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THE UNIVERSITY OF ALBERTA

WINTER OXYGEN DEPLETION IN TEMPERATE ZONE LAKES

by

JAY BABIN

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

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Abstract

Winter oxygen depletion rates (WODR) (g $O_2 \cdot m^{-2} \cdot d^{-1}$) were determined for 13 lakes in central Alberta during the winter of 1982-83. Although oxygen decreased in all lakes for the first three and a half months after freeze-up, the decreases were nonlinear. The highest WODR were observed just after freeze-up. The nonlinear WODR were significantly correlated with estimates of lake productivity (total phosphorus (TP)), but were not significantly correlated with morphometry (eg. mean depth, $P>0.20$).

When the WODR from the Alberta lakes were treated as linear, to enable a comparison with other studies dealing with WODR, a correlation was found between WODR and both morphometry and estimates of summer productivity. This relationship was significantly different from what previous investigators observed. When data from three other sets of temperate zone lakes were combined with data from this study, WODR were best predicted from a combination of mean depth ($\bar{z}$ in m) and mean summer TP (TPsu in $mg \cdot m^{-3}$) in the euphotic zone:

$$WODR = -0.101 + 0.00247\ TPsu + 0.0134\ \bar{z} \qquad r = 0.90$$

The above equation permits the prediction of WODR for a greater range of lake types than previous models.

Models to predict WODR in lakes are based on oxygen profiles obtained from the deepest site in the lake. When the average dissolved oxygen concentration in Wizard Lake was calculated from oxygen profiles obtained from six sites,

the oxygen concentration was 47% higher than when the average concentration was calculated based on the main sampling site. Thus, it appears that one-site sampling may not yield an accurate estimate of the winter oxygen content of lakes.

Acknowledgements

I would like to express my thanks to Dr. E.E. Prepas for her support, insight, and encouragement with this thesis. I also thank G. Linsey for providing unpublished data and Dr. P. Dillon for permission to use his data on some of the Ontario lakes.

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I. General Introduction

"A skillful limnologist can probably learn more about the nature of a lake from a series of oxygen determinations than from any other kind of chemical data"
(Hutchinson, 1957, p575)

Dissolved oxygen (DO) in lakes is used by plants, animals, and bacteria for respiration. If the consumption of oxygen in a lake exceeds the input, a net oxygen deficit occurs. Most oxygen depletion studies concentrate on stratified lakes during the summer. Thus most of the information regarding oxygen depletion in lakes is based on summer oxygen data. To obtain accurate estimates of factors influencing oxygen depletion it is often necessary to bring the "lake" into the laboratory. Thus a lot of the information available on the mechanisms involved in oxygen depletion is from laboratory experiments using sediment cores and water from the lake. It is often difficult to extrapolate directly from observations of laboratory experiments to the situation in the field (Riley and Prepas 1984). However, the general trends from the laboratory may be used to interpret the results from the field.

In a stratified lake during the summer, DO is consumed throughout the water column. In the epilimnion, water regularly comes in contact with the air, thus DO levels are usually close to 100% saturation. Water in the hypolimnion does not regularly come into contact with the atmosphere. Consequently, oxygen respired in the hypolimnion is often not replenished and a deficit may develop (Thienemann 1928).

Oxygen depletion in lakes is expressed in one of two ways: (1) volumetrically as mass of oxygen used per volume of water per day ($g \cdot m^{-3} \cdot d^{-1}$) or (2) areally as mass of oxygen used per unit surface area per day ($g \cdot m^{-2} \cdot d^{-1}$). Oxygen depletion rates were first used to define lake trophic status (Strom 1931; Hutchinson 1938). Recently Charlton (1980) and Cornett (1981) have shown that oxygen depletion is related to morphometry. Thus the earlier attempts by Strom (1931) and Hutchinson (1938) to classify lake trophic status based on the areal hypolimnetic oxygen deficit (AHOD) were incorrect. Oxygen depletion in lakes in winter is expressed areally since the primary site of oxygen consumption is at the sediment-water interface (Hayes and MacAuley 1959; Hargrave 1971) which is a function of lake area.

An ice-covered lake in the winter is similar to the hypolimnion of a stratified lake. Both are isolated from the atmosphere and can develop oxygen deficits (Krumholtz and Cole 1959; Linsey 1981). With fall freeze-over, wind induced circulation ceases in a lake and atmospheric inputs of oxygen stop. Under ice-cover, DO is added during photosynthesis (Rhode 1955; Wright 1964; Jackson 1979) and by inflowing streams (Greenbank 1945; Pennak 1968). Concurrently, DO is lost through white ice formation, respiration and the oxidation of chemical compounds. When DO levels decline during winter, fish populations within the lake are subject to winterkill (Greenbank 1945; Scidmore 1957; Halsey 1968; Pennak 1968; Schneberger 1970; Casselman and Harvey 1975). Consequently, biologists are interested in predicting winter oxygen depletion rates (WODR) to determine which lakes may winterkill.

A. Oxygen Sinks Under Ice-cover

There are three major sinks for oxygen in lakes under ice-cover: (1) slushing, (2) chemical oxidation of reduced compounds, (3) biological consumption. These sinks are discussed in detail below.

When black ice cracks, water seeps up over the ice flooding the snow and white ice forms (Adams 1976), this is termed slushing. As a result of this flooding, DO in the water which forms the white ice is removed from the lake. The total amount of oxygen removed from the lake during slushing events is proportional to the depth of white ice formed and the DO concentration in the flooding water.

Chemical oxidation occurs when reduced compounds are oxidized in the water column, e.g., $2Fe_2O_2 + O_2 \rightarrow 2Fe_2O_3$. Reduced compounds (e.g., manganese, iron and sulfur) are released into the water overlying the sediments when DO levels are low (Mortimer 1971). These reduced compounds are transported via currents and diffusion towards the lake surface and, if oxygen is encountered, they are oxidized. Brewer et al. (1977) found that the oxygen comsumption of sediment cores was reduced by 91 to 99% by poisoning the sediments; the remaining 1 to 9% of the oxygen consumption was presumably due to chemical oxidation. Hargrave (1972) found that chemical oxidation accounted for only 20% of the oxygen consumption of sediment cores in the laboratory. Thus, as the amount of oxidizeable material increases, the consumption of oxygen by chemical oxidation increases. However, chemical oxygen depletion, in general, is not the main sink for oxygen in lakes.

The major sink for DO is respiration by organisms (Hargrave 1969) including fish, invertebrates and microbes (eg. fungi and bacteria). Respiration by fish accounts for a relatively small amount of the oxygen consumed in a lake. In Sharpe Bay (Jack Lake, Ontario), Linsey (1981) calculated that the DO respired by fish (4.4×10^{-5} $mg \cdot L^{-1} \cdot d^{-1}$), was less than 0.2% of the total oxygen consumed. Benthic invertebrates also account for a relatively minor portion of total oxygen consumption in lakes. However, benthic invertebrates can greatly influence the oxygen uptake by bacteria (Edwards and Rolly 1965; Graneli 1979). By burrowing in the sediments and increasing the sediment surface area, benthic invertebrates increase oxygen consumption by bacteria. Benthic invertebrates also bring organic material and reduced substances to the sediment surface where they may be oxidized. Bacteria are the main consumers of DO in lakes (Edberg and Hofsten 1973; Brewer et al. 1977). A correlation was noted between bacteria abundance and oxygen depletion (Zobell and Stodler 1940; Hayes and MacAuley 1959; Brewer et al. 1977). Fungi play a major role in oxygen consumption as they are responsible for the breakdown of large particles of organic matter (eg. dead macrophytes) into smaller particles suitable for bacterial consumption. Bacteria use oxygen for the decomposition of organic matter. As more organic material is made available for decomposition, the number of bacteria increases and the oxygen demand by the bacteria inceases correspondingly (Zobell and Stodler 1940; Hayes and MacAuley 1959; Hayes and Anthony 1959). The site of highest bacterial numbers in lakes is at the sediment-water interface (Hayes and Anthony 1959), thus the role of sediments is an important factor in oxygen depletion in lakes and will be discussed in the following section.

