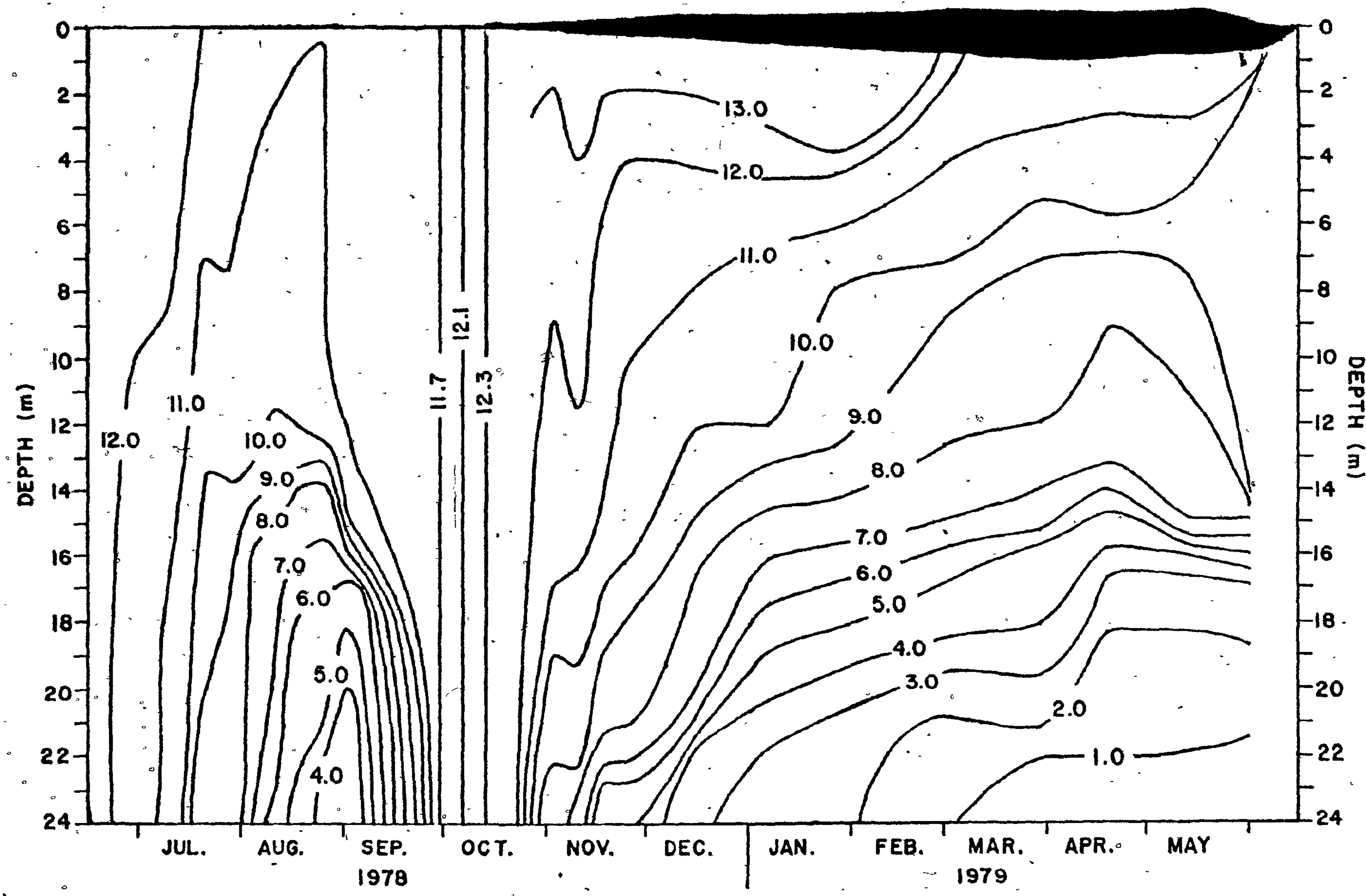


Fig. 8 - Depth-time diagram of dissolved oxygen concentration in Dolly Lake, Summer 1978 and Winter 1978/79. Ice cover drawn to scale. Dissolved oxygen in mg·l^{-1}.

Fig. 9 - Depth-time diagram of dissolved oxygen concentration in Elizabeth Lake, Summer 1978 and Winter 1978/79. Ice cover drawn to scale. Dissolved oxygen in $mg \cdot l^{-1}$.



DEPTH (m)
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11.0
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8.0
7.0
6.0
5.0
4.0
11.7
12.1
12.3
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1978
1979

CHAPTER IV

THE AREAL HYPOLIMNETIC OXYGEN DEFICIT OF ELIZABETH LAKE

There was a marked contrast between temperature regimes of both lakes during the summer of 1978. Dolly remained extremely well mixed (fig. 6) due to its long fetch (4.2 km, Bryan 1965). Elizabeth Lake, which is more protected and has a much shorter fetch (0.7 km, ibid.), stratified between July 14th and September 15th (fig. 7). As a result, dissolved oxygen remained near saturation throughout the water column in Dolly (fig.8), but decreased to a minimum of 2.86 $mg \cdot l^{-1}$ at the bottom of Elizabeth (fig. 9 , Appendix A). Although a metalimnion was present for 63 days, oxygen depletion was observed during the first 49 days of stratification only, from July 14th to September 1st. Unlike the situation in a typical temperate lake, the metalimnion in Elizabeth sunk continuously (table 5).

For the calculation of the AHOD, I arbitrarily fixed the top of the hypolimnion at 14 meters. The period of oxygen consumption under consideration lasted from July 14th to August 25th (42 days), after which the oxygen concentration at 14 m began to increase. The AHOD was estimated as outlined by Cornett and Rigler (1979), beginning

Table 5 - Position of the metalimnion in Elizabeth Lake during the summer of 1978.

Date	Time after first stratification /days	Metalimnetic stratum*
14/07/78	0	6-7 m
21/07/78	7	6-7
28/07/78	14	6-7
11/08/78	28	10-11
18/08/78	35	11-12
25/08/78	42	13-14
1/09/78	49	15-16
8/09/78	56	16-17
15/09/78	63	19-20

*Defined as the stratum showing a temperature decrease greater than or equal to 1°C.

with the calculation of the areal mass of oxygen (M, in $\mathrm{mg \cdot m^{-2}}$) in the hypolimnion at each sampling date:

$$M = \left(\sum V_i G_i \right) / H \qquad \text{Eq.1}$$

where subscript i refers to each 1 m stratum in the hypolimnion (in this case, there are n = 10 strata between 14 and 24 m)
V_i = volume of each stratum (in m^3).
G_i = mean oxygen concentration in each stratum (in $\mathrm{mg \cdot m^{-3}}$).
H = area at the top of the hypolimnion = area at 14 m = 3.51×10^4 m^2.

The AHOD is the slope of the type I least-squares linear regression of the values of M against the time after the onset of stratification. Results show that hypolimnetic oxygen consumption proceeds linearly with time ($r^2 = 0.99$) at a rate of 390.56 $\mathrm{mgO_2 \cdot m^{-2} \cdot day^{-1}}$ (fig. 10). Hypolimnetic metabolism in Elizabeth Lake is therefore not limited by even the lowest oxygen concentrations occuring during stratification. This allows me to test Cornett and Rigler's

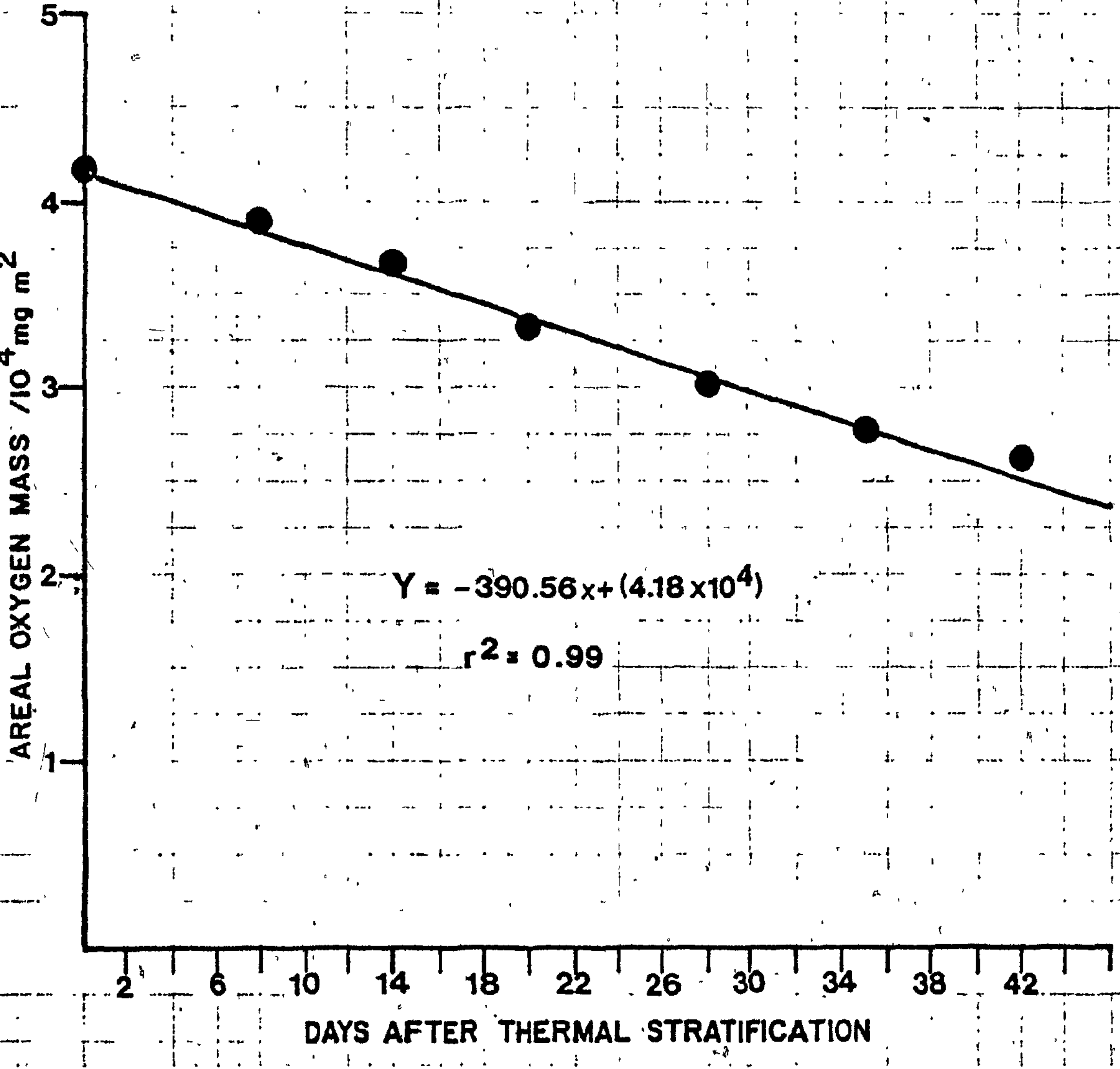

Fig. 10 - Change in the areal oxygen mass below 14 m in Elizabeth Lake during summer stratification. Day 0 = 14/07/78, day 42 = 25/08/78.

Table 6 - Areal masses of oxygen in the hypolimnion of Elizabeth Lake during the summer of 1978.

Date	Time after first stratification /days	Areal mass of oxygen $/10^4 mg \cdot m^{-2}$
14/07/78	0	4.174
21/07/78	7	3.897
28/07/78	14	3.687
4/08/78	21	3.333
11/08/78	28	3.060
18/08/78	35	2.729
25/08/78	42	2.610

model (1979) on this lake. The AHOD is calculated by the following equation:

$$AHOD = -277 + 0.5R_p + 5.0\bar{T}_h^{1.74} + 150 \ln (\bar{Z}_h) \qquad Eq.2$$

Table 7 summarizes the calculation of each variable entering into Eq. 2. Substituting for the values in table 7, I predict the following AHOD:

$$-277 + 0.5(243.397)+5.0(4.98)^{1.74} + 150\ln (4.09)=137.83 \ mgO_2 \cdot m^{-2} \cdot day^{-1}$$

The discrepancy between this predicted rate and the actual one (390.56 $mgO_2 \cdot m^{-2} \cdot day^{-1}$) is enormous, especially when none of the calculated AHOD's which gave rise to the model deviated by more than 50% from their corresponding predicted values. If one supposes the model to be correct, what could have caused the difference? One possible mechanism is the displacement of hypolimnetic water by anoxic groundwater. Flooding problems in the nearby mines (Nichols 1968) confirm the existence of considerable subterranean flow, as one would expect in an area of sedimentary deposits like the Labrador Trough. The chert breccias surrounding most of

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Table 7 - Calculation of the variables entering the Cornett-Rigler equation for predicting AHOD. Elizabeth Lake, Summer 1978. Phosphorus and discharge data courtesy of F.H. Rigler.

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1 - Areal phosphorus retention:

$R_p = PQR/(A(1-R)) = 243.397\ \mathrm{mgP \cdot m^{-2} \cdot yr^{-1}}$

$P = 14.7\ \mathrm{mg \cdot m^{-3}}$ = volume-weighted mean concentration of phosphorus in the lake, from July 14th to August 25th.

$Q = 2.237 \times 10^6 \mathrm{m^3}$ = outflow discharge for 1977/78 water year.

$A = 2.806 \times 10^5 \mathrm{m^2}$ = lake area.

$R = 0.201 \exp(-0.0425Q/A) + 0.574 \exp(-0.00949Q/A)$
$= 0.675$
= fraction of input mass of phosphorus retained by the lake, calculated from an empirical relationship developed by Ostrofsky (1978).
Q/A = areal water load = 7.97 m.

---

2 - Mean hypolimnetic temperature:

$\overline{T}_h = 4.98^\circ C$
= volume-weighted mean temperature of the hypolimnion between July 14th and Aug. 25th., calculated from temperature and morphometric data in Appendix A.

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3 - Mean depth of the hypolimnion:

$\overline{Z}_h = 4.09\ \mathrm{m}$
= Volume of hypolimnion/area at top of hypolimnion
$= (1.435 \times 10^5 \mathrm{m^3}) / (3.51 \times 10^4 \mathrm{m^2})$

Elizabeth Lake are more permeable than the slates and shales which occupy much of the Dolly Lake basin (Findlay 1966a). Groundwater could have flowed over permafrost (Nicholson and Lewis 1976), resulting in a cold dense mass of water which would sink to the bottom of the lake. Temperature (fig. 7) and conductivity (fig. 11) data do not support this interpretation however. The hypolimnion gains heat during stratification and conductivity varies little from top to bottom. In fact, neither lake shows a pronounced seasonal difference in specific conductivity except at the last few depths (fig. 11). Between-lake differences are much more significant. Curiously, Dolly has the highest specific conductivity of the two during both seasons despite its ultraoligotrophic condition. This probably stems from catchment geology and low flushing rate.