B. Sites for Oxygen Depletion

When considering oxygen depletion, a lake may be divided into two distinct compartments: (1)sediment-water interface and (2) open water. Oxygen depletion in these two compartments is termed sediment oxygen demand (SOD) and water oxygen demand (WOD), respectively. In deep lakes, organic material falling out of the trophogenic zone is oxidized to a greater extent in the open water than the same material would be in a shallow lake, since the material has a greater distance to fall in the deep lake, hence a longer residence time (Charlton 1980; Cornett 1981). In laboratory experiments carried out on sediment cores and the overlying water, Edberg and Hofsten (1973) found WOD accounted for 12% of the oxygen consumption when the water overlying the sediment cores was rich in oxidizable substrates; however, when water overlying the cores was from the outflow of a papermill, 40% of the total oxygen consumption was caused by WOD. As the concentration of oxidizable material in the water column increases, the relative contribution of WOD to the total oxygen consumption in the lake increases.

In lakes, the main site for oxygen depletion is at the sediment-water interface. Productivity and the mass of oxidizable material are relatively low in the water column during winter, therefore the contribution of WOD to the total oxygen consumption in the lake is small. In two sub-arctic lakes, Chenard (1980) found that SOD could account for between 50 and 100% of the total oxygen demand in the lakes during the winter. Hargrave (1971) found that oxygen consumption under ice-cover in Lake Esrom, Denmark, could be attributed almost entirely to oxygen uptake by the sediments. The nature of the sediments influences the rate of oxygen depletion and will be discussed in the following section.

C. Factors Controlling Oxygen Depletion in Lakes

Oxygen depletion rates in lakes are governed by two factors: (1) the nature and amount of the substrates to be oxidized (2) the supply of oxygen to the sites of oxygen consumption. In temperate zone lakes, most of the production of organic material takes place during the open-water season (Schindler and Nighswander 1970). Material produced in the open-water season is partially oxidized as it falls to the sediments where it is stored. Production in lakes rapidly declines when lakes freeze over. Thus, most of the material that will be oxidized during the winter is accumulated in the sediments from production that occurred during the ice-free season. Oxygen demand may increase as a lake undergoes eutrophication because of increased production (Brewer et al. 1977). However, Hargrave (1975) and Graneli (1978) found little change in oxygen uptake rate of sediment cores when fresh organic material was added. No correlation was found between the organic content of sediments and oxygen depletion rate (Edberg and Hofsten 1973). However, the nature and quality of the organic material in the sedime[illegible]s not determined in these studies. This can be impo[illegible]ce organic material can be composed of easily oxidiz[illegible]erial such as simple carbohydrates or material which is [illegible]vely difficult to breakdown such as lignins or humic comp[illegible]argrave 1971).

In laboratory experiments, oxygen depletion rates were higher at the beginning of the experiment than at the end

(Zobell and Stodler 1940). Zobell and Stodler (1940) attribute the reduction in the rate of oxygen consumption to a decrease in the availability of substrates suitable for oxidation.

Rate of oxygen depletion is governed in part by the supply of oxygen to the sediments. Since sediments are the primary site for oxygen consumption, water in contact with the sediments quickly goes anoxic. However, as there is circulation under ice-cover (Likens and Hasler 1962; Likens and Ragotzkie 1966) water is transported to the sediment-water interface, bringing DO to the sediments. Horizontal mixing is faster than vertical mixing in the open water. Vertical mixing in the open water is supplemented by the movement of water down the sides of the lake at the sediment surface. As water approaches the sediment-water interface, it warms and becomes denser than the colder surrounding water, and then slides down the sides of the lake displacing the bottom water upwards. This process results in a slow circulation of the lake water and brings oxygen to the sediments.

D. Production of Oxygen Under Ice-Cover

If no water enters the lake in winter, photosynthesis is the only source of oxygen gain in lakes. If snow cover on the lake is thin, enough light may enter the lake to permit a substantial amount of photosynthesis to take place. The depth of snow needed to reduce light penetration to effectively halt photosynthesis would depend on the type and pattern of snow cover present on the lake and also the light regime of the lake (Adams and Roulet 1980). Barica et al. (1983) were unsuccessful in their attempt to increase photosynthesis under the ice by removing the snow cover. The presence of algae in the water column does not mean that there is oxygen production taking place in the water. Schindler and Nighswander (1970) found that the algal population under the ice in Clear Lake, Ontario, was relatively large but the algae were in a state of dormancy. Chlorophyll *a* (Chl *a*) levels in lakes, a measure of algal production, are relatively high just after freeze-up and decline throughout the winter (Greenbank 1945; Barica 1977; Jackson 1979). As a result, oxygen production caused by photosynthesis is negligible in most lakes throughout the the period of ice cover (Jackson 1979).

E. Existing Models to Predict Winter Oxygen Depletion Rates

Whole-lake WODR have been studied and modelled in two distinct lake types in the temperate zone lakes of North America. Deep oligotrophic lakes on the Precambrian shield have been studied by Welch et al. (1976) and the shallow eutrophic prairie pothole lakes have been studied by Barica and Mathias (1979). Both studies reported that WODR (g $O_2 \cdot m^{-2} \cdot d^{-1}$) could best be predicted by models that used morphometry (mean depth ($\bar{z}$)) as the independent parameter. The relationship between $\bar{z}$ and WODR in the two studies was quite different:

$$WODR = 0.08 + 0.012\ \bar{z} \quad \text{(Welch et al. 1976)}$$

$$WODR = 0.14 + 0.062\ \bar{z} \quad \text{(Barica and Mathias 1979)}$$

Mathias and Barica (1980) suggest that this difference is a function of productivity but they did not attempt to incorporate an estimate of lake productivity into a model. Schindler (1971) related winter oxygen depletion to the amount of allochthonous material received by the lakes in the Experimental Lakes Area (ELA). This relationship has never been confirmed in subsequent studies, probably because the vegetation cover in the lake basins in the other studies differs from lake to lake, whereas in the ELA the vegetation cover is similar between lakes. Hence the source, type, and amount of allochthonous material entering the lakes is different for lakes in other regions (Mathias and Barica 1980).

Jackson and Lasenby (1982) developed two models to predict oxygen profiles under ice-covered lakes. The two models are based on data collected for lakes on the Precambrian Shield and lakes in limestone basins in Ontario. The more productive limestone basin lakes had higher oxygen depletion rates, indicating that oxygen depletion is related to productivity.

All of the individual studies on WODR have focused on groups of lakes with similar morphometries or productivities. Thus, models based on these studies are only applicable to the lake type they are based on. To link together the previous studies, I gathered data on WODR in 13 Albertan lakes, and examined the effect of morphometry and estimates of productivity (spring and summer total phosphorus, summer Chl *a*, and loss on ignition of the sediments) on WODR in these lakes. Furthermore, data from the literature and this study were combined to produce a new model to predict WODR over a broader range of lake types than the two existing models.

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II. Modelling Winter Oxygen Depletion Rates in Temperate Zone Lakes

A. Introduction

Several researchers have investigated patterns in winter oxygen depletion rates (WODR) (Welch et al. 1976; Barica and Mathias 1979), factors controlling WODR (eg. Mathias and Barica 1980) and ways to reduce WODR (Wirth 1970; Barica et al. 1983). Recently, Jackson and Lasenby (1982) constructed two models to predict oxygen profiles under ice in lakes located on the Precambrian Shield and in limestone basins in Ontario.

Winter oxygen depletion rates have been studied in two extreme lake types in temperate regions of Canada: the relatively deep, oligotrophic lakes on the Precambrian Shield (Welch et al. 1976) and the shallow, eutrophic, prairie pothole lakes in southwestern Manitoba (Barica and Mathias 1979) (mean depths ($\bar{z}$) ranged from 4-27 and 2-4 m and mean summer chlorophyll *a* (Chl *a*) concentrations in the euphotic zone ranged from 1-2 and 5-102 $mg \cdot m^{-3}$, respectively, for the two lake types). Although $\bar{z}$ was the best predictor of WODR in both lake types, the mathematical relationships were different (Welch et al. 1976; Barica and Mathias 1979). Thus, empirical models to predict WODR pertain to relatively specific lake types in different regions. Winter oxygen depletion rates are also affected by snow cover (Barica et al. 1983) and the amount of organic material produced in a lake (Mathias and Barica 1980). However, neither snow cover nor estimates of lake productivity have been incorporated into models to predict WODR. In contrast, models to predict summer areal hypolimnetic oxygen deficits (AHOD) do incorporate measures of both morphometry and productivity (Cornett and Rigler 1979, 1980; Charlton 1980).

Winterkill is a common phenomenon in lakes in central Alberta. Thus, considerable interest exists in factors controlling WODR in these lakes. However, Albertan lakes are different from other temperate zone lakes studied in Canada; they may be as productive as the prairie pothole lakes, but are much deeper (Prepas and Trew 1983). To test whether either existing WODR models are applicable in Albertan lakes, data were collected on 13 lakes. These data were also used to construct an empirical model to predict WODR for Albertan lakes, and were combined with other data in the literature to test the contribution of lake productivity to WODR.

To estimate WODR, water samples are collected over the deepest part and treated as representative of the whole lake (Welch et al. 1976; Barica and Mathias 1979; Jackson and Lasenby 1982). This approach assumes that oxygen concentrations are homogeneous within horizontal strata; an hypothesis which has never been rigorously tested. To determine if one-site-sampling is adequate for estimating whole-lake oxygen mass, samples were collected from six to seven sites in each of five lakes for comparison with results from a single station.

B. The Study Lakes

The 13 lakes in this study are located in central Alberta within a 160 km radius of the city of Edmonton. The lakes range in size from 0.08 to 4.4 km^2 (see appendix B for bathymetric maps). All lakes are underlain by 10 to 40 m of glacial till. Total dissolved solids in the lakes ranges from 150 to 390 $mg \cdot L^{-1}$ and colour ranges from 2 to 25 $mg \cdot L^{-1}$ Pt. The lakes were chosen to encompass large ranges in morphometry and productivity: $\bar{z}$ of the lakes ranges from 3 to 19 m and trophic status varies from oligotrophic to hypereutrophic (mean summer euphotic zone Chl *a* ranges from 2 to 155 $mg \cdot m^{-3}$). Background data for the lakes are in Prepas and Trew (1983) and Prepas and Wisheu (1984). Two lakes, Amisk and Baptiste, have distinct north and south basins. Both basins of Amisk were sampled and only the deep south basin of Baptiste was sampled; all three basins were treated as separate lakes. Each of the remaining lakes was sampled at only one site. Seven of these lakes have simple basins with a single deep spot, two lakes, Eden and Sauer, each have two distinct deep spots and the remaining lake, Hubbles, has three deep spots. None of the study lakes have major inflows or outflows (Prepas 1983, unpublished), hence the main source of organic matter in the lakes is from autochthonous production.

C. Materials and Methods

The study lakes were permanently ice-covered by 5-11 November, 1982, and remained frozen until the third week in April, 1983. Each lake was visited seven to 13 times from just prior to freeze-up until one month before break-up. On each visit, water samples were collected over the deepest part of the lake with an aluminum drop-sleeve water bottle. Water for dissolved oxygen (DO) analyses was collected every 1 or 2 m from the top of the hydrostatic water level to the lake bottom or to where it became anoxic as evidenced by the smell of hydrogen sulfide. These samples were fixed immediately (Carpenter 1965) and, to avoid freezing, transported back to the laboratory in insulated boxes containing hot-water bottles.

To determine the potential contribution of algae to the lake oxygen mass under ice-cover, water was also collected for Chl *a* analyses. For the first one and a half months, samples were collected at 1-m intervals from 1 to 4 m and for the remainder of the winter, samples were collected to a depth of 5 to 24 m and pooled into strata 2 to 6 m deep. Water samples for Chl *a* analyses were placed in 2-L amber Nalgene bottles and transported to the laboratory. To estimate spring and summer productivity in the lakes, total phosphorus (TP) and Chl *a* levels in the euphotic zone for ten of the lakes are from Prepas and Vickery (1984). For two lakes, Nakamun and Halfmoon, TP and Chl *a* values are from Riley (1983). I sampled the 13th lake, Hubbles, five times from May 14 to Aug. 26, 1982. In this study, water samples for TP and Chl *a* analyses were collected with Tygon tubing at three stations and pooled. These samples were collected from the euphotic zone, defined as the depth to 1% surface irradiance, of the photosynthetically active radiation, as measured with a Lambda L1-185 light meter equipped with an underwater sensor, or 2 times Secchi disc depth (SD).

To determine whether organic content of the sediments is an estimate of lake productivity which can be used to predict WODR, sediment samples were collected from 12 of the study lakes during the summers of 1982 and 1983. The number of samples collected (4-8) on each lake increased in proportion to lake size. These samples were collected randomly from each lake with a four-barrel corer (Hamilton et al. 1970). The top 5 cm was removed from each core and pooled with other cores from that site. The samples were brought back to the laboratory and frozen until they could be analyzed for loss on ignition (LOI).

Detailed morphometric data were already available for five of the study lakes (Prepas and Trew 1983, unpublished). The remaining eight lakes were sounded with a Furuno model Fe-400 depth sounder. Morphometric data were determined from the bathymetric maps with a Tallos digitizer connected to a Hewlett-Packard 9825B desk-top computer supplied by Alberta Energy and Natural Resources.

Dissolved oxygen concentration was determined on duplicate water samples based on Carpenter's (1965) modification of the Winkler technique. Most samples were titrated within 12 h of collection and all were titrated within 24 h. To determine the accuracy of the method for collecting DO samples, I compared the average DO values from duplicate water samples. The average difference between independent oxygen samples collected at the same site and depth was 0.07 $mg \cdot L^{-1}$ and the range was 0.01 to 0.32 $mg \cdot L^{-1}$. Percent oxygen saturation of the lakes was determined based on oxygen saturation tables in Cole (1983). Duplicate samples for Chl *a* analyses were prepared within 12 h of collection by filtering 0.05 to 2 L of lake water, depending on cell density, through glass fiber filters. Chlorophyll *a* was determined with the ethanol extraction technique of Bergmann and Peters (1980). Total phosphorus was determined on duplicate 50 mL samples of lake water with the persulfate method of Prepas and Rigler (1982). Loss on ignition (LOI) was determined by the weight loss of dried sediment samples baked at 550°C for 24 h. The LOI was not corrected for dehydration of the samples (Hargrave 1975). Loss on ignition estimates for all samples on each lake were combined to yield an average whole-lake estimate of LOI.

For each winter visit, oxygen mass was determined for each stratum from the product of stratum volume and oxygen concentration; these data were summed to yield whole-lake oxygen mass. The volume of the top 1-m was corrected for ice thickness. The whole-lake oxygen mass was divided by the under-ice surface area of the lake to yield the areal oxygen mass (g $O_2 \cdot m^{-2}$) (Welch 1974). To calculate WODR (g $O_2 \cdot m^{-2} \cdot d^{-1}$), areal oxygen mass was regressed against days past freeze-up; the slope of this regression line is the WODR.

To develop empirical models for the lakes in central Alberta, WODR were regressed against estimates of spring and summer productivity (TP, Chl *a*, and LOI) and mean and maximum depth ($\bar{z}$ and Zmax, respectively). Volumetric ($mg \cdot m^{-3}$) and areal ($mg \cdot m^{-2}$) expressions were used for TP and Chl *a*; the areal expressions were calculated as the product of TP and Chl *a* concentrations in the euphotic zone and the depth of the euphotic zone. To construct a general model to predict WODR, data (*i.e.*, WODR, $\bar{z}$, TP, and Chl *a*) from other temperate zone lakes (Schindler 1971; Dillon and Rigler 1974; Reid et al. 1975; Welch et al. 1976; Barica et al. 1978; Barica and Mathias 1979) were combined with data from this study and analysed by regression analyses. Spring was defined as 27 May-14 June for Alberta data collected in 1982. Summer was defined as 15 June-15 Sept. for Alberta data collected in 1982 (after Prepas and Vickery 1984), and end of May until end of August for unpublished data collected on Ontario lakes. Spring and summer data from published sources were used as published.

The regression analyses were performed with the BMDP statistical package program P1R (Dixon 1981) on the Amdahl model 5860 computer at the University of Alberta. Other statistical analyses were from Snedecor and Cochran (1980) or Prepas (1984). All values in this report are expressed as means ± standard error, except where noted.