How much groundwater flow would be required to account for the difference between observed and predicted AHOD (390.56 - 137.83 = 252.73 $\mathrm{mgO_2 \cdot m^{-2} \cdot day^{-1}}$)? Is this estimate comparable to others made for the area? A simple mass balance calculation yields the following figure, assuming that the groundwater is anoxic:

$$\frac{\text{AHOD x (Area at 14m)}}{\text{Initial mean } O_2 \text{ concentration below 14m}} = \frac{253.73 \text{x} 0.351 \text{x} 10^5}{10.20 \text{ x } 10^3} = 870$$

$$\text{units:} \quad \frac{(\mathrm{mgO_2 \cdot m^{-2} \cdot day^{-1}}) \text{ x } \mathrm{m^2}}{\mathrm{mgO_2 \cdot m^{-3}}} = \mathrm{m^3 \cdot day^{-1}}$$

The equation used by Lewis (1977) to describe groundwater flow as a function of the disappearance of a tracer substance from a well-hole, when applied to this

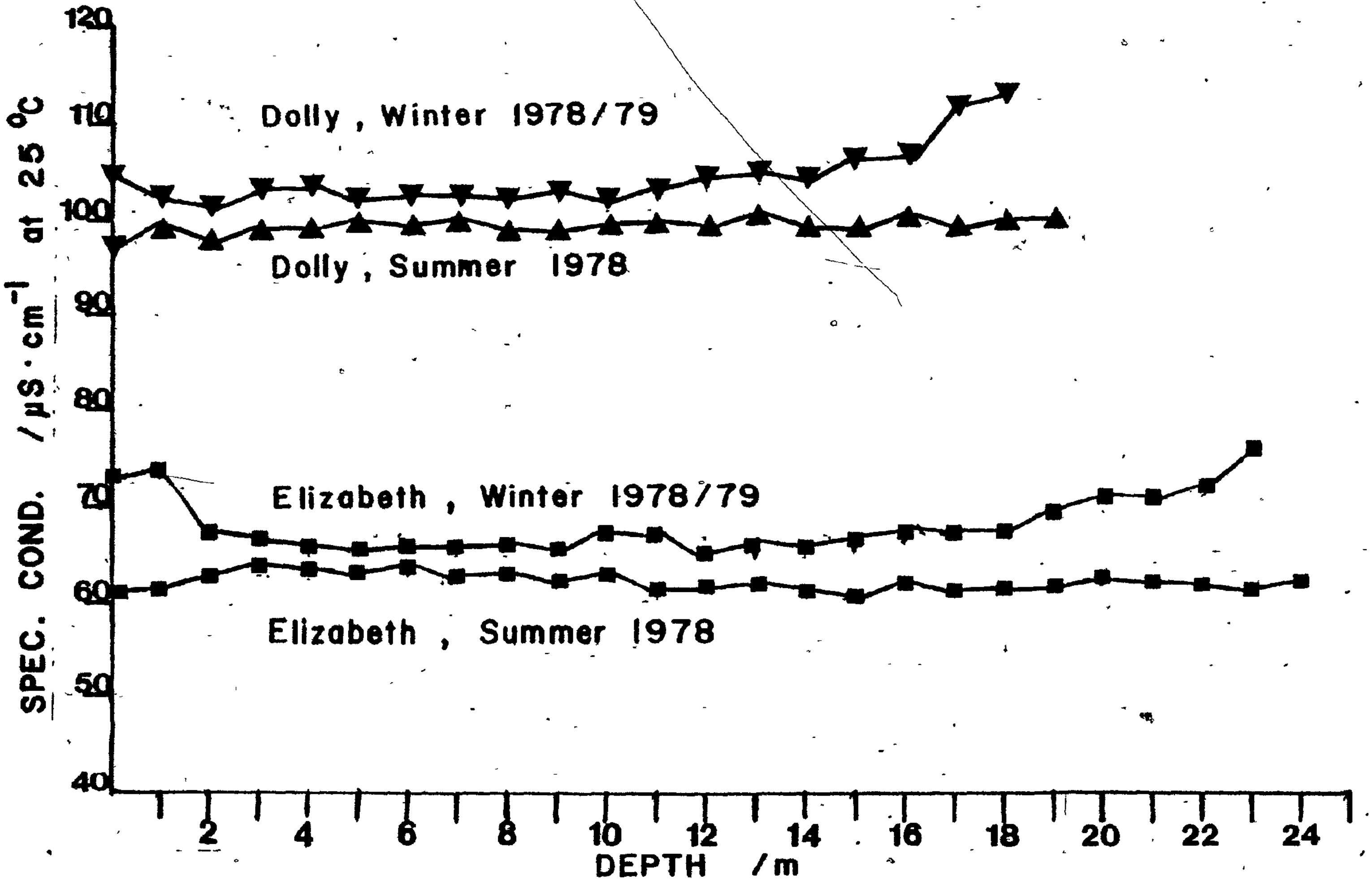

Fig. 11 - Depth profiles of mean seasonal specific conductivity in Dolly and Elizabeth lakes. The standard deviations around each point represent about 8% of their value.

situation, gives an average of 921 $m^3 \cdot day^{-1}$ (std. dev.= 56; see table 8).

Table 8 - Calculation of putative groundwater flow into the hypolimnion of Elizabeth Lake, according to Lewis (1977).

$$Q_d = (V/t) \ln (C_o/C_t)$$

Q_d = groundwater flow in $m^3 \cdot day^{-1}$
V = volume of water in the well. In this case, the hypolimnetic volume of $1.435 \times 10^5 m^3$.
t = time in days.
C_o = concentration of tracer at time zero. In this case, the tracer is O_2, the concentration a weighted mean below 14 m (in $mg \cdot m^{-3}$).
C_t = concentration of tracer at time t. In this case, volume weighted O_2 concentration at time t.

Date	t	C_t	Q_d
14/07/78	0	10.20×10^3	--
21/07/78	7	9.79×10^3	841
28/07/78	14	9.36×10^3	881
4/08/78	21	8.93×10^3	909
11/08/78	28	8.49×10^3	940
18/08/78	35	8.06×10^3	965
25/08/78	42	7.63×10^3	992
		MEAN =	921
		STANDARD DEVIATION =	56

Both of these estimates represent about 9% of the mean daily outflow discharge during this period (July 14th to August 25th; table 9). They are far below Findlay's (1966a,b) calculations for French Mine (6 km NW of Schefferville, catchment about 15 km^2), based on Iron Ore Co. pumping records. His figures varied from $3.19 \times 10^4 m^3 \cdot day^{-1}$ in September 1964 to $4.65 \times 10^4 m^3 \cdot day^{-1}$ in June 1965.

Table 9 - Daily outflow discharges at Elizabeth Lake, Summer 1978. Data courtesy of F.H. Rigler.

Date	Time /days	Discharge* $/m^3 \cdot day^{-1}$
14/07	0	8647
17/07	3	10022
19/07	5	8813
21/07	7	8640
24/07	10	7258
26/07	12	8122
28/07	14	8986
31/07	17	7603
2/08	19	7258
4/08	21	7258
7/08	24	6653
9/08	26	9677
11/08	28	9158
14/08	31	9158
16/08	33	11059
18/08	35	16243
21/08	38	14256
23/08	40	15293
25/08	42	12874
	Time-weighted mean =	9694

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* Mean of lake stage and dye dilution measurements.

If anoxic groundwater does accumulate at the bottom, one would expect an AHOD which increases gradually with depth. This is not the case in Elizabeth Lake (table 10 , fig. 12).

Table 10 - Comparison of observed and predicted AHOD's at different depths in the hypolimnion of Elizabeth Lake.

Depth /m	AHOD / $mg \cdot m^{-2} \cdot day^{-1}$ OBSERVED*	PREDICTED**	$\overline{T}_h$ /°C	$\overline{z}_h$ /m	Error ratio‡
14	390.56	137.83	4.98	4.09	2.8
15	391.28	122.89	4.89	3.77	3.2
16	394.49	111.77	4.83	3.54	3.5
17	374.08	96.26	4.80	3.21	3.9
18	356.94	82.48	4.76	2.95	4.3
19	363.32	78.33	4.74	2.88	4.6
20	356.33	66.42	4.72	2.67	5.4
21	297.97	30.12	4.71	2.10	9.9
22	224.10	***	4.69	1.50	---
23	128.98	***	4.64	0.83	---

* $r^2 \geq 0.90$ in all cases.
** R_p constant at 243.397
*** Negative value obtained.
‡ Error ratio = Observed/Predicted

The AHOD decreases by roughly 70% over a narrow range of hypolimnetic temperatures. The discrepancy between observed and predicted AHOD's increases with depth, indicating that a factor other than hypolimnetic thickness or temperature ~~is~~ influencing significantly the oxygen consumption. Could there be large amounts of dead organic matter consuming oxygen at the top of the hypolimnion as a result of primary production at that depth? It may be possible since the extinction coefficients in Appendix A translate to 1% of incident light between 12 and 14 meters.

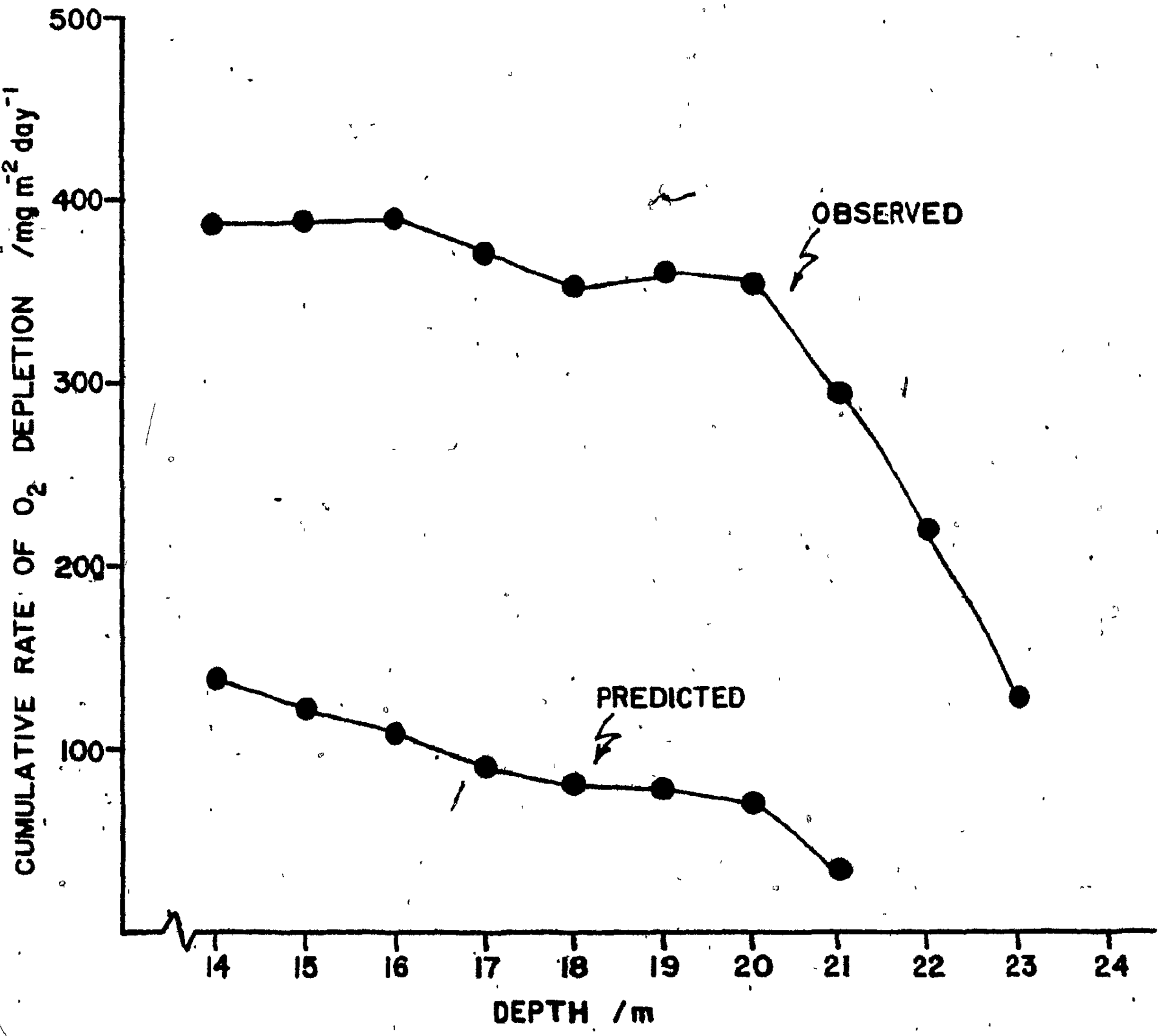

Fig. 12 - Observed and predicted AHOD's below different depths in Elizabeth Lake, Summer 1978.

The decrease of oxygen consumption in successively deeper hypolimnetic strata was observed as early as 1947 in Lake Windermere, a temperate dimictic lake (Lund et al. 1963). This feature of the "respiration" process is therefore not uncommon and deserves further investigation. The Cornett-Rigler model is an excellent first step in the prediction of AHOD but it requires more testing on a broader range of lake types before it can be a useful tool for lake management.

CHAPTER V

THE AREAL WINTER OXYGEN DEFICITS OF DOLLY AND ELIZABETH LAKES.

Dolly and Elizabeth lakes were frozen for 243 days from October 15th, 1978 to June 15th, 1979. They both consumed oxygen (figs. 8,9) with Elizabeth becoming almost anoxic at 23 m at the end of winter (0.49 $mg \cdot l^{-1}$); the minimum concentration in Dolly, on the other hand, was 6.63 $mg \cdot l^{-1}$. Elizabeth was the colder of the two during the entire period by roughly 1°C (figs.6,7). Neither lake reached 4°C at any depth, a phenomenon that Penn (1970) observed in other lakes around Schefferville. The difference in mean temperature is almost certainly due to the larger volume of water, hence the greater heat capacity in Dolly Lake.

Calculation of the AWOD

The AWOD is determined similarly to the AHOD by regressing the mass of dissolved oxygen, this time in the entire lake, vs. the time after freeze-up (AWOD = slope of the regression). Calculations of oxygen masses are identical for the strata that remain unfrozen throughout the winter:

$$M = \sum (V_i G_i) \qquad \text{Eq.1}$$

where M = mass of oxygen in mg.
V_i = volume of individual stratum in m^3.
G_i = mean oxygen concentration of individual stratum in $mg \cdot m^{-3}$.

The ice measurements in Appendix A show that only the top stratum (0 to 1 m) in each lake is gradually occupied by an ever increasing volume of black ice which is never thicker than 1 m. I am assuming that black ice grows downwards into the stratum and that white ice is being formed upwards on top of the black ice. Oxygen is almost totally excluded during the formation of black ice (Welch 1974) and should not change the total 0_2 content of the lake. During a typical winter, the black ice cover will crack in several places due to mechanical stress (weight of snow cover, temperature-induced expansion or contraction). Oxygen-rich water immediately below will seep through and flood the snow cover before freezing. The resulting white ice represents a loss of oxygen from the lake that one can calculate based on the increment of white ice formed and the oxygen concentration of the water that formed it. The addition of oxygen from the concurrent thickening of the black ice must be estimated also in order to find the net gain or loss of 0_2 from the stratum. Instead of proceeding this way, I adopted a more direct approach by simply calculating the total oxygen content of the unfrozen remainder of the 0-1 stratum and adding it to the result of eq. 1 to obtain the total mass of oxygen. Thus:

$$M_{tot.} = M + M' \qquad \text{Eq.2}$$

where M' = mass of oxygen in remainder of 0-1m stratum (in mg)

M = mass of oxygen in the unfrozen strata (in mg)

$$M' = [\bar{O}_2] \times (V - V_{bl} - V_{wl}) \qquad \text{Eq.3}$$

where $[\bar{O}_2]$ = mean of O_2 concentration at 0_m and 1m (in $mg \cdot m^{-3}$).
V = total volume of 0-1m stratum (in m^3).
V_{bl} = water-equivalent of black-ice layer (in m^3).
V_{wl} = water-equivalent of white-ice layer (in m^3).

Assuming a black ice density of 0.92 and a white ice density of 0.88 (Adams 1976), and that the snowcover contributed to 10% of the white ice*, we get:

$$V_{bl} = 0.92\ Z_{bl}\bar{A}_{bl} \qquad \text{Eq.4}$$

$$V_{wl} = (0.88 \times 0.90)\ Z_{wl}A_o \qquad \text{Eq.5}$$

where Z_{bl} = thickness of black ice (in m)
Z_{wl} = thickness of white ice (in m)
A_o = area of the lake at the surface (in m^2)
$\bar{A}_{bl}$ = area of the lake at a depth equal to the mid-point of black ice thicknesses at times t and t-1. This is interpolated linearly from the morphometric data in Appendix A . Units = m^2.

These total masses of oxygen (eq.2) are then expressed per unit area of total lake surface. The results (table 11 , fig.13) indicate that winter oxygen depletion proceeds linearly in both lakes, at a rate of 97.49 $mgO_2 \cdot m^{-2} \cdot day^{-1}$ in Dolly and 204.08 $mgO_2 \cdot m^{-2} \cdot day^{-1}$ in Elizabeth ($r^2 = 0.98$, in both cases). In fig.13 , I excluded the last 2 points of Elizabeth and the last point of Dolly from the regression analysis because the lakes are probably no longer completely sealed. The large decrease of specific conductivity at 0 and 1 m in May suggests that meltwater

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* Inspired by the rule of thumb for converting snowfall to its water equivalent: 1 cm snow = 1 mm water equivalent.

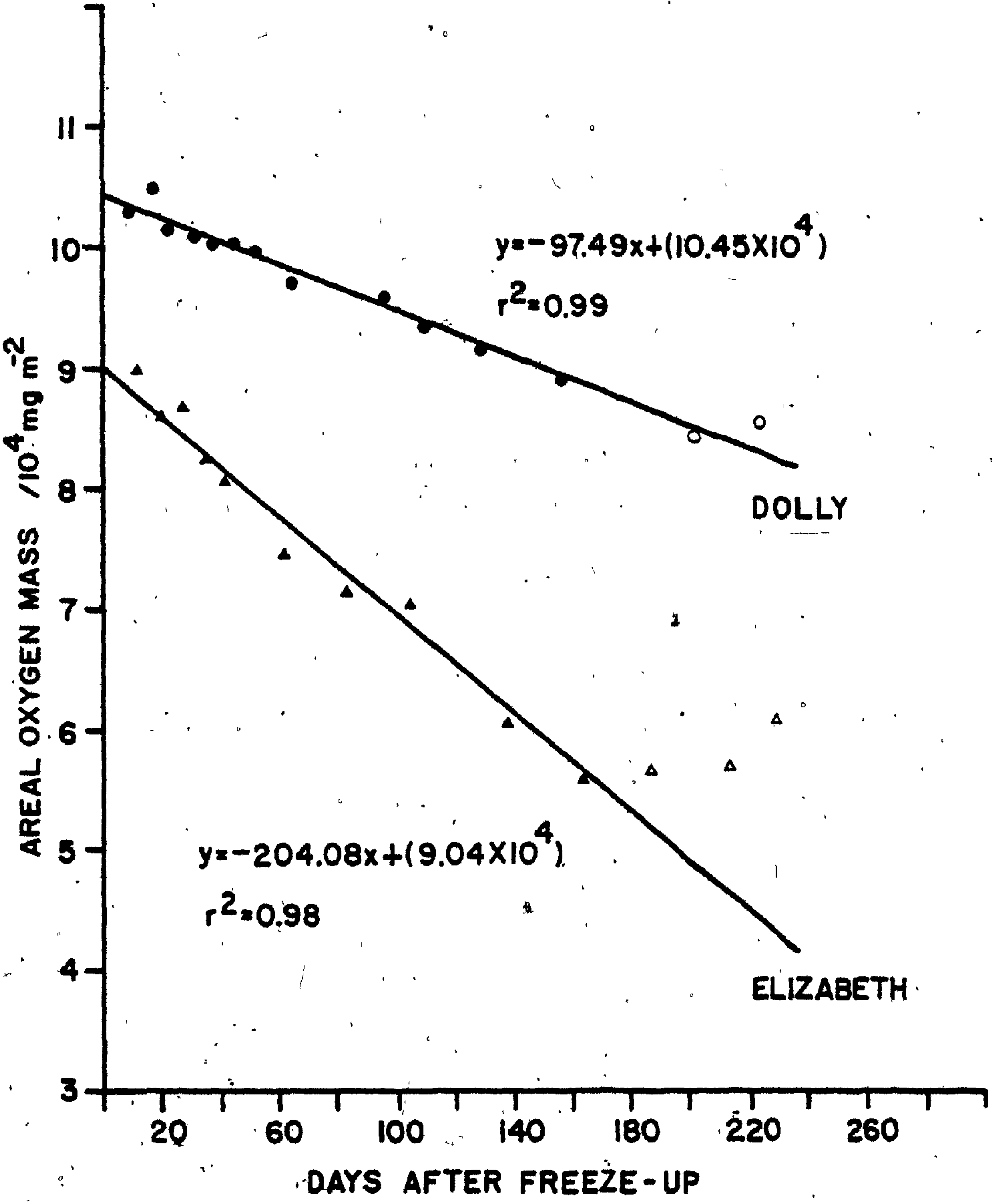


Fig. 13 - Areal masses of oxygen in Dolly and Elizabeth lakes throughout the winter of 1978/79. Open circles and triangles were not included in the regression analysis (explanation in text).

from the shrinking ice cover is entering the lakes (Appendix A).

Table 11 - Areal masses of oxygen in Dolly and Elizabeth lakes throughout Winter 1978/79.

DOLLY			ELIZABETH		
Date	Time after freeze-up /days	Areal O_2 Mass $/10^4 mg \cdot m^{-2}$	Date	Time after freeze-up /days	Areal O_2 Mass $/10^4 mg \cdot m^{-2}$
24/10/78	10	10.29	27/10/78	13	8.98
31/10/78	17	10.48	3/11/78	20	8.60
7/11/78	24	10.16	10/11/78	27	8.68
14/11/78	31	10.12	17/11/78	34	8.25
21/11/78	38	10.04	24/11/78	41	8.06
28/11/78	45	10.01	15/12/78	62	7.44
5/12/78	52	9.98	6/01/79	84	7.14
17/12/78	66	9.73	26/01/79	104	7.02
18/01/79	96	9.59	28/02/79	137	6.04
2/02/79	111	9.35	29/03/79	166	5.59
22/02/79	131	9.15	18/04/79	186	5.45
20/03/79	157	8.93	13/05/79	211	5.69
9/04/79	177	8.78	31/05/79	229	6.10
3/05/79	201	8.46			
17/05/79	215	8.58			

Oxygen concentrations of individual strata in both lakes decrease linearly throughout the winter at rates that increase with depth (fig. 14). Each lake shows roughly the same pattern but the absolute rates are much higher in Elizabeth at all depths.

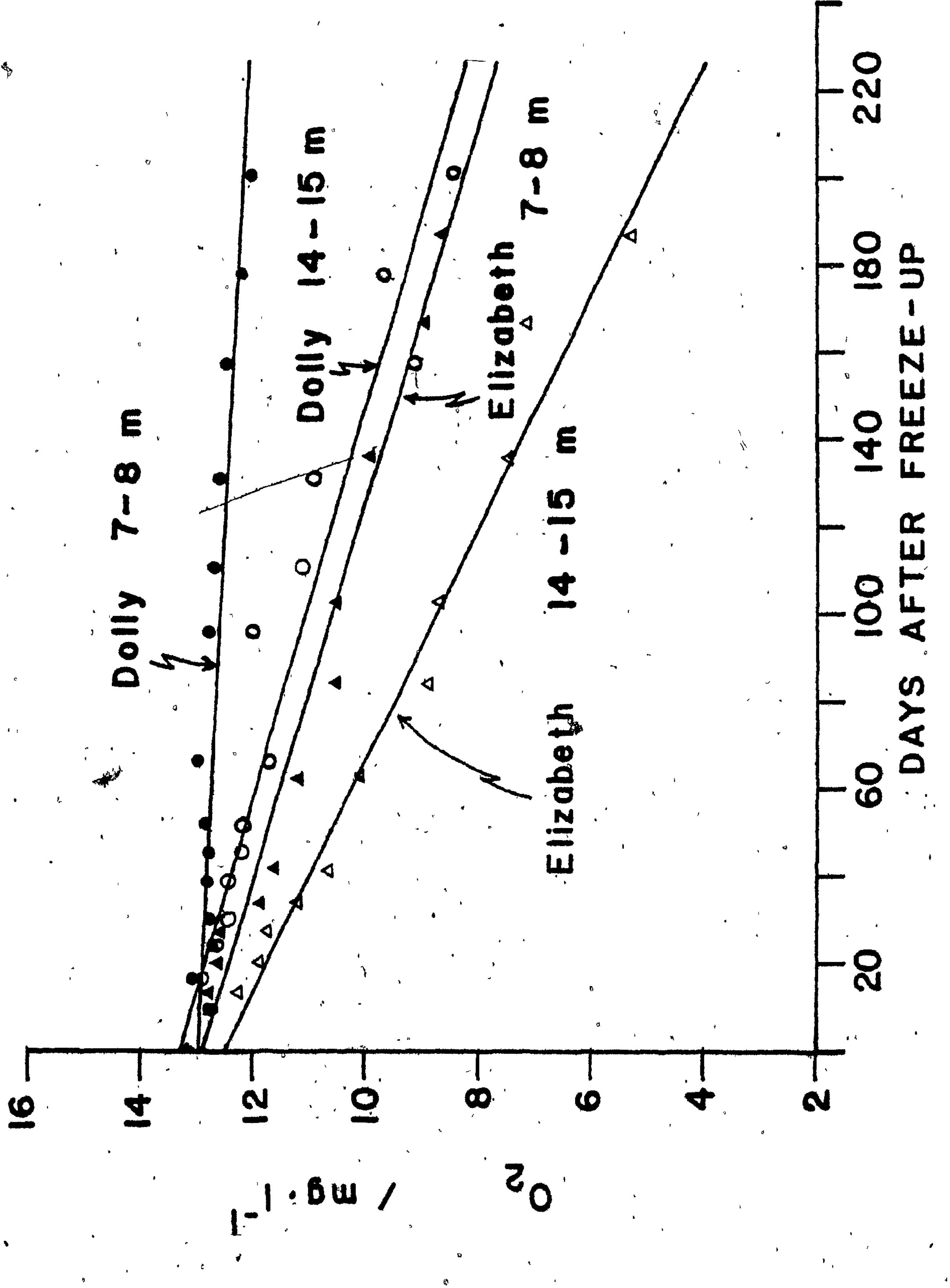
Predicting the AWOD

The next step is to apply Welch et al.'s (1976) model and compare its predictions to the measured AWOD's. Of the two equations given, I used the one based on morphometric variables only because the other one requires a nitrogen to phosphorus ratio which has not been deter-

Fig. 14 - Decrease of dissolved oxygen concentration in two strata of Dolly and Elizabeth lakes during the winter of 1978/79.

Regressions:

Dolly, 7-8 m: $Y= -0.004X + 12.95$, $r^2=0.99$
Elizabeth, 7-8 m: $Y= -0.023X + 12.84$, $r^2=0.97$
Dolly, 14-15 m: $Y= -0.022X + 13.25$, $r^2=0.99$
Elizabeth, 14-15 m: $Y= -0.037X + 12.51$, $r^2=0.97$


Dolly 7-8 m
Dolly 14-15 m
Elizabeth 7-8 m
Elizabeth 14-15 m
O_2 / mg·l^{-1}
16
14
12
10
8
6
4
2
20
60
100
140
180
220
DAYS AFTER FREEZE-UP

mined for the Schefferville lakes. The morphometric version is:

$$AWOD = 0.3157 + 0.0208\bar{Z} - 0.0015\tau - 0.0018Z_m \qquad \text{Eq.6}$$

where AWOD is in $gO_2 \cdot m^{-2} \cdot day^{-1}$

$\bar{Z}$ = mean depth (in m)
$\bar{S}$ = mean Secchi depth (in m)
τ = flushing rate (in yr^{-1})
Z_m = maximum depth (in m)

Table 12 gives the results for both lakes. The prediction is very close to the observed rate in the case of Dolly (error ratio = 1.07), but not so for Elizabeth (error ratio = 0.63). Both observed rates lie within the range of AWOD's which gave rise to the model.

Table 12 - Calculation of predicted AWOD's for Dolly and Elizabeth lakes, Winter 1978/79.

	DOLLY	ELIZABETH
Mean depth	8.4 m	8.7 m
Mean secchi depth	9.6 m	3.4 m
Flushing rate*	0.32 yr^{-1}	1.13 yr^{-1}
Maximum depth	18 m	23 m
Predicted AWOD	90.82 $mg \cdot m^{-2} \cdot day^{-1}$	323.69 $mg \cdot m^{-2} \cdot day^{-1}$
Observed AWOD	97.49 $mg \cdot m^{-2} \cdot day^{-1}$	204.08 $mg \cdot m^{-2} \cdot day^{-1}$

* For 1978 water year.

A closer examination of Welch et al's (1976) choice of parameters reveals that some may not be independent of each other as is required for performing a multiple regression analysis. For example, the phosphorus concentrations were sometimes used to predict the chlorophyll concentrations entering the regression. Furthermore, I do not believe that a valid comparison of correlation coefficients between mean depth and winter respiration rates expressed areally (per m^2 of lake surface) and volumetrically (per m^3 of water volume) can be made as in table 2 of their paper (p.1811), when either quantity converts to the other by "... dividing or multiplying by the mean depth" (ibid., p. 1810).

In any case, observed AWOD's for my two lakes differ markedly despite their similar mean depths. One would certainly suspect nutrient loading or retention of exerting some influence on winter oxygen depletion since Dolly and Elizabeth have such different values for some indicators of trophic status (table 13). The data base on which to build an empirical model of AWOD is still

Table 13 - A comparison of some indicators of trophic status for Dolly and Elizabeth lakes. Data for 1977/78, courtesy of F.H. Rigler.

	DOLLY	ELIZABETH
Mean Secchi depth	11.5 m	4.7 m
Mean Phosphorus	$1.51\ ug \cdot l^{-1}$	$12.38\ ug \cdot l^{-1}$
Areal phosphorus retention*	$11.35\ mgP \cdot m^{-2} \cdot yr^{-1}$	$209.43\ mgP \cdot m^{-2} \cdot yr^{-}$
Fraction of P retained**	0.74	0.68

* $R_p = PQR/(A(1-R))$ as defined by Cornett and Rigler (1979).
** $R = 0.201 \exp(-0.0425Q/A) + 0.574 \exp(-0.00949\ Q/A)$ as defined by Ostrofsky (1978).

too narrow. No doubt will there be an effort to broaden it during the next few years. The correspondence between AWOD and actual lake respiration is still open to debate.

Vertical mixing was postulated by Rigler (1974) as a possible explanation for a linear decrease of oxygen content throughout the winter in Char Lake despite an apparent "levelling-off" of respiratory activity in different strata. Whatever oxygen is frozen out by ice formation should accumulate just beneath the ice surface if there is no circulation. Figs. 8 and 9 show a decrease of O_2 concentration below the ice in Dolly and Elizabeth especially after January. Some could have been lost through the outflow (mean O_2 concentrations ± std. dev. are 13.55 ± 0.40 $mg \cdot l^{-1}$ for Dolly and 13.20 ± 0.67 $mg \cdot l^{-1}$ for Elizabeth; see table 14). If cold water moves downwards in the lake, there would be a gradual cooling of the lower strata. The temperature profiles of both lakes show the exact opposite (figs. 6, 7): below 5m, there is a heat gain after January as well as a persistent vertical temperature gradient. One cannot dismiss the possible heating from solar radiation but it seems unlikely that the thick snow and ice cover would allow enough light to penetrate. Snow and ice thicknesses were comparable if not greater than those measured on Welch et al.'s (1976) lakes where there wasn't even enough light for significant photosynthesis to occur.

The model at my disposal was unsatisfactory for predicting AWOD in the most productive of the two lakes under study. The strong indication of a relationship between AWOD and parameters of trophic status emphasizes the necessity of incorporating the latter in a successful model.

Table 14 - Dissolved oxygen concentrations in the outflow of Dolly and Elizabeth lakes, Winter 1978/79.

DOLLY		ELIZABETH	
Date	O_2 /mg·l^{-1}	Date	O_2 /mg·l^{-1}
24/10/78	13.65	27/10/78	13.82
31/10/78	13.99	3/11/78	13.63
7/11/78	13.24	17/11/78	13.86
14/11/78	13.53	24/11/78	13.60
21/11/78	13.72	6/01/79	12.48
28/11/78	13.70	26/01/79	12.37
5/12/78	13.68	28/02/79	12.63
19/12/78	13.63		
18/01/79	13.97		
2/02/79	13.98		
22/02/79	13.43		
20/03/79	13.95		
9/04/79	13.09		
3/05/79	13.11		

One aspect of the calculation of whole-lake oxygen masses which must be improved is the estimation of ice thicknesses. Extrapolation of measurements taken at one location to the entire lake surface is risky because of wide variations between individual measurements (Adams and Brunger 1975). A comparison between a comprehensive ice survey of Elizabeth Lake and my single point measurements at around the same time shows a good agreement for black ice thickness but far less concordance with figures for total and white ice, snow and hydrostatic water level (table 15).

Table 15 - Comparison of ice, snow and water level measurements on Elizabeth Lake between a comprehensive survey (n = 126) and a single point survey. Survey data courtesy of W.P. Adams and N.T. Roulet (1979). Standard deviations in brackets.

	Snow	Total ice /cm	White ice /cm	Black ice /cm	Hydrost.water level /cm
Adams and Roulet, Feb. 23-25	26.88 (9.07)	94.23 (12.89)	20.65 (13.82)	73.66 (17.82)	- 0.75 (3.46)
My survey, Feb.28	13.5	121.0	47.0	74.0	-10.0

CHAPTER VI

MEASUREMENTS OF SEDIMENT OXYGEN CONSUMPTION

Sediment oxygen consumption (SOC) was measured in an attempt to ascertain what fractions of the AWOD can be attributed to sediment and water column respiration. This information might explain why deep lakes have higher areal oxygen consumption rates, all other factors being equal (Welch et al. 1976, Cornett and Rigler 1979). In my lakes, the observed AWOD's (97.49 $mg\cdot m^{-2}\cdot day^{-1}$ in Dolly and 204.08 $mg\cdot m^{-2}\cdot day^{-1}$ in Elizabeth) should represent the upper limit of the measured SOC's in the laboratory.