To evaluate the differences between predictions of WODR with summer areal hypolimnetic oxygen depletion (AHOD) models and WODR models, I compared the residual mean squares (RMS) for each of four AHOD models with the RMS for the WODR model(s). The RMS for each model was calculated as follows:

$$RMS = \sum_{i=1}^{n} (pred_i - obs_i)^2/df$$

where $pred_i$ is the predicted WODR (from the AHOD model) and obs_i is the observed WODR for each lake (i), and df is the degrees of freedom. For each model, df was defined as number of data points minus one minus the number of independent variables in the model. Since multiple comparisons were made in this analysis, the chance of committing a type I error was greater than the value given in a standard *F*-table; therefore, a probability level of 0.02 was used to distinguish significance.

D. Results

Fall Turnover

Just prior to freeze-up, DO levels were surprisingly low in 12 of the 13 study lakes; the average oxygen saturation level was calculated to be 69% at the time of freeze-up, with values as low as 51%. Only one lake, Hasse, was almost fully saturated (94%) (Table 1). These findings are contrary to observations in other areas; e.g. in the pothole lakes of Manitoba, oxygen saturation levels are 80-100% just prior to freeze-up (Barica and Mathias 1979). Jackson and Lasenby (1982) reported that the maximum volume-weighted oxygen content of the Ontario lakes that they studied, was achieved approximately 15 days after freeze-up; this is not the case in the Albertan lakes. In only four of the 13 lakes, the saturation level increased between the time of freeze-up and the first sampling date, possibly due to relatively high oxygen consumption relative to the inputs of oxygen via freezeout and photosynthesis. Not only were DO levels low in the study lakes in the fall, but mixing was incomplete in two of them. A layer of anoxic water up to 5-m high remained over at least 18% of the sediments in the deepest part of Twin Lake. In Hubbles Lake, up to 9-m of water, overlying 15% of the sediments, was anoxic. Since oxygen consumption in lakes is mainly caused by bacteria at the sediment-water interface (Brewer et al. 1977), incomplete circulation could reduce oxygen depletion rates in the water column. Consequently, for the subsequent analyses, WODR for Twin and Hubbles lakes were not pooled with those from the remaining 11 study lakes where DO levels were above zero over the entire sediment area prior to freeze-up.

Lake Cover and Chlorophyll *a*

During the visits to the lakes while they were ice-covered, ice thickness at the sampling sites averaged 44.1 ± 1.35 cm and average snow depth was 8.2 ± 0.94 cm. White ice was noted only on Twin Lake; it was 2.5 cm deep. The total snowfall at Edmonton International Airport during the winter of 1982-83 was 0.92 m, which was lower (*t*-test, $P<0.001$) than the previous 30-yr average (1.25 m) (Environment Canada). Consequently, the amount of light entering the lakes during the winter of 1983 was greater than during an average winter.

In 12 of the study lakes, Chl *a* concentration in the top 4 m decreased with the onset of ice-cover and remained low until late February or early March, as illustrated with data from Lessard Lake (Fig. 1). In these 12 lakes, average Chl *a* concentration in the top 4 m between freeze-up and March 6, 1983, was 2.9 ± 0.55 $mg \cdot m^{-3}$ while after March 6 it rose to 4.6 ± 1.42 $mg \cdot m^{-3}$. For the same lakes, average snow depth during these two periods was 7.3 ± 0.89 cm and 10.3 ± 1.15 cm, respectively. In the 13th lake, Halfmoon, a bloom of algae (32 $mg \cdot m^{-3}$ Chl *a*) was recorded at a depth of 1 m on December 14 but decreased to 3 $mg \cdot m^{-3}$ Chl *a* 10 days later. This algae bloom could have introduced oxygen under the ice but the DO level at 1 m decreased from 6.6 $mg \cdot L^{-1}$ on December 14 to 4.8 $mg \cdot L^{-1}$ on December 24. Snow-cover on Halfmoon Lake for these same two dates was 4 cm and 5 cm, respectively. In March, 1983, DO and Chl *a* levels increased in the top few meters in 10 of the lakes as illustrated in Fig. 2 with data from Sauer Lake. In Sauer Lake, Chl *a* increased five fold (from 3.3 to 15.8 $mg \cdot m^{-3}$) in the top 4 m while DO increased 18 fold (from 0.06 to 1.2 $mg \cdot L^{-1}$) in the same stratum between March 2 and March 25, 1983. Since DO and Chl *a* levels began systematic increases under ice only after early March, 1983, photosynthesis probably contributed an insignificant amount to oxygen levels between freeze-up and early March, 1983.

Dissolved Oxygen

For the first 112 days past freeze-up, the mass of DO ($g \cdot m^{-2}$) decreased systematically in all lakes. Beginning in early March, changes in the mass of DO followed two distinct patterns: in three lakes DO increased while in the remaining 10 lakes it continued to decrease, but at a lower rate than previously. Since DO levels systematically decreased in all lakes during the first 112 days past freeze-up and during the same period there was no evidence that a significant amount of oxygen was added to the lakes via photosynthesis, WODR were calculated for this 112-day period. Winter oxygen depletion rates, although systematic, were not linear during the 112-day period; rather WODR were more rapid at the beginning than at the end of this period. To illustrate this pattern, the data for the 112-day period were subdivided into two periods: (1) the first three sampling dates and (2) the remaining sampling dates, and WODR were calculated for both periods. Since a minimum of three points are needed to construct a regression line, subdivided WODR were only calculated for the eight lakes which had a minimum of six sampling dates during the 112-day period. For these eight lakes, the WODR for the first three sampling dates were consistantly higher than rates based on the remaining dates (Wilcoxon signed-rank test, $P<0.05$) (Table 2). These results were surprising; WODR are traditionally considered as linear until average whole-lake DO levels fall below 3 $mg \cdot L^{-1}$ (Mathias and Barica 1980). My data do not support this hypothesis; e.g., in two lakes, Lessard and Eden, average whole lake DO levels remained above 3.6 and 4.0 $mg \cdot L^{-1}$, respectively, during the 112-day period when WODR were calculated. Yet in these same lakes, WODR just after freeze-up were 54 and 68% higher, respectively, than later in the 112-day period (Table 2). Thus, in this study, WODR were nonlinear regardless of DO levels. Since changes in the mass of DO were nonlinear in the study lakes, a suitable transformation was sought for these data. The best transformation for the mass of DO (X) vs. time was a power function: $X' = X^{0.65}$. For 12 of the 13 lakes, the correlation between the transformed DO data and days past freeze-up was better than or equal to the correlation based on the untransformed data (Table 2). These data are the first WODR treated as a nonlinear process. Thus these data cannot be compared with any existing WODR models. I examined the relationship between two morphometric parameters ($\bar{z}$ and

Zmax), four parameters used as estimates of annual production of organic matter (LOI, spring TP, summer TP and summer Chl *a* levels) and WODR based on the transformed data (WODR') (Table 3). Winter oxygen depletion rates based on transformed data (WODR') were positively correlated with all variables except LOI. The significant negative relationship between LOI and WODR' is hard to explain. Surprisingly, the only positive significant relationships were between estimates of open water productivity (TP and Chl *a*) and WODR' (Table 3); the best predictors of WODR' were summer TP and Chl *a* (TPsu and Chl *a*) in $mg \cdot m^{-2}$:

$$WODR' = 0.005 + 0.00047 \, TPsu \quad (1)$$

$$WODR' = 0.062 + 0.00052 \, Chl \; a \quad (2)$$

These results are contrary to investigations on two other groups of lakes (Welch et al. 1976; Barica and Mathias 1979) where DO data were not transformed prior to calculating WODR. In the other investigations, morphometric parameters were much better predictors of WODR than estimates of summer productivity, whereas summer productivity was the best estimator of WODR with the transformed WODR data from this study.

Although data from this study suggest that models to predict WODR are best based on transformed DO data, untransformed data must be used to compare WODR in Albertan lakes with temperate zone lakes in other regions. Thus the subsequent discussion is based on WODR calculated with the original data.