Since there is no standard method of measuring SOC (Pamatmat 1975, Granéli 1978), I chose to follow the change in dissolved oxygen of a known volume of water overlying a known area of mud in a sealed chamber, like in most studies. A direct comparison with whole-lake measurements is possible, unlike other approaches which require a conversion of results to O_2 consumption (Pamatmat 1975, Rich 1975). Controls for water respiration were incubated concurrently. The SOC represents the difference between total respiration in the chambers and respiration of the water-filled controls. I chose laboratory microcosms over in situ devices for reasons of flexibility and ease of sampling. Moreover, SOC appears to be primarily influenced by temperature (Edwards and Rolley 1965, Hargrave 1969 a,b, McDonnell and Hall 1969) which is easily controlled in the laboratory.

The majority of experiments are performed on sediment cores. The major assumption is that they are undisturbed samples, therefore in a natural state. But some disturbance is inevitable during sampling and transportation, and may increase SOC for some time after sampling (Granéli 1977), although Edberg (1976) found no change in SOC even after six months of storage. Cores *do* disturb the top layer of sediment since new designs are still being created to overcome this problem (Williams and Pashley 1979). Hayes and MacAulay (1959) reported no difference between rates of cores and those of resuspended mud-water systems. This prompted me to sample with a grab and let the mud equilibrate over a long time period before incubating.

Results of the Schefferville experiments

The results gathered in Schefferville (tables 16 and 17)do not show any significant pattern because of enormous variability between replicates. Standard deviations can represent from 8% to 80% of their respective means. There is some suggestion of a decrease of SOC with increased incubation time but I could reach a firm conclusion only with far more reproducible data.

The chambers were difficult to purge of air bubbles trapped during replacement of sampled water. The thermal stirring occasionally produced air bubbles on the

Table 16 - Means of sediment oxygen consumption (SOC) rates for Dolly Lake samples. All values are in $mgO_2 \cdot m^{-2} \cdot day^{-1}$ ± standard deviation. Negative rates excluded from calculations. Raw data in Appendix D.

Depth	Time after start of expt., in hours	SOC /$mg \cdot m^{-2} \cdot day^{-1}$		
		Unstirred	Stirred	Overall mean
12	24	147.17±14.40	62.58	118.97±49.89
12	41.5	70.13±40.40	125.05	88.44±42.68
15	22	124.85±33.89	216.91±125.64	170.88±79.76
15	44.5	92.65±52.95	29.44± 2.25	61.05±27.60
20	26	47.71±19.47	66.74± 32.48	56.17±26.19
20	46	90.65±26.71	216.48±162.16	137.84±110.28
20	164	31.49±24.35	30.73± 13.06	29.92±15.63

Table 17.- Means of sediment oxygen consumption (SOC) rates for Elizabeth Lake samples. All values are in mgO$_2$·m^{-2}·day^{-1} ± standard deviation. Negative rates excluded from calculations. Raw data in Appendix D.

Depth /m	Time after start of expt., in hours	SOC /mg·m^{-2}·day^{-1} Unstirred	Stirred	Overall mean
8	20	12.66± 0.52	220.36± 1.24	116.51±119.92
8	28	84.53± 3.07	--	84.53± 3.07
8	49	36.91±46.55	44.49	39.43± 33.21
8	66	21.67±26.42	26.11± 15.90	23.89± 17.98
16	20	119.92±19.60	240.52±121.77	180.22±102.22
16	28	116.63± 9.79	267.34	188.06± 53.46
16	49	62.13± 7.36	73.41	64.95± 8.24
16	66	22.78±10.46	75.07± 40.81	48.93± 39.12
24.5	24	240.16±26.71	179.75± 5.05	209.96± 37.29
24.5	41.5	53.28±12.60	81.65± 38.07	67.46± 29.74

funnel-shaped support which might explain why stirred controls have higher values than unstirred ones most of the time (Appendix D). Because the complexity of the design may be a source of variability, I decided to do another series of experiments in Montreal with a far simpler system consisting of Mason jars in a water bath (see Chapter III).

Results of the Montreal experiments

Because the simpler chambers had no built-in stirring device, I first tested to see if an oxygen concentration gradient formed and whether such a gradient could be eliminated before sampling without resuspending sediment. Results in table 18 show that a gradient does form and that it can be abolished by gentle stirring. This also provides indirect evidence that oxygen consumption is mainly taking place at the sediment surface and not on the chamber walls or at the top of the jar.

Table 18 - The effect of gentle mechanical mixing on the vertical oxygen gradient in the incubators. The gradients in question resulted from 24 hours of closure.

	Stagnant chambers		Mixed chambers		Stagnant chambers,
Depth /cm	O_2 /mg·l^{-1}	O_2 /mg·l^{-1}	O_2 /mg/l^{-1}	O_2 /mg·l^{-1}	mean temp./°C
0.9	9.96	10.35	8.61	8.13	5.66
2.4	9.48	7.50	8.27	8.10	5.66
3.6	5.74	6.80	--	--	5.66
Mean	8.39	8.22	8.44	8.12	

All the SOC measurements were made after 24 hours of incubation because the preliminary results in table 18 showed that a measurable change of O_2 concentration occurs without anoxia near the sediments. The results in table 19 show no consistent decreasing trend over 81 days as would have been seen if the resuspended sediments had not equilibrated or if organic matter available for respiration were decreasing. The considerable variability from day to day can be attributed in large part to variations of oxygen consumption in the controls (fig. 15).

Table 19 - Mean sediment oxygen consumption rates for Dolly and Elizabeth lakes as a function of equilibration time. All values are in $mg \cdot m^{-2} \cdot day^{-1}$ ± standard deviation. Negative rates excluded from calculations. Raw data in Appendix E.

Equilibration time /days	SOC /$mg \cdot m^{-2} \cdot day^{-1}$ Dolly	Elizabeth
8	143.89±19.91	160.37±34.96
15	193.43±23.09	184.80±61.77
66	----	48.22±43.88
76	84.63±17.90	97.54±40.29
81	211.73±17.16	188.43±13.87

This poses an interesting question. Since there is no reason to assume that the real SOC would have varied erratically for 6 to 81 days, it is reasonable to assume that sediment respiration was constant and that the entire range of values observed by the experiments was generated by artefacts in the measurement of control respiration. If the controls are ignored, the mean SOC

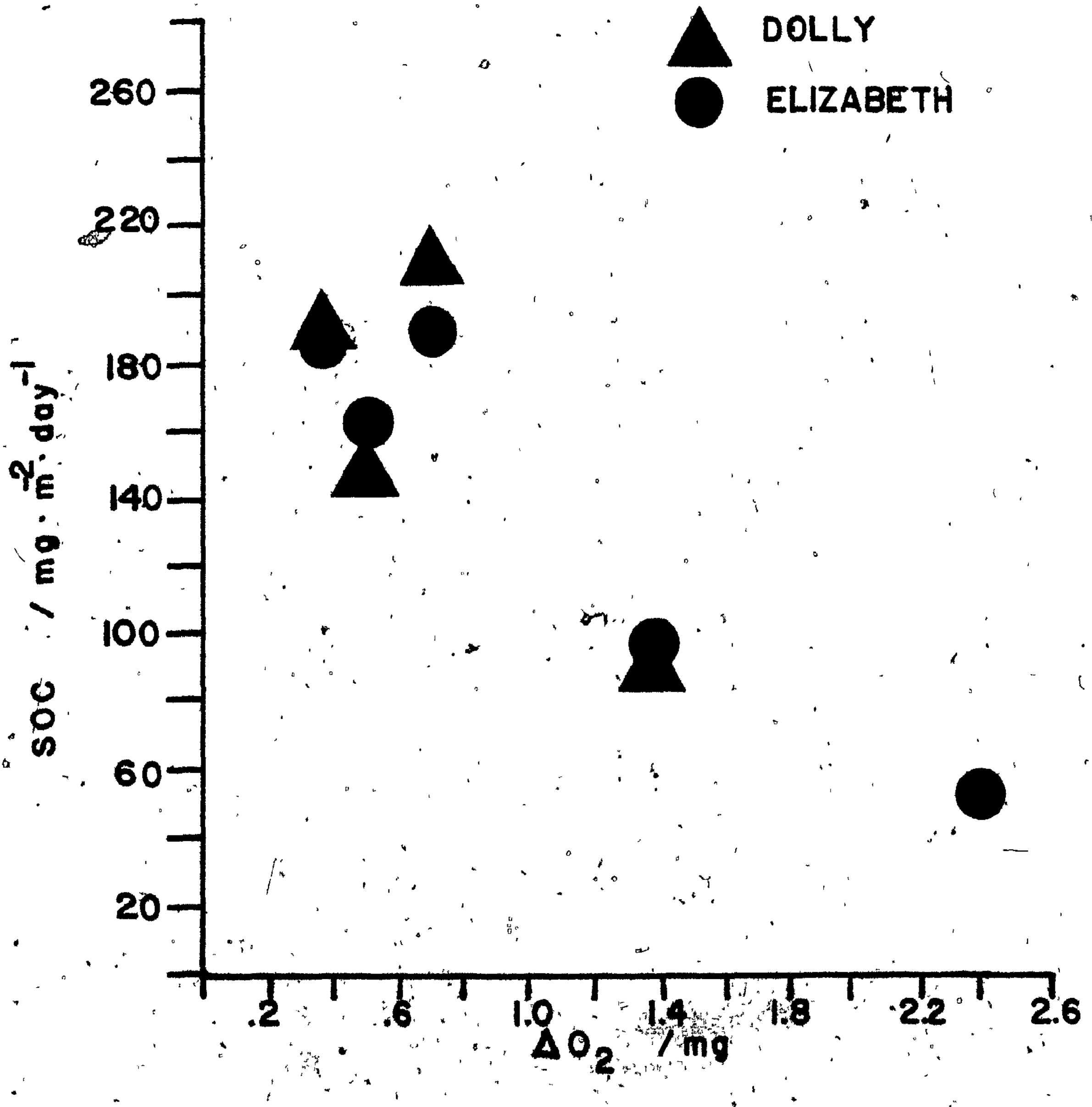


Fig. 15 - Variation of SOC measurements as a function of respiration in the control bottles: Montreal experiments.

for Dolly is 189.30 $mg \cdot m^{-2} \cdot day^{-1}$ and the one for Elizabeth is 191.53 $mg \cdot m^{-2} \cdot day^{-1}$. Since the Dolly value is much higher than the observed AWOD, it seems reasonable to expect that some control value must be subtracted. My results suggest that designing appropriate control chambers may be one of the most important remaining problems if we are to obtain meaningful laboratory measurements of SOC. In my experiments, I took precautions to ensure that the same water was used in control and experimental chambers. Volume of water overlying the sediments was almost the same within a set of replicates from the same lake. The effects of surface to volume ratios on water respiration has not been studied systematically in the pertinent literature. I believe that this is a general problem in all the attempts to measure SOC.

For the purpose of further discussion, I will merely take an average of calculated respiration rates while bearing in mind that the real SOC's in my incubators could have been ± 100% of the average.

Comparison of direct and indirect measurements

Table 20 compares sediment respiration rates estimated directly and indirectly. Although the direct measurements do not consistently agree with the whole-lake rates and Hargrave's (1969a) predictions, even the highest values in Appendices D and E lie within the range of results reported in the literature (Tables 21 and 22). We are still uncertain about the validity of our measurements

Table 20 - Direct and indirect estimates of sediment oxygen consumption in Dolly and Elizabeth lakes, Winter 1978/79.

Type of Estimate	Sediment oxygen consumption $/mg\cdot m^{-2}\cdot day^{-1}$	
	DOLLY	ELIZABETH
Indirect: AWOD	97.49	204.08
Predicted from Hargrave (1969a)*	79.79	47.96
Direct: Schefferville results**	94.75	102.39
Direct: Montreal results‡	158.42	135.88

* $\ln(SOC) = 1.74 \ln(\text{temperature}) - 1.30, r^2$; prediction in $ml\cdot m^{-2}\cdot hr^{-1}$ converted to $mg\cdot m^{-2}\cdot day^{-1}$.

** Overall mean of values in tables 16 and 17.

‡ Overall mean of values in table 19.

of SOC. Predicting SOC remains out of our grasp because numerous methodological problems remain to be solved. The best guess that can be made is that sediment oxygen uptake represents between 50% and 100% of the AWOD in my lakes.

Table 21- Oxygen uptake of various freshwater benthic environments measured directly in situ or in the laboratory.

Type of environment	Oxygen uptake rate /mg $O_2 \cdot m^{-2} \cdot day^{-1}$	Source
Lakes and ponds in Eastern Canada	149-1063	Hayes and MacAulay 1959
English rivers	720-2400 (unpolluted) 1440-3120 (polluted)	Edwards and Rolley 1965
Sludge from paper mill effluent	216-3312	Hanes and Irvine 1966
English rivers	144-9840	Rolley and Owens 1967
Sludge from paper mill effluent	200-800 (stagnant) 2700-4400 (scoured)	McKeown et al.. 1968
Marion Lake, British Columbia	134-336	Hargrave 1969b
Spring Creek, Penna. (hypereutrophic)	1440 ("typical rate")	McDonnell and Hall 1969
French oligotrophic ponds	80-360	Bertru 1971
Bay of Quinte and Lake Ontario	150-350	Johnson and Brinkhurst 1971
Lake Esrom, Denmark (eutrophic)	171-1371	Hargrave 1972
Swedish lakes and running waters	300-3000 (in situ) 310-1500 (in the laboratory)	Edberg and Hofsten 1973
Lake Washington	450-1270	Pamatmat and Bhagwat 1973
English lakes and running waters	1680-27120	James 1974
High Arctic lake (Char lake, Cornwallis Is.)	114	Welch and Kalff 1974
Swedish lakes	170-600	Edberg 1976
Lake Hartwell, S. Carolina (impoundment)	308-985	Brewer et al, 1977
South Swedish lakes	380-800	Granéli 1977
Shagawa Lake, Minn. (entrophic)	170	Sonzogni et al.. 1977
South Swedish lakes	180-450	Granéli 1978
South Swedish lakes (eutrophic)	143-388 (no animals added)	Granéli 1979
Lake Myvatn, Iceland	394-2690	Hunding 1979

Table 22 – Oxygen uptake of various marine benthic environments measured directly in situ or in the laboratory.

Type of Environment	Oxygen uptake rate $/\mathrm{mg}\ O_2 \cdot m^{-2} \cdot \mathrm{day}^{-1}$	Source
Intertidal sandflat, False Bay, B.C.	309	Pamatmat 1968*
Puget Sound	137-1371	Pamatmat and Banse 1969
Tidal flats, Yaquina Estuary, Oregon	1400-2100 (landward site)	Crook and Bella 1970
	4800-8500 (seaward site)	
Yaquina Estuary, Oregon	1250-3920	Martin and Bella 1971
Puget Sound	175-288	Pamatmat 1971a
North-East Pacific	51-281	" "
East tropical Pacific	21-487	" "
Puget Sound	137-1920	" 1971b
Castle Harbor, Bermuda	655-926	Smith et al. 1972
North-East Pacific coast	31-247	Pamatmat 1973

* Contains a synoptic table similar to this one for the literature before 1966.

CONCLUSION

This project has attempted to examine the process of oxygen consumption in lakes from the two complementary approaches of holism and reductionism.

I can conclude from the results outlined and discussed that the empirical models for predicting whole-lake oxygen consumption are unsuitable for the subarctic lakes that were studied. The first two questions asked at the end of the Introduction thus have negative answers. The third query about the relationship between trophic status during the summer and the subsequent winter oxygen consumption is supported by the data. But they are not abundant enough to allow a new predictive model to emerge.

The contribution of the sediments remain uncertain because of methodological problems associated with its measurement. Further progress on explanatory theory will depend on the development of methods capable of producing accurate estimates of sediment or water respiration.

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APPENDIX A

WHOLE-LAKE MEASUREMENTS

Table A1 - Morphometric data for Dolly Lake.

Stratum	Area at top $/10^5 m^2$	Volume $/10^5 m^3$	Fraction of total volume
0-1	10.530	10.026	0.117
1-2	9.530	9.078	0.106
2-3	8.635	8.290	0.096
3-4	7.950	7.498	0.087
4-5	7.055	6.763	0.079
5-6	6.476	6.238	0.073
6-7	6.002	5.737	0.067
7-8	5.476	5.210	0.061
8-9	4.949	4.683	0.054
9-10	4.423	4.130	0.048
10-11	3.843	3.631	0.042
11-12	3.422	3.263	0.038
12-13	3.106	2.893	0.034
13-14	2.685	2.499	0.029
14-15	2.317	2.075	0.024
15-16	1.843	1.682	0.020
16-17	1.527	1.338	0.016
17-18	1.158	0.968	0.011
	TOTAL	86.002	

Table A2 - Morphometric data for Elizabeth Lake.

Stratum	Area at top $/10^5 m^2$	Volume $/10^5 m^3$	Fraction of total volume*	Fraction of hypolimnetic volume**
0-1	2.806	2.679	0.137	---
1-2	2.553	2.390	0.122	---
2-3	2.231	2.096	0.107	---
3-4	1.964	1.844	0.094	---
4-5	1.726	1.634	0.084	---
5-6	1.543	1.437	0.074	---
6-7	1.333	1.241	0.064	---
7-8	1.150	1.065	0.055	---
8-9	0.982	0.904	0.046	---
9-10	0.828	0.771	0.039	---
10-11	0.716	0.659	0.034	---
11-12	0.603	0.561	0.029	---
12-13	0.519	0.469	0.024	---
13-14	0.421	0.385	0.020	---
14-15	0.351	0.322	0.016	0.224
15-16	0.295	0.266	0.014	0.185
16-17	0.239	0.217	0.011	0.151
17-18	0.196	0.175	0.009	0.122
18-19	0.154	0.133	0.007	0.093
19-20	0.112	0.098	0.005	0.068
20-21	0.084	0.077	0.004	0.054
21-22	0.070	0.063	0.003	0.044
22-23	0.056	0.049	0.003	0.034
	TOTAL	19.535		
23-24	0.042	0.035		0.024
	TOTAL	19.570		

* Excluding 23-24 m stratum.

** Total volume = $1.435 \times 10^5 m^3$. Hypolimnion considered to be below 14 m.

Table A3 - Dolly Lake temperatures, Summer 1978.

/°C

Depth /m	27/06/78	4/07/78	11/07/78	18/07/78	25/07/78	1/08/78	8/08/78	15/08/78
0	0.10	8.00	10.60	11.20	12.10	12.20	11.70	12.60
1	1.80	8.00	10.60	11.00	12.20	12.20	11.70	12.80
2	1.60	7.90	10.70	11.00	12.30	12.20	11.70	12.80
3	1.60	7.90	10.40	11.00	12.50	12.20	11.70	12.80
4	1.70	7.90	10.20	11.00	12.50	12.20	11.70	12.60
5	1.70	7.80	10.10	10.90	12.50	12.20	11.70	12.60
6	1.70	7.80	9.90	10.80	12.40	12.20	11.70	12.60
7	1.70	7.80	9.60	10.80	12.20	12.10	11.70	13.00
8	1.70	7.80	9.30	10.70	12.20	12.10	11.70	12.80
9	1.70	7.40	9.10	10.70	12.10	12.10	11.70	12.80
10	1.70	7.30	8.90	10.50	12.10	12.00	11.70	12.80
11	1.80	7.20	8.70	10.00	12.00	12.00	11.70	12.60
12	1.80	7.20	8.30	9.60	11.70	12.00	11.70	12.60
13	1.80	7.10	8.20	9.10	11.40	12.00	11.70	12.60
14	1.90	7.00	8.10	9.00	10.90	11.80	11.70	12.60
15	2.00	7.00	8.00	8.30	10.60	11.60	11.70	12.60
16	2.00	7.00	8.00	8.50	10.20	11.50	11.60	12.60
17	2.20	6.90	7.90	8.20	10.00	11.40	11.40	12.50
18	2.50	6.80	7.80	8.00	9.90	11.20	11.20	12.50

/....Cont'd

Table A3 - (cont'd) Dolly Lake temperatures, Summer 1978.

/°C

Depth /m	22/08/78	29/08/78	5/09/78	12/09/78	19/09/78	3/10/78	10/10/78
0	11.83	10.51	9.94	9.39	7.11	3.97	3.49
1	11.83	10.48	9.99	9.40	7.10	4.00	3.51
2	11.84	10.48	10.01	9.40	7.08	3.97	3.52
3	11.84	10.48	10.02	9.38	7.07	3.99	3.52
4	11.85	10.49	10.02	9.37	7.08	4.02	3.51
5	11.85	10.49	10.02	9.39	7.08	4.01	3.55
6	11.85	10.49	10.02	9.38	7.08	4.02	3.57
7	11.86	10.49	10.02	9.38	7.08	4.02	3.58
8	11.87	10.49	10.02	9.38	7.07	4.02	3.58
9	11.87	10.49	10.01	9.37	7.07	4.02	3.57
10	11.87	10.49	10.00	9.37	7.04	4.01	3.57
11	11.87	10.48	10.00	9.37	7.04	4.02	3.58
12	11.89	10.48	10.01	9.41	7.07	4.03	3.62
13	11.88	10.48	10.01	9.40	7.06	4.02	3.63
14	11.88	10.48	10.01	9.41	7.06	4.02	3.65
15	11.88	10.48	10.01	9.40	7.04	4.02	3.67
16	11.88	10.48	9.99	9.39	7.04	4.08	3.66
17	11.88	10.48	9.97	9.39	7.04	4.06	3.66
18	11.88	10.45	9.97	9.39	7.03	4.09	3.65

Table A4 - Elizabeth Lake temperature, Summer 1978.

/°C

Depth /m	30/06/78	7/07/78	14/07/78	21/07/78	28/07/78	11/08/78	18/08/78	25/08/78
0	7.27	7.6	10.3	12.0	12.0	10.8	10.65	9.15
1	7.01	7.4	10.6	12.1	12.0	11.3	10.70	9.20
2	6.97	7.2	10.6	12.0	11.9	11.5	10.73	9.28
3	6.93	7.0	10.4	11.8	11.9	11.0	10.80	9.30
4	6.90	7.0	10.3	11.7	11.9	11.0	11.12	9.30
5	6.51	7.0	10.0	11.6	11.6	11.0	11.26	9.30
6	5.92	7.0	10.0	11.0	11.3	11.0	11.25	9.30
7	5.40	6.8	7.3	10.0	9.7	11.0	11.19	9.30
8	4.99	6.3	6.9	7.4	8.3	11.0	11.13	9.30
9	4.90	6.2	6.7	6.6	6.9	10.8	11.02	9.29
10	4.81	5.8	6.1	6.0	6.0	10.0	10.95	9.29
11	4.73	5.3	5.8	5.6	5.5	8.2	10.74	9.27
12	4.70	4.8	5.1	5.3	5.1	6.9	8.52	9.16
13	4.67	4.5	5.1	5.0	4.9	6.2	6.46	8.49
14	4.59	4.2	4.7	4.9	4.8	6.0	5.91	5.98
15	4.59	4.0	4.7	4.8	4.5	5.8	5.71	5.59
16	4.59	4.0	4.4	4.6	4.4	5.8	5.58	5.23
17	4.58	4.0	4.4	4.4	4.3	5.6	5.48	5.20
18	4.62	4.0	4.4	4.2	4.2	5.6	5.41	5.15
19	4.56	4.0	4.4	4.2	4.2	5.6	5.36	5.10
20	4.55	4.0	4.1	4.2	4.2	5.6	5.33	5.07
21	4.57	3.9	4.1	4.2	4.2	5.6	5.31	5.06
22	4.55	3.9	4.1	4.2	4.2	5.6	5.37	5.03
23	4.55	4.0	4.1	4.2	4.2	5.5	5.09	5.02
24	4.55	3.9	4.0	4.2	4.2	5.5	----	4.98

/....cont'd.

Table A4- (cont'd.) Elizabeth Lake temperature, Summer 1978.

/°C

Depth /m	1/09/78	8/09/78	15/09/78	22/09/78	29/09/78	6/10/78	13/10/78
0	8.91	8.39	7.41	5.63	4.29	3.48	3.09
1	8.90	8.38	7.43	5.61	4.33	3.37	3.06
2	8.89	8.37	7.43	5.62	4.34	3.33	3.06
3	8.88	8.36	7.43	5.61	4.34	3.31	3.05
4	8.88	8.35	7.43	5.61	4.35	3.30	3.05
5	8.88	8.34	7.45	5.61	4.35	3.30	3.05
6	8.88	8.34	7.45	5.61	4.35	3.30	3.05
7	8.88	8.34	7.47	5.61	4.35	3.30	3.05
8	8.87	8.34	7.46	5.61	4.36	3.30	3.05
9	8.87	8.33	7.46	5.61	4.35	3.30	3.05
10	8.85	8.30	7.46	5.61	4.36	3.29	3.05
11	8.80	8.29	7.47	5.61	4.37	3.30	3.08
12	8.76	8.25	7.46	5.62	4.38	3.33	3.08
13	8.48	8.19	7.46	5.62	4.37	3.33	3.08
14	8.20	8.09	7.43	5.62	4.39	3.33	3.08
15	7.28	8.00	7.41	5.62	4.38	3.33	3.08
16	5.81	7.92	7.40	5.62	4.37	3.33	3.08
17	5.36	6.51	7.38	5.62	4.37	3.33	3.08
18	5.24	5.55	7.34	5.61	4.36	3.33	3.08
19	5.14	5.07	7.16	5.61	4.37	3.33	3.08
20	5.05	5.02	5.47	5.61	4.38	3.33	3.09
21	5.01	5.00	5.15	5.61	4.38	3.33	3.08
22	4.99	4.99	5.06	5.61	4.38	3.33	3.07
23	4.97	----	5.05	5.59	4.38	3.33	3.08
24	4.97	----	5.05	5.59	4.38	3.33	3.08

Table A5 - Dolly Lake temperature, Winter 1978/79.

/°C

Depth /m	24/10/78	31/10/78	7/11/78	14/11/78	21/11/78	28/11/78	5/12/78	19/12/78
0	0.42	0.14	0.38	-0.03	0.20	0.12	0.24	0.01
1	2.19	2.09	1.67	1.86	2.24	1.64	0.99	0.64
2	2.31	2.53	2.26	2.56	2.37	2.33	1.84	2.01
3	2.37	2.54	2.38	2.62	2.62	2.59	2.61	2.50
4	2.39	2.55	2.44	2.64	2.69	2.67	2.70	2.63
5	2.41	2.56	2.48	2.66	2.71	2.71	2.75	2.66
6	2.43	2.57	2.53	2.70	2.74	2.74	2.79	2.74
7	2.48	2.59	2.60	2.73	2.78	2.78	2.83	2.82
8	2.51	2.61	2.68	2.75	2.81	2.82	2.86	2.84
9	2.54	2.63	2.73	2.77	2.84	2.85	2.88	2.88
10	2.56	2.65	2.76	2.80	2.86	2.88	2.91	2.92
11	2.57	2.67	2.78	2.83	2.90	2.88	2.93	2.96
12	2.62	2.74	2.87	2.90	2.95	2.99	2.98	2.99
13	2.63	2.77	2.91	2.94	3.00	3.02	3.07	2.99
14	2.64	2.80	2.94	2.96	3.04	3.06	3.12	3.00
15	2.66	2.82	2.98	3.01	3.11	3.11	3.16	3.03
16	2.70	2.87	3.02	3.07	3.16	3.21	3.29	3.06
17	2.75	2.95	3.10	3.23	3.34	3.40	3.53	3.22
18	2.82	3.06	3.21	3.36	3.43	3.47	3.57	3.45

/....cont'd.

Table A5 -(cont'd.) Dolly Lake temperature, Winter 1978/79.

/°C

Depth /m	18/01/79	2/02/79	22/02/79	20/03/79	9/04/79	3/05/79	17/05/79
0	0.01	0.01	0.51	1.04	1.48	0.50	0.93
1	0.06	0.06	0.27	0.29	0.46	0.43	0.78
2	1.37	1.50	1.58	1.41	1.11	1.49	1.72
3	2.11	2.44	2.42	2.22	1.99	2.11	2.14
4	2.33	2.64	2.75	2.64	2.51	2.64	2.54
5	2.56	2.70	2.80	2.84	2.77	2.80	2.98
6	2.70	2.80	2.86	2.92	2.90	2.94	3.11
7	2.71	2.85	2.90	2.96	2.98	3.03	3.14
8	2.78	2.90	2.95	3.01	3.02	3.07	3.17
9	2.93	2.95	2.98	3.06	3.04	3.09	3.20
10	2.99	2.99	3.02	3.08	3.08	3.14	3.22
11	3.01	3.01	3.06	3.12	3.11	3.17	3.25
12	3.04	3.04	3.09	3.16	3.15	3.22	3.30
13	3.08	3.09	3.15	3.21	3.21	3.29	3.35
14	3.15	3.15	3.22	3.30	3.29	3.37	3.44
15	3.15	3.23	3.33	3.42	3.38	3.48	3.53
16	3.36	3.37	3.46	3.52	3.58	3.61	3.63
17	3.59	3.55	3.54	3.71	3.68	3.72	3.77
18	3.61	3.66	3.74	3.77	3.85	3.82	3.79

Table A6 - Elizabeth Lake temperatures, Winter 1978/79.

/°C

Depth /m	27/10/78	3/11/78	10/11/78	17/11/78	24/11/78	15/12/79	6/01/79
0	0.88	0.09	0.11	0.27	0.05	0.05	----
1	1.88	1.26	1.46	1.08	1.12	1.05	0.09
2	2.01	1.98	1.93	1.84	1.99	1.65	0.83
3	2.04	2.09	2.04	2.11	2.15	1.90	1.78
4	2.05	2.13	2.08	2.22	2.21	2.14	2.16
5	2.05	2.17	2.15	2.24	2.23	2.16	2.21
6	2.07	2.22	2.19	2.27	2.26	2.18	2.25
7	2.08	2.24	2.21	2.29	2.27	2.24	2.28
8	2.10	2.25	2.24	2.30	2.29	2.26	2.29
9	2.11	2.26	2.25	2.31	2.31	2.29	2.32
10	2.12	2.27	2.27	2.33	2.32	2.30	2.31
11	2.14	2.28	2.28	2.35	2.34	2.32	2.28
12	2.16	2.32	2.32	2.38	2.37	2.33	2.34
13	2.18	2.35	2.35	2.42	2.41	2.35	2.36
14	2.19	2.36	2.36	2.43	2.42	2.38	2.40
15	2.22	2.37	2.38	2.45	2.44	2.41	2.42
16	2.23	2.38	2.39	2.47	2.45	2.44	2.46
17	2.25	2.41	2.41	2.49	2.47	2.46	2.48
18	2.27	2.43	2.43	2.51	2.49	2.48	2.51
19	2.29	2.44	2.44	2.54	2.52	2.48	2.53
20	2.30	2.45	2.46	2.55	2.53	2.49	2.53
21	2.31	2.46	2.47	2.56	2.53	2.50	2.54
22	2.32	2.47	2.48	2.57	2.54	2.54	2.57
23	2.34	2.49	2.52	2.59	2.63	----	----

/....Cont'd.

Table A6 - (cont'd.) Elizabeth Lake temperatures, Winter 1978/79.

/°C

Depth /m	26/01/79	28/02/79	29/03/79	18/04/79	13/05/79	31/05/79
0	0.08	0.02	0.15	1.00	0.33	1.91
1	0.28	0.07	0.07	0.29	0.26	4.15
2	1.30	0.64	0.74	0.62	0.94	3.25
3	1.95	1.86	1.61	1.22	1.30	3.08
4	2.10	2.10	2.05	1.83	1.74	3.02
5	2.21	2.23	2.19	2.21	2.09	2.98
6	2.24	2.29	2.30	2.30	2.33	2.96
7	2.28	2.33	2.33	2.35	2.43	2.96
8	2.32	2.35	2.35	2.37	2.46	2.96
9	2.34	2.37	2.38	2.38	2.47	2.95
10	2.35	2.37	2.38	2.39	2.48	2.94
11	2.36	2.38	2.39	2.40	2.49	2.94
12	2.37	2.38	2.43	2.42	2.51	2.92
13	2.39	2.41	2.46	2.44	2.53	2.92
14	2.41	2.43	2.48	2.49	2.54	2.82
15	2.45	2.48	2.51	2.52	2.56	2.71
16	2.48	2.51	2.55	2.57	2.58	2.66
17	2.50	2.55	2.58	2.59	2.61	2.67
18	2.54	2.58	2.60	2.61	2.63	2.68
19	2.55	2.58	2.62	2.62	2.64	2.65
20	2.56	2.59	2.64	2.63	2.64	2.66
21	2.58	2.61	2.65	2.64	2.65	2.67
22	2.59	2.61	2.66	2.68	2.66	2.68
23	2.63	2.64	2.71	2.70	2.70	2.70

Table A7 - Dolly Lake dissolved oxygen, Summer 1978.