In the 13 Albertan lakes, WODR covered twice the range, 0.193 to [illegible]48 g $O_2 \cdot m^{-2} \cdot d^{-1}$, as that observed in the two previous studies on WODR in Canadian lakes (Fig. 3). The WODR for the Albertan lakes were tested against existing empirical models. The model for lakes on the Precambrian Shield which are similar in depth but less productive (Welch et al. 1976) consistently underestimated WODR in the Albertan lakes (Wilcoxon signed-rank test, $P<0.01$). Conversely, the model for the generally shallower prairie pothole lakes (Barica and Mathias 1979) consistently overestimated WODR in the Albertan lakes (Wilcoxon signed-rank test, $P<0.05$) (Table 4, Fig. 3).

To compare WODR in Albertan lakes with the lakes on the Precambrian shield and in southern Manitoba, WODR in the Albertan lakes were regressed against parameters indicative of lake morphometry and productivity (Table 3). Based on untransformed data, patterns in the Albertan lakes were comparable with the studies in other regions (Welch et al. 1976; Barica and Mathias 1979); morphometry was a stronger predictor of WODR than estimates of productivity. The best predictor of WODR was mean depth ($\bar{z}$ in m):

$$\mathrm{WODR} = 0.20 + 0.036\ \bar{z} \qquad (3)$$

Unfortunately, too few Albertan lakes were sampled to construct multiple regressions on these data alone. Productivity, as estimated by spring and summer TP, was significantly correlated with WODR only when TP was expressed on an areal basis. Thus all further calculations are based on areal expressions of productivity estimates.

A serious limitation with the existing models to predict WODR is that they work only in the region where they were developed. These published models to predict WODR are based only on morphometry (Welch et al. 1976; Barica and Mathias 1979). However, there are numerous suggestions that oxygen depletion rates are a function of both $\bar{z}$ and lake productivity (Table 3, this study; Mathias and Barica 1980; Charlton 1980; Cornett and Rigler 1980). Previously, data were insufficient to test whether a model incorporating both morphometry and estimates of productivity: (1) could be developed to predict WODR and (2) would be generally applicable to north temperate zone lakes. To develop a model to predict WODR over a wide range of lake types, estimates of WODR, open-water productivity, and morphometry from 48 lakes in Alberta, central and northwestern Ontario, and Manitoba (Table 5) were combined. These lakes covered a broad range in terms of mean depth ($1.5 \leq \bar{z} \leq 22.7$ m), and estimates of summer productivity ($2 \leq$ Chl $a \leq 184$ $mg \cdot m^{-2}$ and $24 \leq$ TP ≤ 222 $mg \cdot m^{-2}$) in the euphotic zone. Unfortunately TP data were not collected for the Manitoban lakes and TP estimates were available for only six lakes in northwestern Ontario. In the combined data set, WODR were strongly correlated with estimates of lake productivity and morphometry (Table 6). However, contrary to the results reported for regional data sets (excluding the transformed data set for the Albertan lakes), estimates of productivity were stronger single predictors of WODR than morphometry. Thus morphometric variables are better predictors of WODR within regions of similar productivity, but between regions of differing productivity, productivity is the strongest predictor of WODR. Next, I combined $\bar{z}$ with the estimates of productivity to examine whether a multiple regression would improve on the linear models to predict WODR. In all three cases, including estimates of both morphometry and open-water productivity improved the WODR models (Table 6). In each multiple regression, the estimate of open-water productivity explained more of the variation in WODR than morphometry. The WODR model based on summer TP ($mg \cdot m^{-2}$) and $\bar{z}$ had the highest correlation:

$$WODR = -0.101 + 0.00247\ TPsu + 0.0134\ \bar{z} \qquad (4)$$

However, TP data were available for fewer lakes than Chl *a*. When regressions were run on the lakes where summer TP data were available, but incorporating WODR, Chl *a*, and $\bar{z}$ in the regression, the correlation was highly significant (r = 0.78, $P<0.0001$) but lower than when summer TP was used. Thus, summer TP is a better predictor of WODR than Chl *a*. However, models based on $\bar{z}$ and some estimate of productivity, TP or Chl *a*, can be used to predict WODR over a wide range of lakes in north temperate regions.

One-Site-Sampling

In the five lakes where DO profiles were taken at more than one site, considerable horizontal variations in DO levels were found. There was no consistent pattern in the DO profiles at the various stations; depth at site sampled did not influence DO levels. For instance, on 22 January, 1983, in Lessard Lake at a depth of 1 m, DO concentration increased from 7.4 $mg \cdot L^{-1}$ at the site of maximum depth to 9.6 $mg \cdot L^{-1}$ at the site where the depth was only 1 m; whereas on 9 January, 1983, in Halfmoon Lake at a depth of 1 m, DO concentration decreased from 2.1 $mg \cdot L^{-1}$ at the site of maximum depth to 0.9 $mg \cdot L^{-1}$ at the site where the depth was only 1 m. To illustrate the possible error when only one site is sampled and the whole-lake oxygen mass is based on that site, oxygen profiles collected at six sites in Wizard Lake on 7 March, 1983, (Table 7) were used. To calculate DO mass for the whole lake based on all the sampling sites, DO mass was calculated for each site and summed together. To calculate the mass of oxygen at each site, the volume of each stratum was divided by the number of samples taken at that stratum depth. The DO concentration of each sample from each site, was multiplied by the corresponding volume associated with the sample, and all were summed together to provide the whole-lake oxygen mass. Whole-lake oxygen mass was divided by the volume of the lake to yield average oxygen concentration. The average DO value was 47% higher when data from all stations were used rather than data from the site of maximum depth (2.2 and 1.5 $mg \cdot L^{-1}$, respectively).

To further illustrate the possible errors which could result when whole-lake oxygen mass is calculated from data collected at only one site, three separate estimates of oxygen mass ($g \cdot m^{-2}$) were made for the upper 8 m of Wizard Lake. At each station that was a minimum of 8 m deep, the DO concentration at each depth was multiplied by the whole-lake stratum volume corresponding to the depth of the sample. The results were summed to yield oxygen mass in the upper 8 m and divided by the under-ice surface area. Oxygen mass calculated in this manner ranged from 8.1 to 16.8 $g \cdot m^{-2}$; the main station had 8.5 $g \cdot m^{-2}$. Thus, it appears that sampling at more than one site would improve estimates of whole-lake oxygen mass over one-site-sampling for Albertan lakes. However, in all sampling programmes, a trade-off must be made between the number of lakes sampled during the winter and the number of sites sampled on a lake at each visit.

E. Discussion

Previous authors (Welch et al. 1976; Barica and Mathias 1979; Mathias and Barica 1980) have reported that WODR are linear throughout the winter as long as average lake DO remains above anywhere from 1 to 3 $mg \cdot L^{-1}$. Data from this study do not support the generality of this observation. One possible explanation for the non-linear trends in my data is that WODR for the Albertan lakes are based on a longer time interval than previous studies. The WODR for the prairie pothole lakes were based on approximately 90 d (Barica and

Mathias 1979) as were the Ontario lakes (Welch et al. 1976). The nonlinear trends in WODR in this study can be explained if some organic material in the sediments is more easily oxidized and is used up first (Edberg 1976; Jackson and Lasenby 1982). The rate of oxygen supply to the sediments may also influence WODR. Since oxygen depletion rates are greatest at the sediment-water interface, whole-lake oxygen depletion is, in part, governed by the rate of oxygen supply to the sediments. The rate of oxygen supply to the sediment is a function of the distance to the sediments from water containing oxygen and the concentration of the water containing oxygen:

oxygen flux rate = K·(oxygen concentration gradient)

where K is the eddy diffusion constant (Mathias and Barica 1980). All of the Albertan lakes that mixed to the bottom at fall overturn developed clinograde oxygen profiles during the winter as shown by data from Baptiste South (Fig. 4). As the winter progressed, the DO in the lake decreased, the distance from the sediments to water containing DO increased, thus the oxygen flux rate could have also decreased. Methods to accurately measure the movement of oxygen from open water to the sediment-water interface need to be developed to assess the effect(s) of changing oxygen supply rates on WODR.

To test whether incomplete mixing at fall overturn would depress WODR, the data on Hubbles and Twin lakes were examined. Total phosphorus in Twin Lake (69 $mg{\cdot}m^{-2}$) is outside of the range of TP values used to construct Eq. 1 (97 to 223 $mg \cdot m^{-2}$), thus no comparison should be made between the predicted and observed WODR' for Twin Lake. The observed transformed WODR for Hubbles Lake (0.0846) was inside the 95% confidence interval predicted from Eq. 1 (0.0576 ± 0.0472), however the observed value was 41% higher than the predicted value. A possible explanation for why the observed WODR' is higher, rather than lower, than the predicted rate is that Hubbles Lake was sampled at only one location and there are three distinct deep spots, thus the error in the measured WODR may be greater than in the other Albertan lakes. Both Twin and Hubbles lakes have summer Chl *a* levels (6 and 21 $mg \cdot m^{-2}$) below the range of Chl *a* values used to generate Eq. 2 (27 to 147 $mg \cdot m^{-2}$), thus it is not possible to accurately predict WODR from Eq. 2 for these two lakes. Both Twin and Hubbles lakes have summer TP and mean depth values within the range of data used to generate Eq. 4; the predicted WODR, calculated from Eq. 4, for these two lakes (± 95% confidence interval) were: Hubbles, 0.311 ± 0.1638 and Twin, 0.279 g $O_2 \cdot m^{-2} \cdot d^{-1}$ ± 0.1702. The observed WODR for the lakes were: Hubbles, 0.475 and Twin, 0.193 g $O_2 \cdot m^{-2} \cdot d^{-1}$. As noted earlier, the observed WODR for Hubbles Lakes is probably incorrect due to inadequate sampling. Thus, more data are needed to determine the effect(s) of incomplete fall overturn on WODR.

To obtain better estimates of the oxygen content in lakes, data from this study suggest samples should be collected at several stations. Further research is needed to determine the extent, magnitude and cause(s) of spatial heterogeneity of DO profiles in lakes under ice-cover. Some likely causes are: (1) groundwater entering the lake, (2) differential oxygen depletion at various sites in the lake (Linsey 1981) and, (3) localized inputs of oxygen to the lake.

Jackson and Lasenby (1982) constructed two models that predict oxygen profiles in lakes under ice-cover: one model for lakes situated on the Precambrian Shield and another for lakes situated in limestone basins. These models are based on the oxygen concentration in the lake 5 to 15 [illegible]fter freeze-up. The two models were tested against t[illegible]bertan lake data to determine if oxygen profiles could be predicted. The model developed for lakes located on the Precambrian Shield consistently overestimated the final DO levels in the Albertan lakes by an average of 2.5 mg·L^{-1}; conversely, the model for lakes in limestone basins consistently underestimated the final oxygen levels by an average of almost 2.0 mg·L^{-1}. An underlying assumption of the models is that lakes in limestone basins are more productive than those on the Precambrian Shield; hence, DO is depleted faster in the limestone basin lakes. Jackson and Lasenby's model for lakes on the Precambrian Shield is based on only five lakes where the maximum depth ranges from eight to 33 m and average summer Chl *a* is approximately 2 mg·m^{-3}. The model developed for lakes in limestone basins is based on only three lakes where the maximum depth ranges from 16 to 18 m; summer productivity estimates are not available for these lakes, however they are probably more productive than the shield lakes but less productive than the Albertan lakes. Since the Albertan lakes are more productive than Ontario lakes, both on the Precambrian Shield and in limestone basins (mean summer Chl a concentration ($mg \cdot m^{-3}$ in 19 Ontario lakes was 1.4 (Dillon and Rigler 1974) and in 27 Albertan lakes was 26.5 (Prepas and Trew 1983)) it was expected that both models would predict higher final oxygen levels than observed in the Albertan lakes. Thus, the results were unexpected. However, it is possible that with a larger data set, incorporating an estimate of productivity into models which predict oxygen profiles under ice-cover will improve their generality.

If the same processes are influencing WODR and summer areal hypolimnetic oxygen deficits (AHOD), AHOD models may predict WODR. Four AHOD models were chosen and tested with WODR data from the Albertan lakes. The four AHOD models chosen require inputs which were available for the Albertan lakes: estimates of open-water productivity (SD, summer TP and Chl *a* levels), morphometry ($\bar{z}$), and water temperature (Lasenby 1975; Charlton 1980; Cornett and Rigler 1980). To assess the accuracy with which the AHOD models predicted WODR, I compared the residual mean squares (RMS) from the predicted WODR and the observed WODR for the 11 Albertan lakes (Table 4) with the RMS from Eq. 3 (RMS of equation 3 is 0.0078). Although the RMS for the AHOD models were four to 50 times greater than for Eq. 3, only Lasenby's model explained statistically less variation than the WODR model on the Albertan lakes (*F*-test, two tailed, $P<0.005$). The AHOD models by Cornett and Rigler, and Charlton each explained approximately the same amount of variation of WODR in the 11 Albertan lakes, and although the RMS's for the AHOD models were four times greater than the RMS from Eq. 3, the differences were not statistically significant (*F*-test, two tailed, $0.05<P<0.20$).

To determine if the AHOD models could predict WODR over a broad range of lake types, I compared the RMS from Eq. 4 (RMS = 0.0065) to the RMS for the two AHOD models of Cornett and Rigler, based on the same lakes used to construct Eq. 4. The RMS for model #3, Table 4, based on mean summer TP and mean depth, was 0.0124 and the RMS for model #4, Table 4, based on mean summer SD and mean depth, was 0.0137. Although the RMS for the two AHOD models are approximately twice as great as the RMS for Eq. 4, the differences are not statistically significant ($0.02<P<0.10$). Thus, it appears that WODR can be accurately predicted from equations that incorporate estimates of both productivity and morphometry.

The most important parameter in the models to predict WODR and AHOD over a broad range of lake types are estimates of open-water productivity (summer TP or Chl *a*) (This study, Table 6; Cornett and Rigler 1980; Charlton 1980). Both WODR and AHOD are influenced by morphometry but to a lesser degree than productivity. Summer hypolimnetic oxygen depletion is also influenced by temperature (Charlton 1980; Cornett 1981) and WODR could be as well, although sufficient data do not exist to test this hypothesis. Incorporating temperature in equations to predict AHOD is warranted since there may be large temperature differences in the hypolimnia of various lakes in summer; Charlton (1980) reported mean summer hypolimnetic temperatures ranging from 4.0 to 11.0°C in the Laurentian Great Lakes. During the period of ice-cover, the temperature variation between lakes is not as great as the temperature variation between lake hypolimnia during summer; Jackson (1979) reported mean winter volume-weighted temperatures ranging from 3.0 to 3.4°C in three lakes in Ontario, and the variation in mean winter volume-weighted temperatures in the Albertan lakes was 2.2 to 3.4°C. Although biological processes are influenced by temperature, there is little variation in temperature between ice-covered lakes, and thus the influence of temperature on WODR is likely less than on AHOD.

The models developed to predict WODR over a broad range of lake types need to be tested with an independent data set to determine their accuracy. Data from lakes outside the original data set, e.g. shallow and unproductive, need to be collected to improve the generality of the models.

Table 1. Percent oxygen saturation in 13 Alberta lakes during fall and early winter, 1982. Measured oxygen saturation on the last visit before freeze-up (Prior), the first visit after freeze-up (Post), and predicted oxygen saturation on date of freeze-up calculated from the Y-intercept of the regression of transformed oxygen mass against time (Predicted). Numbers in parenthesis refer to the number of days before or after freeze-up when the lake was visited.† indicates lake did not mix to the bottom at fall turnover.

	% OXYGEN SATURATION		
	Measured		Predicted
LAKE	Prior	Post	
Amisk N	64(5)	64(21)	66
Amisk S	52(1)	54(21)	55
Baptiste S	58(5)	67(21)	70
Eden	62(1)	72(12)	67
Halfmoon	48(11)	55(9)	64
Hasse	94(9)	97(11)	97
Hubbles†	53(12)	54(9)	55
Lessard	65(19)	82(14)	77
Nakamun	60(9)	52(12)	52
Peanut	66(21)	70(7)	68
Sauer	72(11)	72(10)	77
Twin†	47(4)	59(12)	51
Wizard	88(9)	67(15)	81

Table 2: Winter oxygen depletion rates (g $O_2 \cdot m^{-2} \cdot d^{-1}$) during the first 112 days past freeze-up, and correlation coefficients, r, for the mass of oxygen (on linear and transformed, $X' = X^{0.45}$, data) vs days past freeze-up: All, rate covering entire 112-day period; Early, rate based on first three sampling dates; Later, rate based on remaining dates; Trans, rate calculated on All data transformed. Sample size is indicated in parenthesis. † indicates lake did not mix to bottom at fall turnover.