/mg·l^{-1}

Depth /m	27/06/78	4/07/78	11/07/78	18/07/78	25/07/78	1/08/78	8/08/78
0	12.00	11.25	10.87	10.30	10.33	10.03	9.91
1	12.00	11.31	10.75	10.42	10.32	10.02	9.90
2	12.00	11.31	10.87	10.47	10.19	10.03	9.94
3	12.01	11.31	10.99	10.43	10.30	10.02	9.94
4	12.02	11.31	11.00	10.45	10.36	9.99	9.90
5	12.04	11.28	11.03	10.43	10.36	9.99	9.91
6	12.05	11.31	11.04	10.44	10.14	10.06	9.91
7	12.05	11.38	11.07	10.43	10.24	10.07	9.92
8	12.04	11.40	11.10	10.47	10.33	10.09	9.93
9	12.04	11.52	11.10	10.47	10.29	10.03	9.99
10	12.03	11.55	11.15	10.46	10.25	10.00	9.96
11	12.09	11.48	11.32	10.61	10.42	10.03	10.07
12	12.14	11.58	11.35	10.60	10.30	10.09	10.07
13	12.11	11.62	11.29	10.78	10.43	10.07	10.09
14	12.07	11.47	11.32	10.88	10.65	10.06	9.96
15	12.10	11.57	11.30	11.01	10.66	10.07	9.99
16	12.11	11.56	11.33	11.05	10.58	10.00	9.92
17	12.13	11.59	11.30	11.06	10.84	10.08	9.94
18	12.14	11.74	11.28	11.09	10.88	10.18	9.92
19	----	11.70	11.26	11.07	10.78	10.20	9.91

/....Cont'd.

Table A7 - (cont'd.) Dolly Lake dissolved oxygen, Summer 1978.

/mg·l^{-1}

Depth /m	15/08/78	22/08/78	29/08/78	5/09/78	3/10/78	10/10/78
0	10.15	10.50	10.66	10.71	12.26	12.28
1	10.19	10.38	10.66	10.90	12.26	13.00
2	10.14	10.27	10.69	10.66	12.21	13.59
3	10.13	10.31	10.61	10.60	12.37	13.43
4	10.20	10.22	10.60	10.84	12.30	13.48
5	10.15	10.31	10.63	10.80	12.31	13.24
6	10.13	10.51	10.61	10.82	12.31	12.98
7	10.15	10.12	10.71	10.82	12.21	13.26
8	10.23	10.22	10.76	10.69	12.32	13.27
9	10.26	10.34	10.56	10.81	12.25	13.28
10	10.23	10.35	10.65	10.78	12.35	13.17
11	10.21	10.42	10.68	10.84	12.43	13.23
12	10.30	10.21	10.53	10.78	12.31	13.17
13	10.21	10.24	10.71	10.74	12.16	13.09
14	10.15	10.27	10.67	10.69	12.16	13.03
15	10.19	10.43	10.63	10.75	12.16	12.96
16	10.19	10.29	10.62	10.72	12.16	13.08
17	10.18	10.44	10.66	10.77	12.14	13.20
18	10.06	10.32	10.64	10.81	12.24	12.73
19	10.08	10.15	10.36	10.77	12.21	12.68

Table A8 - Elizabeth Lake dissolved oxygen, Summer 1978.

/mg·l^{-1}

Depth /m	30/06/78	7/07/78	14/07/78	21/07/78	28/07/78	4/08/78	11/08/78
0	12.10	11.71	10.76	10.46	10.68	10.96	10.85
1	12.10	11.38	10.86	10.42	10.59	10.96	10.82
2	12.10	11.58	10.96	10.47	10.46	10.91	10.98
3	12.10	11.68	11.02	10.43	10.43	11.00	10.67
4	12.10	11.76	10.78	10.56	10.52	11.07	10.79
5	12.10	11.84	10.81	10.63	10.59	10.97	10.71
6	12.10	11.64	10.91	10.95	10.75	11.00	10.65
7	12.14	11.87	10.97	11.08	10.85	11.10	10.65
8	12.18	11.84	11.71	11.92	11.51	11.08	10.77
9	11.99	11.99	11.77	11.90	11.71	11.03	10.83
10	11.82	11.80	11.54	11.37	11.22	11.03	10.75
11	11.92	11.76	11.25	10.90	11.18	10.86	10.47
12	12.04	11.62	11.27	10.51	10.87	10.55	9.84
13	11.98	11.52	11.07	10.28	10.50	10.11	9.18
14	11.91	11.34	10.66	9.86	9.88	9.41	9.11
15	11.94	11.19	10.26	9.84	9.46	8.54	8.10
16	11.98	11.23	10.18	9.71	9.07	7.98	7.59
17	11.90	11.04	10.17	9.50	9.06	7.68	7.28
18	11.83	11.00	10.16	9.42	8.81	7.45	7.12
19	11.78	11.01	9.98	9.27	8.64	7.41	6.77
20	11.74	10.97	10.08	9.07	8.34	7.37	6.69
21	11.75	10.71	10.12	9.06	8.22	7.31	6.49
22	11.77	10.76	10.05	9.06	8.18	7.19	6.29
23	11.77	10.62	10.00	9.02	8.12	7.15	6.01
24	11.77	10.55	9.92	8.95	8.14	6.95	5.71

/....cont'd.

Table A8 - (cont'd.) Elizabeth Lake dissolved oxygen, Summer 1978.

/mg·l^{-1}

Depth /m	18/08/78	25/08/78	1/09/78	29/09/78	6/10/78	13/10/78
0	10.85	11.25	11.34	11.89	12.20	12.22
1	10.91	11.06	11.24	11.78	12.29	12.57
2	10.91	11.24	10.94	11.68	12.40	12.48
3	10.90	11.54	11.44	11.97	12.23	12.48
4	10.82	11.25	11.28	11.75	12.43	12.47
5	10.94	11.23	11.31	11.96	12.34	12.49
6	10.72	11.44	11.21	12.06	12.30	12.58
7	10.60	11.18	11.37	11.93	12.12	12.47
8	10.66	11.27	11.26	11.86	12.40	12.53
9	10.90	11.17	11.17	11.90	12.19	12.47
10	10.68	11.13	11.13	12.01	12.27	12.58
11	10.61	11.40	11.14	11.93	12.33	12.47
12	10.21	11.11	11.16	11.79	12.32	12.45
13	9.39	9.27	10.76	11.84	12.22	12.52
14	7.99	7.89	10.42	11.99	12.20	12.52
15	7.74	7.56	10.03	11.93	12.33	12.56
16	7.01	6.61	8.03	11.89	12.33	12.45
17	6.34	6.14	5.65	11.84	12.28	12.60
18	6.01	5.99	5.25	11.86	12.10	12.59
19	5.94	5.82	4.31	11.85	12.20	12.41
20	5.78	5.47	4.08	11.65	12.40	12.35
21	5.46	5.02	3.51	11.70	12.22	12.51
22	5.16	4.14	3.09	11.72	12.22	12.51
23	4.90	3.57	2.87	11.76	12.26	12.52
24	4.72	3.21	2.86	11.78	12.15	12.52

Table A9 - Dolly Lake dissolved oxygen, Winter 1978/79.

/mg·l^{-1}

Depth /m	24/10/78	31/10/78	7/11/78	14/11/78	21/11/78	28/11/78	5/12/78	19/12/78
0	12.99	14.15	13.66	14.32	13.56	14.45	14.28	14.57
1	12.85	13.45	13.14	13.15	13.52	13.64	13.68	13.85
2	12.66	13.06	12.90	13.09	13.06	13.22	13.27	13.16
3	12.79	13.11	12.86	12.97	13.00	13.10	13.24	13.08
4	12.54	13.16	12.78	12.84	12.88	12.94	13.16	13.00
5	12.79	13.13	12.73	12.82	12.85	12.86	12.99	12.94
6	12.52	13.10	12.70	12.76	12.81	12.79	12.82	12.94
7	12.70	13.02	12.68	12.73	12.76	12.71	12.77	12.94
8	12.61	13.15	12.65	12.71	12.73	12.64	12.66	12.72
9	12.52	13.12	12.70	12.66	12.71	12.63	12.53	12.70
10	12.33	13.08	12.69	12.56	12.48	12.60	12.52	12.49
11	12.98	12.99	12.71	12.58	12.48	12.58	12.51	12.35
12	12.91	13.17	12.70	12.53	12.72	12.55	12.50	12.29
13	12.85	13.16	12.68	12.49	12.66	12.38	12.49	12.23
14	12.79	12.92	12.66	12.42	12.52	12.25	12.40	11.81
15	12.73	12.98	12.51	12.32	12.29	12.14	12.02	11.39
16	12.66	12.90	12.37	12.07	11.97	11.89	11.64	11.34
17	12.50	12.91	12.07	11.85	11.43	10.85	10.68	10.58
18	12.33	12.55	11.79	10.60	10.93	10.75	9.76	9.78

/....cont'd.

Table A9 - (cont'd.) Dolly Lake dissolved oxygen, Winter 1978/79.

/mg·l^{-1}

Depth /m	18/01/79	2/02/79	22/02/79	20/03/79	9/04/79	3/05/79	17/05/79
0	13.49	13.56	13.59	13.45	13.40	13.34	12.70
1	13.27	13.59	13.59	13.39	13.40	13.19	12.86
2	13.29	13.29	13.05	13.04	13.07	12.61	12.26
3	13.31	12.85	12.75	12.87	12.62	12.40	12.19
4	13.22	12.87	12.75	12.71	12.58	12.34	12.17
5	13.13	12.82	12.68	12.66	12.49	12.28	12.15
6	12.97	12.78	12.63	12.62	12.25	12.34	12.07
7	12.82	12.72	12.58	12.53	12.16	12.29	11.95
8	12.67	12.56	12.54	12.45	12.17	11.73	11.79
9	12.52	12.41	12.47	12.38	11.78	11.39	11.32
10	12.49	12.18	12.39	12.09	11.41	10.54	10.96
11	12.43	12.14	11.88	11.81	11.41	10.41	10.73
12	12.37	12.12	11.81	11.59	11.38	10.14	10.28
13	12.31	12.04	11.72	10.66	10.92	9.73	10.12
14	12.26	11.51	11.24	9.72	10.35	8.58	9.21
15	11.73	10.71	10.49	8.52	8.80	8.40	8.47
16	9.49	10.50	9.37	8.50	8.78	7.85	7.42
17	9.16	8.58	8.42	7.96	7.96	7.15	7.29
18	8.43	8.55	8.49	7.95	7.18	6.63	7.21

Table A10- Elizabeth Lake dissolved oxygen, Winter 1978/79.

/mg·1^{-1}

Depth /m	27/10/78	3/11/78	10/11/78	17/11/78	24/11/78	15/12/78	6/01/79
0	15.09	14.38	14.32	14.55	15.07	14.27	13.74
1	13.97	13.88	14.64	13.76	14.04	13.73	13.21
2	13.57	12.91	14.05	13.25	13.13	13.29	12.79
3	13.04	12.79	13.63	12.70	12.72	12.16	12.51
4	13.00	12.75	13.20	12.55	12.20	12.26	12.07
5	12.95	12.69	12.56	12.26	12.01	11.94	12.24
6	12.91	12.66	12.57	12.19	11.82	11.62	12.46
7	12.81	12.56	12.63	12.00	11.64	11.26	10.52
8	12.76	12.53	12.44	11.89	11.47	11.15	10.47
9	12.69	12.15	12.38	11.78	11.38	10.79	10.42
10	12.70	12.04	12.33	11.77	11.21	10.54	10.38
11	12.56	11.85	12.28	11.62	11.05	10.32	10.34
12	12.64	11.86	12.06	11.50	10.98	10.18	10.29
13	12.60	11.87	11.85	11.22	10.76	10.04	9.24
14	12.57	11.89	11.71	11.19	10.60	9.99	8.57
15	12.07	11.78	11.58	11.10	10.51	8.90	7.84
16	11.75	11.75	11.35	11.02	10.33	8.59	7.15
17	11.74	11.12	10.96	10.20	9.70	7.82	6.43
18	11.50	10.52	10.56	9.75	9.11	7.81	5.73
19	11.48	10.14	10.33	9.13	8.85	7.29	5.04
20	11.19	10.08	9.79	8.68	8.24	7.25	4.33
21	11.16	9.84	9.69	8.25	8.22	6.05	3.63
22	10.65	9.33	9.62	7.84	7.35	3.65	2.90
23	10.60	8.34	7.99	5.51	5.79	3.65	2.90

/....Cont'd.

Table A10-(cont'd.) Elizabeth Lake dissolved oxygen, Winter 1978/79.

/mg.l^{-1}

Depth /m	26/01/79	28/02/79	29/03/79	18/04/79	13/05/79	31/05/79
0	13.99	14.26	12.06	10.78	12.97	8.51
1	13.83	12.68	11.77	10.84	11.66	12.23
2	13.69	12.14	11.64	11.37	11.59	9.94
3	13.55	11.27	11.18	11.06	11.06	9.71
4	13.09	11.19	11.00	10.80	10.70	9.65
5	11.32	10.83	10.27	10.42	9.97	9.64
6	11.28	10.58	9.83	10.08	9.70	9.53
7	10.74	10.32	9.15	9.06	9.64	9.51
8	10.12	9.52	8.81	8.24	8.82	9.43
9	9.81	9.03	8.56	8.20	8.59	9.38
10	9.62	8.69	8.39	7.61	8.46	9.41
11	9.43	8.36	8.23	7.62	8.19	9.47
12	9.25	8.31	8.15	7.52	7.70	9.49
13	9.08	7.97	7.43	7.36	7.65	9.27
14	8.35	7.64	7.06	6.13	7.24	9.27
15	7.61	7.07	6.97	4.53	7.09	6.74
16	6.85	5.76	4.20	3.97	4.33	5.06
17	6.04	5.05	4.17	2.67	2.43	2.96
18	5.26	4.71	4.14	2.16	2.19	2.30
19	4.46	3.51	3.58	1.78	1.65	1.89
20	3.66	2.59	2.61	1.39	1.67	1.55
21	2.86	1.88	2.34	1.19	1.56	1.22
22	2.79	1.47	1.05	1.09	1.22	0.83
23	2.33	1.11	0.82	0.54	1.22	0.49

Table A11 - Snow, ice and hydrostatic water level at the sampling station on Dolly Lake, Winter 1978/79.

Date	Time after freeze-up /days	Snow depth /cm	Total ice thickness /cm	White ice thickness /cm	Black ice thickness /cm	Hydrostatic water level /cm
24/10/78	10	7.0	7.2	0.0	7.2	+ 1.0
31/10/78	17	0.0	24.0	9.0	15.0	- 1.0
7/11/78	24	3.6	26.5	11.0	15.5	- 0.5
14/11/78	31	7.8	32.0	11.0	21.0	0.0
21/11/78	38	9.4	40.4	13.6	26.8	- 6.0
28/11/78	45	9.0	45.0	14.0	31.0	- 4.0
5/12/78	52	9.0	50.0	14.5	35.5	- 5.0
19/12/78	66	24.0	64.0	16.0a	51.0	- 0.5
18/01/79	96	30.0	74.2	14.0	60.2	+ 1.5
2/02/79	111	53.5	85.0	20.0	65.0	- 1.0
22/02/79	131	15.0	79.0	28.0	66.5a	- 5.0
20/03/79	157	11.0	101.0	33.0	68.0	0.0
9/04/79	177	55.0	120.0	26.0a	75.5a	+ 2.5
3/05/79	201	13.0	102.0	16.0	86.0	0.0
17/05/79	215	0.0	85.0	14.0	71.0	0.0

a) Estimated.

Table A12 - Snow, ice and hydrostatic water level at the sampling station on Elizabeth Lake, Winter 1978/79.

Date	Time after freeze up /days	Snow depth /cm	Total ice thickness /cm	White ice thickness /cm	Black ice thickness /cm	Hydrostatic water level /cm
27/10/78	13	8.2	13.2	0.0	13.2	+ 1.0
3/11/78	20	25.0	24.0	4.5	17.5	0.0
10/11/78	27	0.0	35.0	9.0	26.0	- 4.0
17/11/78	34	10.8	36.8	10.4	26.4	- 5.0
24/11/78	41	5.0	40.5	11.0	29.5	- 4.5
15/12/78	62	4.6	70.0	23.0	47.0	- 4.5
6/01/79	84	22.0	81.2	22.0	59.2	- 14.0
26/01/79	104	28.0	95.0	22.0	73.0	+ 1.0
28/02/79	137	13.5	121.0	47.0	74.0	- 10.0
29/03/79	166	44.0	137.0	42.0	95.0	0.0
18/04/79	186	55.5	131.0	45.0	86.0	+ 3.5
13/05/79	211	5.0	119.0	45.0	74.0	- 9.0
31/05/79	229	0.0	57.0	0.0	57.0	0.0

Table A13- Dolly Lake specific conductivities, Summer 1978.