	WINTER OXYGEN DEPLETION RATES				r	
LAKE	ALL	EARLY	LATER	TRANS	ALL	TRANS
Amisk N	0.554(5)	---	---	0.0877	0.98	0.99
Amisk S	0.848(5)	---	---	0.1162	0.98	0.99
Baptiste S	0.775(5)	---	---	0.1180	0.99	0.99
Eden	0.331(7)	0.481(3)	0.286(4)	0.0582	0.99	1.00
Halfmoon	0.462(6)	0.373(3)	0.448(3)	0.1352	0.99	0.98
Hasse	0.373(6)	0.426(3)	0.315(3)	0.0799	1.00	1.00
Hubbles†	0.475(7)	0.345(3)	0.520(4)	0.0846	0.99	0.99
Lessard	0.243(8)	0.342(3)	0.222(5)	0.0518	0.99	0.99
Nakamun	0.281(10)	0.587(3)	0.184(7)	0.0773	0.96	0.98
Peanut	0.405(7)	0.512(3)	0.363(4)	0.0881	1.00	1.00
Sauer	0.363(6)	0.428(3)	0.271(3)	0.0988	0.99	1.00
Twin†	0.193(5)	---	---	0.0258	0.99	0.99
Wizard	0.533(5)	---	---	0.1052	0.99	0.99

Table 3: Correlation coefficients for winter oxygen depletion rates (g $O_2 \cdot m^{-2} \cdot d^{-1}$), both transformed ($X' = X^{0.65}$) and linear data vs six parameters: mean depth ($\bar{z}$), maximum depth (Zmax), loss on ignition (LOI), spring and summer total phosphorus (TPsp and TPsu), and summer chlorophyll a (Chl *a*), in Albertan lakes. Phosphorus and chlorophyll are expressed per unit area of the lake and per unit volume of the trophogenic zone. Significant correlations are indicated by: *(P<0.05), **(P<0.01), and ***(P<0.005).

Parameter	Transformed	Linear
$\bar{z}$ (m)	0.41	0.90***
Zmax (m)	0.36	0.82**
LOI (%)	-0.72*	-0.36
TPsp ($mg \cdot m^{-2}$)	0.46	0.73**
TPsu ($mg \cdot m^{-2}$)	0.72*	0.64*
Chl *a* ($mg \cdot m^{-2}$)	0.72*	0.37
TPsp ($mg \cdot m^{-3}$)	0.68*	0.23
TPsu ($mg \cdot m^{-3}$)	0.46	0.01
Chl *a* ($mg \cdot m^{-3}$)	0.40	-0.09

Ta : Deviations of predicted winter oxygen depletion rates (WODR) from e WODR for 11 Albertan lakes. The predicted values are based on six mo which are listed below: two WODR models (1&2) and four summer areal hypolimnetic oxygen depletion (AHOD) models (3,4,5&6). RMS is the residual mean square associated with the model, and df is the degrees of freedom associated with each model. (---- indicates WODR were not calculated since SD is less than 1 m)

Lake	MODEL 1	2	3	4	5	6
Amisk N	-0.345	0.253	-0.085	-0.050	0.139	-0.212
Amisk S	-0.535	0.502	-0.254	-0.158	0.326	-0.562
Baptiste S	-0.544	0.149	-0.243	-0.287	0.040	-0.360
Eden	-0.168	0.242	-0.030	-0.074	-0.011	0.312
Halfmoon	-0.325	-0.025	0.079	0.088	0.019	1.503
Hasse	-0.248	-0.004	-0.116	-0.150	-0.127	0.172
Lessard	-0.116	0.141	0.037	0.084	0.131	0.058
Nakamun	-0.152	0.131	0.261	----	0.195	----
Peanut	-0.261	0.076	-0.109	-0.175	-0.078	0.226
Sauer	-0.233	0.036	-0.083	-0.174	-0.099	0.327
Wizard	-0.379	-0.008	-0.072	0.079	-0.021	-0.278
RMS	0.1322	0.0491	0.0306	0.0313	0.0308	0.3894
df	9	9	8	7	7	9

(Table 4 cont'd)

1. $WODR = 0.08 + 0.012\,\bar{z}$ (Welch et al. 1976)

2. $WODR = 0.14 + 0.062\,\bar{z}$ (Barica and Mathias 1979)

3. $\log_{10}AHOD = 1.52 + 0.48\log_{10}(TP) + 0.38\log_{10}(\bar{z})$ (Cornett and Rigler 1980)

4. $\log_{10}AHOD = 2.45 - 0.67\log_{10}(SD) + 0.47\log_{10}(\bar{z})$ (Cornett and Rigler 1980)

5. $AHOD = \left(\frac{3.8(1.15(Chl\ a)^{1.33})\cdot\bar{z}\cdot 2^{(t/10)}}{(9 + 1.15(Chl\ a)^{1.33})\cdot(50 + \bar{z})} + \frac{0.12(1.15(Chl\ a)^{1.33})}{9 + 1.15(Chl\ a)^{1.33}}\right.$ (modified from Charlton 1980)

6. $\log_{10}AHOD = -1.37\log_{10}(SD) - 0.65$ (Lasenby 1975)

Where $\bar{z}$ is mean depth, SD is mean summer Secchi disc depth, TP is mean summer total phosphorus in the euphotic zone, Chl a is mean summer chlorophyll a in the euphotic zone and t is mean lake temperature under ice-cover (modified from the original expression where t was (t-4)).

Table 5: Winter oxygen depletion rates (WODR) (g $O_2 \cdot m^{-2} \cdot d^{-1}$), mean depth ($\bar{z}$), total phosphorus (TP) ($mg \cdot m^{-2}$), and chlorophyll *a* (Chl *a*) ($mg \cdot m^{-2}$) from four sets of temperate zone lakes in Canada.

LAKE	WODR	$\bar{z}$ (m)	SPRING TP ($mg \cdot m^{-2}$)	SUMMER TP ($mg \cdot m^{-2}$)	SUMMER CHl *a* ($mg \cdot m^{-2}$)
ALBERTA[1]					
Amisk N	0.554	10.7	502	222	61
Amisk S	0.848	19.4	422	219	86
Baptiste S	0.775	12.6	320	202	64
Eden	0.331	6.9	223	177	27
Halfmoon	0.462	4.8	257	215	147
Hasse	0.372	3.7	199	174	26
Lessard	0.243	3.9	115	97	42
Nakamun	0.285	4.5	181	135	72
Peanut	0.407	5.5	260	211	37
Sauer	0.363	4.2	265	208	28
Wizard	0.533	6.2	235	192	64
CENTRAL ONTARIO[2, 3, 4]					
Beech	0.282	9.8	81	73	10
Bob	0.273	18.0	100	79	14
Boshkung	0.393	23.4	88	69	14
Cameron	0.217	7.1	83	88	14
Cranberry	0.075	3.5	70	83	11
Eagle	0.169	7.9	92	76	22

(Table 5 cont'd)

LAKE	WODR	$\bar{z}$ (m)	SPRING TP ($mg \cdot m^{-2}$)	SUMMER TP ($mg \cdot m^{-2}$)	SUMMER Chl *a* ($mg \cdot m^{-2}$)
Four Mile	0.282	9.3	124	98	16
Green	0.117	6.1	91	87	16
Haliburton	0.295	19.6	82	58	12
Halls	0.373	27.2	71	63	13
L.Boshkung	0.127	7.6	80	59	19
Maple	0.242	11.6	72	79	11
Moose	0.295	16.6	77	73	13
Oblong	0.186	11.2	73	66	25
Pine	0.097	7.4	71	85	13
Twelve Mile	0.286	11.5	76	68	16
NORTH-WEST ONTARIO[5,6,7]					
122	0.253	7.2			24
132	0.110	3.3			17
227	0.223	4.4		73	16
230	0.138	6.2			41
239	0.186	10.5		74	11
240	0.199	6.1		50	7
261	0.045	2.9			9
265	0.171	9.8			18
303	0.036	1.5		24	2
304	0.236	3.2		71	3
305	0.207	15.1		92	11

(Table 5 cont'd)

LAKE	WODR	$\bar{z}$ (m)	SPRING TP ($mg \cdot m^{-2}$)	SUMMER TP ($mg \cdot m^{-2}$)	SUMMER CHl *a* ($mg \cdot m^{-2}$)
MANITOBA[8,9]					
885	0.260	1.8			184
882	0.270	2.1			90
255	0.290	1.8			37
318	0.220	1.6			64
587	0.260	2.5			53
721	0.240	1.6			26
675	0.340	2.7			55
200	0.320	2.8			54
019	0.330	3.4			49
Nora	0.420	4.2			57

[1]Data on TP and Chl *a* for Nakamun and Halfmoon lakes from Riley (1983); all other TP and Chl *a* data from Prepas and Vickery (1984).