/$\mu S \cdot cm^{-1}$ @ 25°C

Depth /m	27/06/78	4/07/78	11/07/78	18/07/78	25/07/78	1/08/78	8/08/78	15/08/78
0	85.5	91.5	91.1	95.5	98.9	92.0	93.7	94.6
1		97.6	91.1	99.9	98.9	96.7	95.0	98.5
2	87.7	96.1	91.8	84.0	98.9	92.3	92.3	98.8
3		97.9	92.9	91.3	100.9	92.3	91.0	98.5
4	90.0	101.2	92.0	98.6	100.2	95.3	93.0	101.2
5		98.9	94.6	97.4	100.2	95.3	93.7	102.6
6	86.7	99.4	91.8	93.8	99.5	93.9	96.3	97.7
7		101.6	92.5	95.0	99.5	92.5	93.7	95.5
8	87.2	102.4	89.7	97.4	97.7	98.9	95.0	92.9
9		102.2	95.3	---	98.3	93.9	89.7	93.6
10	95.3	98.4	86.9	106.1	100.2	93.9	93.7	95.0
11		99.3	93.9	95.0	99.9	96.7	92.3	107.2
12	88.9	99.9	91.8	97.4	98.9	93.9	93.7	94.2
13		98.5	91.1	97.7	100.2	95.3	93.0	99.9
14	90.3	96.5	91.8	96.5	99.5	96.7	96.3	95.9
15		101.1	95.3	91.6	98.9	100.9	89.7	96.7
16	87.8	100.8	95.7	97.7	98.6	95.3	92.3	91.4
17		101.3	91.8	98.9	100.9	95.3	93.7	94.6
18	90.3	100.1	96.7	96.5	100.2	96.7	92.3	91.4
19		98.9	95.3	101.3	100.2	98.1	95.0	100.5

/...cont'd.

Table A13-(cont'd.) Dolly Lake specific conductivities, Summer 1978.

/$\mu S \cdot cm^{-1}$ @ 25°C

Depth /m	22/08/78	28/08/78	5/09/78	12/09/78	19/09/78	3/10/78	10/10/78
0	98.8	95.0	99.7	103.7	102.6	109.4	113.2
1	98.5	90.1	99.4			110.4	113.4
2	100.7	93.5	101.3	100.5	100.8	109.3	113.2
3	102.8	92.7	99.7			111.6	113.2
4	103.0	91.5	99.7	97.3	100.5	111.6	114.9
5	104.4	92.1	97.9			109.4	112.6
6	103.0	92.6	100.0	99.9	101.2	111.2	113.2
7	102.3	92.5	100.0			113.3	116.6
8	101.6	92.7	101.3	100.8	102.2	107.5	112.4
9	103.0	92.8	100.0			109.1	113.6
10	104.0	92.7	98.7	107.3	101.5	110.2	114.6
11	102.6	89.1	97.4			110.0	114.9
12	102.0	93.3	97.4	97.7	102.2	111.6	116.1
13	104.0	95.1	101.3			110.2	116.1
14	103.3	92.6	100.3	97.1	100.6	109.0	115.1
15	104.0	91.1	95.0			107.8	114.6
16	103.3	91.1	101.1	101.2	135.8	109.0	114.6
17	102.0	93.0	97.3			108.5	115.9
18	103.3	92.5	100.3	101.7	115.8	110.4	114.6
19	102.6	91.6	100.5			110.1	114.9

Table A14- Elizabeth Lake specific conductivities, Summer 1978.

/$\mu S \cdot cm^{-1}$ @25°C

Depth /m	30/06/78	7/07/78	14/07/78	21/07/78	28/07/78	4/08/78	11/08/78	18/08/78
0	52.6	67.0	46.1	62.0	54.9	52.8	63.5	61.0
1		61.7	59.5	52.0	60.4	55.3	62.0	60.2
2	52.6	63.4	59.5	61.2	59.0	52.8	61.5	62.5
3		61.0	59.5	61.2	56.3	62.7	61.5	64.0
4	51.0	60.9	61.0	86.3	60.4	59.4	62.2	63.2
5		61.0	61.6	74.6	57.7	58.0	62.2	62.5
6	56.6	63.4	59.9	63.0	59.0	58.0	60.8	61.0
7		61.5	59.5	60.3	60.4	59.4	62.2	61.7
8	55.0	61.1	61.0	61.7	59.0	60.0	61.5	63.2
9		63.3	59.5	62.3	57.7	59.4	60.8	64.0
10	53.4	63.3	58.8	63.1	61.3	60.0	61.8	65.4
11		62.1	59.5	63.1	56.3	59.4	61.8	61.7
12	53.2	59.3	58.8	61.7	54.3	60.7	61.1	61.7
13		60.9	59.5	60.5	56.3	58.7	60.4	61.7
14	53.2	61.6	59.5	61.2	57.7	59.4	59.7	61.7
15		59.7	60.2	60.5	54.9	55.4	61.8	61.0
16	56.4	60.3	59.5	61.3	54.9	58.0	60.4	59.5
17		60.8	61.0	60.7	56.3	58.0	60.4	61.0
18	50.0	61.5	61.6	60.7	54.9	56.7	60.4	61.7
19		60.3	59.9	61.8	54.2	57.5	60.4	61.0
20	55.6	62.1	----	60.5	57.7	56.9	61.8	61.7
21		60.9	59.4	60.5	65.9	59.4	61.8	62.5
22	54.0	61.1	59.0	60.5	61.8	58.0	61.1	63.2
23		61.5	58.8	59.9	57.7	58.0	61.8	----
24	----	62.0	59.1	61.1	60.4	58.0	61.1	----

/....:Cont'd.

Table A14 (cont'd.) Elizabeth Lake specific conductivities, Summer 1978.

/μS·cm^{-1} @ 25°C

Depth /m	25/08/78	1/09/78	8/09/78	15/09/78	22/09/78	29/09/78	6/10/78	13/10/78
0	61.5	57.2	70.4	63.6	59.9	62.9	71.8	69.6
1	59.3	56.1				68.1	71.4	69.3
2	60.7	71.4	71.7	62.5	59.8	62.4	79.8	67.5
3	61.5	69.1				60.9	71.1	68.1
4	60.0	69.6	67.8	62.8	59.3	62.9	71.9	68.4
5	64.3	62.0				61.1	69.9	68.5
6	61.5	62.7	76.8	63.6	59.7	62.4	71.2	68.1
7	61.5	64.1				72.0	77.8	69.0
8	60.0	63.3	73.8	64.2	59.4	63.4	72.8	68.0
9	62.1	66.9				67.2	72.6	68.2
10	60.6	61.9	66.2	64.2	59.3	62.2	69.1	69.2
11	61.4	64.1				71.3	72.6	68.5
12	61.4	62.7	65.7	63.5	58.5	60.9	71.8	68.6
13	61.4	63.0				62.3	72.5	66.8
14	62.1	64.0	65.7	63.0	59.4	64.7	73.6	69.3
15	57.7	62.4				69.2	70.6	68.5
16	60.6	61.0	64.2	65.3	58.4	66.4	70.1	68.5
17	57.7	62.3				72.3	68.8	69.2
18	61.4	61.9	64.0	67.4	62.9	62.1	71.1	68.5
19	61.2	61.6				62.1	70.4	68.9
20	59.8	56.6	69.4	63.6	63.1	66.4	70.4	69.8
21	64.2	61.6				63.8	68.1	68.6
22	61.2	61.3	64.8	64.1	63.0	64.8	70.0	68.5
23	63.4	61.1				----	71.1	66.7
24	64.2	61.4	----	66.0	----	----	72.4	68.0

Table A15- Dolly Lake specific conductivities, Winter 1978/79.

/µS·cm^{-1} @ 25°C

Depth /m	24/10/78	31/10/78	7/11/78	21/11/78	28/11/78	5/12/78	19/12/78
0	108.6	85.8	101.9	108.1	111.2	106.8	109.8
1	98.7	100.9	104.5	105.0	111.2	103.6	83.8
2	101.9	100.3	99.9	106.4	110.9	107.7	104.4
3	90.5	99.9	102.2	104.8	107.4	100.2	104.4
4	93.1	99.4	106.3	106.6	106.8	104.3	109.8
5	100.1	106.7	----	104.2	110.0	107.2	103.0
6	101.9	95.6	106.9	102.9	108.0	102.5	103.0
7	102.6	99.6	109.9	104.2	114.3	101.1	103.0
8	100.9	100.0	106.9	106.2	106.1	101.1	100.9
9	103.0	102.2	106.3	104.6	104.6	101.6	103.0
10	102.8	100.2	104.3	104.2	110.8	98.3	105.0
11	101.3	100.9	105.4	104.5	106.7	101.0	107.1
12	99.3	102.1	103.0	110.2	108.1	103.3	110.5
13	103.0	103.7	105.0	104.9	107.7	100.0	109.8
14	102.4	99.2	105.0	105.3	106.8	102.6	109.8
15	100.6	103.6	106.9	116.5	106.9	99.6	111.2
16	97.9	106.0	103.7	119.9	98.9	101.3	112.6
17	104.3	104.7	107.5	----	108.4	105.6	116.2
18	97.3	----	105.6	----	98.9	108.1	----

/....cont'd

Table A15- (cont'd.) Dolly Lake specific conductivities, Winter 1978/79.

/$\mu S \cdot cm^{-1}$ @25°C

Depth /m	18/01/79	2/02/79	22/02/79	20/03/79	9/04/79	3/05/79	17/05/79
0	105.6	104.2	105.1	109.9	106.4	42.5	0.44
1	105.6	106.3	111.4	104.9	106.4	74.5	11.6
2	103.4	111.2	108.8	101.4	103.3	98.3	86.0
3	102.2	105.3	104.5	105.8	104.4	101.2	97.3
4	105.5	107.7	104.9	101.9	104.9	102.7	101.7
5	97.4	106.1	106.0	105.5	104.9	103.2	103.3
6	97.4	105.5	106.0	99.0	104.9	105.8	99.5
7	102.3	104.7	104.6	103.6	104.0	102.2	97.7
8	101.7	102.6	104.4	105.8	103.3	100.3	98.1
9	113.6	100.5	105.1	100.2	103.8	100.9	103.6
10	99.2	104.7	105.1	98.5	103.8	101.4	103.0
11	107.4	106.8	104.1	104.2	103.8	102.7	103.0
12	109.5	104.8	107.6	105.0	106.5	106.6	103.0
13	108.8	108.8	106.2	103.3	107.0	105.0	103.5
14	99.3	108.2	106.2	107.0	108.0	110.3	104.6
15	102.2	110.9	109.7	104.6	104.8	110.9	109.3
16	109.2	108.8	110.3	106.5	111.4	110.9	111.4
17	118.8	119.5	114.1	115.7	113.3	121.6	115.6
18	117.1	117.6	114.7	115.7	125.7	127.9	125.5

Table A16- Elizabeth Lake specific conductivities, Winter 1978/79.

/µS·cm^{-1} @ 25°C

Depth /m	27/10/78	3/11/78	10/11/78	17/11/78	24/11/78	15/12/78	6/01/79
0	73.2	67.3	68.5	78.1	79.4	72.8	68.7
1	66.6	67.3	76.2	71.4	73.5	69.3	91.6
2	63.3	66.6	67.0	64.6	66.6	70.0	77.3
3	65.0	62.1	64.3	63.2	66.6	68.0	66.6
4	64.6	62.1	---	62.6	64.0	65.2	67.2
5	63.3	64.0	66.0	67.2	66.6	63.8	67.2
6	63.3	74.4	61.9	62.4	67.3	65.3	69.0
7	65.6	66.6	66.6	63.5	69.9	67.3	67.8
8	69.5	64.0	62.3	64.5	64.5	75.6	69.0
9	63.7	63.7	65.8	65.9	63.7	67.6	70.5
10	66.9	65.0	72.2	63.5	70.2	74.2	67.8
11	64.2	68.6	69.5	65.3	69.8	67.9	66.6
12	64.4	68.3	61.7	68.6	65.3	71.4	65.8
13	64.6	65.3	74.6	63.0	65.3	66.5	66.6
14	69.2	63.7	67.9	62.7	68.1	68.3	66.0
15	63.9	63.7	64.3	68.4	70.4	68.3	---
16	69.5	65.9	69.0	65.0	66.4	67.2	68.7
17	63.6	66.3	66.5	66.8	69.1	68.6	---
18	63.9	67.3	67.5	64.9	73.5	70.0	66.9
19	65.6	66.6	72.6	65.9	65.2	71.5	---
20	66.6	68.8	---	72.3	68.7	70.0	66.9
21	65.3	78.9	72.1	66.9	67.9	71.5	---
22	67.8	---	66.5	71.3	69.8	73.6	68.4
23	69.3	---	72.6	80.5	73.1	---	---

/...cont'd

Table A16 (cont'd) Elizabeth Lake specific conductivities, Winter 1978/79.

/$\mu S \cdot cm^{-1}$ @ 25°C

Depth /m	26/01/79	28/02/79	29/03/79	18/04/79	13/05/79	31/05/79
0	74.7	81.7	76.1	71.1	16.3	4.0
1	73.9	79.6	74.2	71.1	36.6	22.8
2	71.5	72.2	72.9	69.8	50.0	62.2
3	75.3	70.2	70.3	68.7	67.6	62.9
4	72.1	66.9	68.1	67.6	69.0	64.4
5	67.2	64.6	66.6	66.5	67.5	64.6
6	64.6	67.0	66.2	65.3	67.5	64.6
7	---	65.2	65.5	67.2	67.5	63.3
8	66.6	64.7	65.9	65.6	66.7	64.7
9	63.0	64.2	66.4	66.1	66.7	64.7
10	64.8	70.1	66.5	65.9	65.8	66.1
11	---	65.8	66.8	65.4	66.3	64.2
12	65.4	63.7	66.3	65.8	66.9	63.7
13	---	70.7	67.5	66.7	66.9	64.2
14	64.2	65.8	67.8	66.4	67.7	64.6
15	---	64.1	66.7	68.1	66.4	68.1
16	67.2	67.6	68.9	69.4	69.9	66.9
17	---	67.5	68.5	69.5	71.1	70.4
18	63.3	68.5	71.2	70.8	72.2	64.9
19	---	68.6	71.2	71.0	73.4	73.8
20	---	71.8	71.2	73.9	74.0	76.3
21	71.1	71.0	71.8	73.5	74.0	76.9
22	71.3	71.6	76.8	76.1	78.1	79.9
23	73.9	76.5	81.0	81.8	78.1	82.2

Table A17 - Secchi depths and light extinction coefficients for Dolly and Elizabeth lakes, Summer 1978.

DOLLY			ELIZABETH		
Date	Secchi depth /m	Extinction coefficient /m^{-1}	Date	Secchi depth /m	Extinction coefficient /m^{-1}
27/06/78	10.25		7/07/78	2.63	
4/07/78	9.00		14/07/78	3.25	
11/07/78	8.63		28/07/78	4.88	0.271
18/07/78	10.13		4/08/78	3.40	0.322
25/07/78	7.75		11/08/78	2.85	0.289
1/08/78	9.50	0.056	18/08/78	2.25	
8/08/78	11.13		25/08/78	2.30	0.384
15/08/78	9.35	0.083	1/09/78	2.28	0.382
29/08/78	9.00		29/09/78	3.93	
5/09/78	12.00		6/10/78	4.50	
3/10/78	8.80		13/10/78	4.75	
10/10/78	8.00				

Appendix B - Persulfate digestion for the Determination of Total Phosphorus, modified from Menzel and Corwin (1965).

Materials:

1) $K_2S_2O_8$ (Reagent Grade) in a fine crystaline Form (Source: Fisher Certified -- Fisher Scientific).
2) Plexiglass scoops -- precalibrated to deliver 0.4g±0.01g $K_2S_2O_8$.
3) Kimax culture tubes (25mmX200mm) screw-top with teflon lined Bakelite caps.

Method:

1) Add 1 scoop of $K_2S_2O_8$ to each tube.
2) Add 50 ml of sample to a tube with a plastic graduate cylinder. Cap each tube tightly.
3) Autoclave at 15 psi. for 30 min.
4) Cool to room temperature.
5) Add 5 ml of mixed reagent, mix, and let stand.
6) After 5 min. read at 885 um in a 10 cm cuvette and against a d.d. H_2O Blank.

Mixed Reagent:

1875 ml	Distilled water
0.34 g	Potassium antimonyl-tartrate
15.0 g	Ammonium molybdate
175 ml	Concentrated sulfuric acid.

Mix well and store in a cool dark place. Immediately before using, add Ascorbic acid solution in the ratio 4 parts mixed reagent to 1 part ascorbic acid solution. The concentration of ascorbic acid is 2.7 g per 50 mls of distilled water.

Standard solutions:

Prepare a 1000 $mg.l^{-1}$ stock solution of Potassium dihydrogen orthophosphate (KH_2PO_4). This is diluted 100 times to make a 10 $mg.l^{-1}$ solution which is then diluted 100 times again to give a 100 $\mu g.l^{-1}$ solution. Store all three solutions in a refrigerator.

Preparation of blanks and standards:

For each batch of samples to be analyzed, prepare 3 tubes of each of the following:

i) Blanks: 50 mls of double distilled water into P-clean tube.
ii) 6 $\mu g \cdot l^{-1}$ standard: 3 mls of 100 $\mu g \cdot l^{-1}$ standard +47 mls of d.d. H_2O
iii) 10 $\mu g \cdot l^{-1}$ standard: 5 mls of 100 $\mu g \cdot l^{-1}$ standard solution +45 mls of d.d. H_2O.
iv) 20 $\mu g \cdot l^{-1}$ standard: 10 mls of 100 $\mu g \cdot l^{-1}$ standard solution +40 mls of d.d. H_2O.

Appendix C - Chlorophyll-a analysis using ethanol

1) Filter a suitable volume of lakewater through a 47 mm glass fiber filter. As the last 25-50 ml are being filtered, add 1 ml of $MgCO_3$ solution (1 g $MgCO_3$ in 100 ml water). Be certain to remove as much water as possible from the filter.

2) At this point, the chlorophyll may be extracted, or stored for extraction at a more convenient time. If the filter is to be stored, place it in a numbered petri dish with a tight-fitting lid. Keep frozen until extraction is possible.

3) Filters are folded and placed in a centrifuge tube containing 10.0 ml 96% ethanol. Tubes are capped, shaken vigorously and placed in the dark under refrigeration for 18-24 hours. It is probably a good practice to shake the tubes again after 1 hour to ensure more complete extraction.

4) After the extraction period, the contents of the centrifuge tubes are refiltered through a 25 mm glass fiber filter <u>or</u> centrifuged to separate the extracted chlorophyll from glass fibers and bits of filter. If refiltration is used, about 9.5 ml are commonly recovered and turbidity blanks are generally somewhat lower.

5) Read optical density in a 10 cm cell against 96% ethanol at 750, 665 and 649 nm. Correct optical densities for both cell to cell blanks and turbidity blanks.

6) Chlorophyll-<u>a</u> is calculated from the formula:

$$\text{Chyll-}\underline{a} = \frac{(13.7\ A665 - 5.76\ A649)\ v}{V \cdot 1}$$

where A665 and A649 are the corrected optical densities at 665 and 649 nm, respectively.

v is the volume of extractant used (10 ml) in ml.

V is the volume of lake water filtered in liters.

l is the length of the light path of the cell (10 cm).

APPENDIX D

Raw data collected during sediment incubation experiments in Schefferville

Table D1 - Results of long-term incubation of Dolly Lake sediments collected at 20 m. Times indicated in hours from beginning of experiment.

Chamber #	Condition	Volume of H_2O /l	Oxygen concentrations in $mg \cdot l^{-1}$			
			Initial	t=26 hrs.	t=46 hrs.	t=164 hrs.
1	Unstirred control	0.420	11.69	10.81	10.75	9.32
2	"	0.315	"	9.69	9.01	6.49
3	"	0.325	"	10.35	9.31	7.87
4	"	0.325	"	9.88	9.10	8.05
5	"	0.330	"	10.35	8.81	5.29
6	"	0.340	"	10.26	9.31	4.83
7	Stirred control	0.415	"	9.45	8.58	8.51
8	"	0.355	"	9.15	5.74	4.16
9	"	0.345	"	11.37	6.41	4.84
10	"	0.335	"	8.05	7.90	7.34
11	"	0.350	"	8.55	8.39	5.48
12	"	0.335	"	8.29	7.26	5.58
--	Added water	0.060	"	11.25	11.45	---

/cont'd...

Table D1 (cont'd.) - Results of long term incubation of Dolly Lake sediments collected at 20 m. Times indicated in hours from beginning of experiment.

Chamber #	Condition	Net oxygen uptake rate in $mg \cdot m^{-2} \cdot day^{-1}$		
		t=26 hrs.	t=46 hrs.	t=164 hrs.
1	Unstirred control	0.37*	0.08*	0.64*
2	"	73.65	67.31	21.19
3	"	31.17	89.66	4.66
4	"	63.09	74.37	-0.60
5	"	31.65	135.63	37.62
6	"	39.00	86.28	52.18
7	Stirred control	0.93*	0.47*	0.20*
8	"	22.18	253.83	33.72
9	"	-138.47	356.71	31.28
10	"	97.92	-37.25	11.01
11	"	65.74	-48.45	47.58
12	"	81.12	38.91	30.05
	Incubation period	26 hrs.	20 hrs.	118 hrs.

* Number of mgO_2 consumed during the incubation period by the volume of H_2O in the control.

Table D2 - Results of a short-term incubation of sediments collected at 15 m in Dolly Lake. Times indicated in hours after beginning of experiment.

Chamber #	Condition	Volume of water /l	Oxygen concentrations /mg·l⁻¹ Initial	t=22 hrs.	t=44.5 hrs.	Net O₂ uptake rate /mg·m⁻²·day⁻¹ t=22 hrs.	t=44.5 hrs.
1	Unstirred control	0.431	11.44	10.76	10.66	0.32*	0.11*
2	"	0.330	"	9.06	8.03	133.43	102.44
3	"	0.337	"	8.68	8.54	167.89	36.84
4	"	0.313	"	8.86	8.48	142.02	53.03
6	"	0.309	"	9.49	8.38	92.13	98.25
9	"	0.316	"	9.56	7.48	88.76	172.68
7	Stirred control	0.433	"	9.67	8.41	0.79*	0.68*
5	"	0.312	"	5.41	4.67	323.99	31.03
8	"	0.315	"	7.75	7.22	145.10	-19.44
10	"	0.296	"	4.42	3.97	379.74	27.85
11	"	0.302	"	8.22	7.59	104.07	-15.70
12	"	0.309	"	7.89	7.52	131.66	-31.90
--	Added water	0.060	11.87	11.87	---		
					Incubation period	22 hrs.	22.5 hrs.

* Number of mgO$_2$ consumed during the incubation period by the volume of water in the control.

Table D3 - Results of a short-term incubation of sediments collected at 12 m in Dolly Lake. Times indicated in hours after beginning of experiment. Samples from 24.5 m in Elizabeth Lake were also incubated during this experiment. The results are given in table D4.

Chamber #	Condition	Volume /l	Oxygen concentrations /$mg \cdot l^{-1}$			Net O_2 uptake rate /$mg \cdot m^{-2} \cdot day^{-1}$	
			Initial	t=24 hrs.	t=41.5 hrs.	t=24 hrs.	t=41.5 hrs.
1	Unstirred control	0.434	11.37	11.24	10.83	0.06*	0.19*
2	"	0.312	"	9.43	8.35	136.99	98.70
3	"	0.316	"	9.17	8.73	157.35	41.56
7	Stirred control	0.423	"	9.73	9.66	0.69*	0.13*
5	"	0.321	"	13.66?	10.40	---	28.00**
8	"	0.312	"	8.85	7.74	62.58	125.05
-	Added water	0.060	11.39	11.39	---		
				Incubation period		24 hrs.	17.5 hrs.

* Number of mgO_2 consumed during the incubation period by the volume of water in the control.
** Calculated by taking $[O_2]$ at time zero and not at t=24 hrs.

Table D4 - Results of a short term incubation of sediments collected at 24.5 m in Elizabeth Lake. Times indicated in hours from the beginning of the experiment. Samples from 12 m in Dolly Lake were also incubated during this experiment. The results are given in table D3.

Chamber #	Condition	Volume /l	Oxygen concentrations /mg·l^{-1}			Net O$_2$ uptake rates /mg·m^{-2}·day^{-1}	
			Initial	t=24hrs.	t=41.5 hrs.	t=24 hrs.	t=41.5 hrs.
1	Unstirred control	0.434	11.37	11.24	10.83	0.06*	0.19*
4	"	0.316	"	8.44	7.89	209.56	65.07
6	"	0.282	"	7.42	7.37	252.12	40.00
9	"	0.297	"	7.52	7.27	258.81	54.77
7	Stirred control	0.423	"	9.73	9.66	0.69*	0.13*
10	"	0.326	"	7.23	7.17	184.92	52.45
11	"	0.321	"	7.33	7.53	174.82	124.71
12	"	0.302	"	7.11	6.93	179.51	67.78
--	Added water	0.060	11.39	11.39	---		
					Incubation period	24 hrs.	17.5 hrs.

* Number of mgO$_2$ consumed during the incubation period by the volume of water in the control.

Table D5 - Results of a long-term inducation experiment on sediments collected at 8 m in Elizabeth Lake. Times indicated in hours from beginning of experiment. Samples from 16 m were also incubated at the same time. Results are given in table D6.

Chamber #	Condition	Volume /l	Oxygen concentrations /mg·l^{-1}					Net O_2 uptake rates /mg·m^{-2}·day^{-1}			
			Initial	t=20 h.	t=28 h.	t=49 h.	t=66 h.	t=20h.	t=28h.	t=49h	t=66h.
1	Unstirred control	0.420	10.03	9.78	10.31	10.88	10.83	0.14*	0.05**	0.05**	0.12*
5	Unstirred	0.327	"	9.55	9.34	8.44	8.30	13.03	86.70	69.82	2.99
9	"	0.331	"	9.56	9.37	9.24	8.60	12.29	82.36	3.99	40.35
7	Stirred control	0.423	"	9.55	9.76	9.95	9.75	0.23*	0.09**	0.24**	0.20**
11	Stirred	0.317	"	7.46	8.87	7.80	7.30	221.24	---	---	14.87‡
12	"	0.322	"	7.52	7.58	6.89	6.52	219.48	---	44.49§	37.35
--	Added water	0.060	10.54	10.54	10.88	9.39	---				
							Incubation period	20 h.	8 h.	21 h.	17 h

* Number of mgO_2 consumed during the insubation period by the volume of water in the control.
** Extrapolated from the value at t=20 hrs.
‡ Incubation time = 46 hours.
§ Incubation time = 29 hours.

Table D6 - Results of long-term incubation experiments on sediments collected at 16 m in Elizabeth Lake. Times indicated in hours from beginning of experiment. Samples from 8 m were also incubated at the same time. Results are given in table D5.

Chamber #	Condition	Volume /l	Oxygen concentrations /mg·l^{-1}					Net O_2 uptake rates /mg·m^{-2}·day^{-1}			
			Initial	t=20h.	t=28h.	t=49h.	t=66h.	t=20h.	t=28h.	t=49h.	t=66h.
1	Unstirred control	0.420	10.03	9.78	10.31	10.88	10.83	0.14*	0.05**	0.15**	0.12**
2	Unstirred	0.313	"	8.02	7.69	7.15	6.95	142.54	172.56	64.32	34.37
3	"	0.309	"	8.41	8.09	7.60	7.46	107.99	153.68	53.92	19.93
4	"	0.315	"	8.42	8.08	7.42	7.37	109.23	158.64	68.14	14.04
7	Stirred control	0.423	"	9.55	9.76	9.95	9.75	0.23*	0.09**	0.24**	0.20**
6	Stirred	0.290	"	8.75	7.55	7.68	5.93	100.78	267.34	---	67.62‡
8	"	0.316	"	6.57	6.89	5.84	5.66	296.93	---	73.41§	38.50
10	"	0.293	"	5.96	6.15	7.12	5.84	323.86	---	---	119.10
-	Added water	0.060	10.54	10.54	10.88	9.39	---				
					Incubation period			20h.	8h.	21h.	17h.

* Number of mgO_2 consumed during the incubation period by the volume of water in the control.

** Extrapolated from the value at t=20 hrs.

‡ Incubation time = 38 hrs.

§ Incubation time = 29 hrs.

APPENDIX E

Raw data collected during sediment incubation experiments in Montreal

Table E1 - Results of first incubation experiment in Montreal. Equilibration time = 66 days. Incubation time = 1 day.

Jar #	Lake	Height of sediment /cm	Oxygen concentrations /mg·l^{-1} Initial	Oxygen concentrations /mg·l^{-1} Final	Net O_2 uptake rates /mg·m^{-2}·day^{-1}
1	Dolly	4.6	10.75	8.88	-42.21
2	"	5.0	10.08	8.15	-35.94
3	"	5.0	11.01	8.50	0.00
4	"	4.9	9.82	8.88	-98.85
5	"	4.8	10.65	8.61	-30.06
13	Elizabeth	5.6	9.33	7.42	-33.58
14	"	5.8	10.88	7.39	50.88
15	"	5.7	9.98	7.43	2.20
17	"	5.7	11.41	7.27	89.59

Control bottle #	Volume /l	Oxygen concentrations /mg·l^{-1} Initial	Oxygen concentrations /mg·l^{-1} Final
1	0.147	12.39	9.37
3	0.148	"	9.31
2	0.147	"	10.93
4	0.149	"	9.91
	Mean	12.39	9.98

Table E2 - Results of second incubation experiment in Montreal. Equilibration time = 76 days. Incubation time = 1 day.

Jar #	Lake	Height of sediment /cm	Oxygen concentrations $/mg \cdot l^{-1}$		Net O_2 uptake rates $/mg \cdot m^{-2} \cdot day^{-1}$
			Initial	Final	
7	Dolly	4.7	9.18	6.90	58.47
8	"	4.8	9.47	6.46	104.26
9	"	4.7	9.70	7.16	75.35
10	"	4.6	10.14	7.36	92.35
11	"	4.8	10.09	7.26	92.74
19	Elizabeth	5.4	9.43	6.76	74.77
20	"	6.1	9.05	5.27	122.31
21	"	6.3	10.30	5.74	155.71
22	"	5.8	9.82	7.02	76.63
23	"	5.8	10.04	7.58	58.28

Control bottle #	Volume /l	Oxygen concentrations $/mg \cdot l^{-1}$	
		Initial	Final
1	0.147	11.71	10.17
2	0.146	11.71	9.97
3	0.148	11.71	10.46
4	0.149	11.71	10.70
	Mean	11.71	10.33

Table E3 - Results of the third incubation experiment in Montreal. Equilibration time = 81 days. Incubation time = 1 day.

Jar #	Lake	Height of sediment /cm	Oxygen concentrations /mg·l^{-1}		Net O_2 uptake rates /mg·m^{-2}·day^{-1}
			Initial	Final	
6	Dolly	4.9	10.37	6.41	199.59
12	"	4.8	9.97	5.68	223.86
18	Elizabeth	5.4	10.11	5.90	198.23
24	"	5.8	10.16	6.06	178.62

Control bottle #	Volume /l		Oxygen concentrations /mg·l^{-1}	
			Initial	Final
2	0.146		11.68	11.44
3	0.148		11.68	10.75
4	0.149		11.68	10.71
5	0.148		11.68	10.64
		Mean	11.68	10.89

Table E4 - Results of the fourth incubation experiment in Montreal. Equilibration time = 15 days. Incubation time = 1 day.

Jar #	Lake	Height of sediment /cm	Oxygen concentrations /mg·l^{-1}		Net O_2 uptake rates /mg·m^{-2}·day^{-1}
			Initial	Final	
1	Dolly	4.7	10.36	7.49	162.40
2	"	4.9	10.48	6.54	224.77
3	"	4.9	9.98	6.45	198.96
4	"	5.0	10.74	7.43	182.17
5	"	4.5	10.55	7.21	198.87
13	Elizabeth	6.0	9.82	6.32	162.65
14	"	5.8	9.94	4.93?	250.39?
15	"	6.0	8.29?	6.20	89.38?
16	"	5.8	10.33	6.10	208.30
17	"	5.7	10.58	6.33	213.26

Control bottle #	Volume /l	Oxygen concentrations /mg·l^{-1}	
		Initial	Final
3	0.148	11.58	11.22
4	0.149	11.58	11.23
6	0.147	11.68	11.28
	Mean	11.61_8	11.24

Table E5 - Results of the fifth incubation experiment in Montreal. Equilibration time = 8 days. Incubation time = 1 day.

Jar #	Lake	Height of sediment /cm	Oxygen concentrations /mg·l^{-1}		Net O_2 uptake rates /mg·m^{-2}·day^{-1}
			Initial	Final	
7	Dolly	4.7	10.34	7.18	174.10
8	"	5.0	10.26	7.41	146.85
9	"	4.9	10.05	7.68	119.00
10	"	4.8	10.09	7.46	137.52
11	"	4.8	10.17	7.47	141.99
19	Elizabeth	5.8	10.35	6.10	203.44
20	"	5.6	8.97?	6.58	106.89
21	"	5.9	10.24	6.72	161.01
22	"	5.9	9.88	6.13	173.19
23	"	5.9	9.98	6.53	157.30

Control bottle #	Volume /l	Oxygen concentrations /mg·l^{-1}	
		Initial	Final
1	0.147	11.67	11.13
2	0.146	11.67	11.14
5	0.148	11.67	11.06
7	0.147	11.67	11.32
8	0.145	11.67	11.29
	Mean	11.67	11.19