[2]Data on WODR from Welch et al. (1976).

[3]Data on spring TP and summer Chl *a* from Dillon and Rigler (1974).

[4]Data on summer TP from Dr. P.J. Dillon (unpublished).

[5]Data on WODR from Schindler (1971).

[6]Data on summer TP from Reid et al. (1975) and G. Linsey (Freshwater Institute, Winnipeg, Manitoba, Pers. Comm.)

(Table 5 cont'd)

[7]Data on summer Chl *a* from Armstrong and Schindler (1971) and Reid et al. (1975)

[8]Data on WODR from Barica and Mathias (1979).

[9]Data on summer Chl *a* from Barica et al. (1978) and Mathias and Barica (1980).

Table 6: Regression analysis of winter oxygen depletion rates (WODR) (g $O_2 \cdot m^{-2} \cdot d^{-1}$) vs four parameters: mean depth ($\bar{z}$), spring and summer total phosphorus (TPsp and TPsu) ($mg \cdot m^{-2}$), and summer chlorophyll *a* (Chl *a*) ($mg \cdot m^{-2}$) for the lakes in Table 5. Number of lakes used in each regression (*n*), correlation coefficient of each regression (*r*). Significant correlations are incicated by *(P<0.05), **(P<0.005), and ***(P<0.001).

PARAMETER	*n*	EQUATION	*r*
$\bar{z}$	48	WODR = 0.214 + 0.00894 $\bar{z}$	0.34*
TPsp	27	WODR = 0.124 + 0.00128 TPsp	0.81***
TPsu	33	WODR = 0.052 + 0.00227 TPsu	0.77***
Chl *a*	48	WODR = 0.212 + 0.00201 Chl*a*	0.44**
TPsp,$\bar{z}$	27	WODR = −0.001 + 0.00134 TPsp + 0.0119 $\bar{z}$	0.89***
TPsu,$\bar{z}$	33	WODR = −0.101 + 0.00247 TPsu + 0.0134 $\bar{z}$	0.90***
Chl *a*,$\bar{z}$	48	WODR = 0.093 + 0.00257 Chl *a* + 0.0127 $\bar{z}$	0.65***

Table 7: Dissolved oxygen ($mg \cdot L^{-1}$) profiles at six sampling sites on Wizard Lake, March 7, 1983.

	DISSOLVED OXYGEN					
	SITE					
DEPTH (m)	1	2	3	4	5	6
1	3.22	5.95	2.75	4.82	5.15	4.16
2	2.24	3.91	2.25	3.89	4.16	3.50
3	1.97	3.73	2.04	3.59	3.85	
4	1.89	3.37	1.24	3.21	3.35	
5	1.30	3.25	1.11	2.86	3.22	
6	0.89	2.00	0.90	2.75		
7	0.89	2.11	0.69			
8	0.38	1.41	0.87			
9	0.22					
10	0.08					
11	0.05					

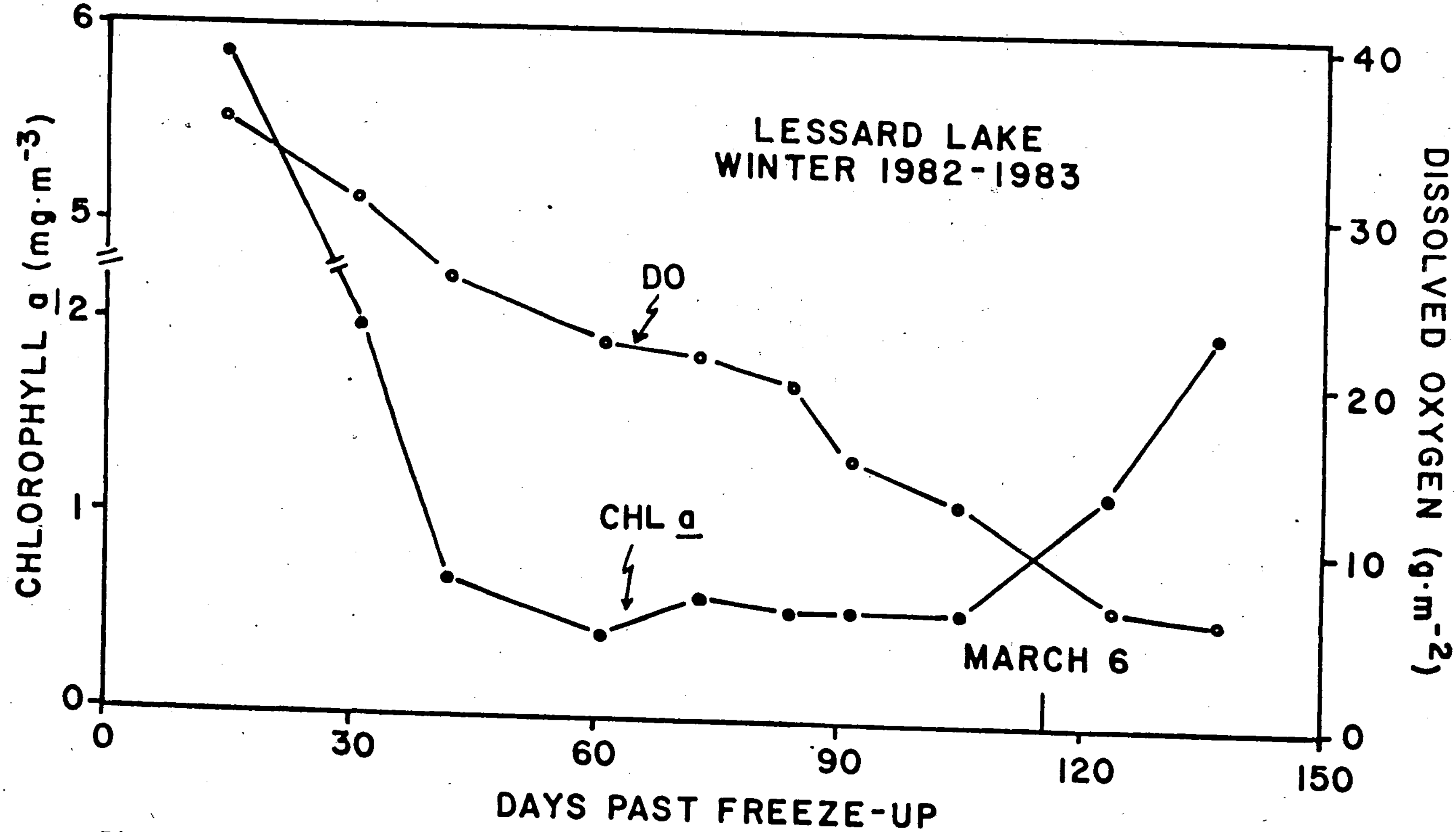

Figure 1: Average chlorophyll a (Chl a) ($mg \cdot m^{-3}$) (●) in the top 4 m of Lessard Lake, and whole-lake mass of dissolved oxygen (DO) ($g \cdot m^{-2}$) (o) during the winter of 1982-83.

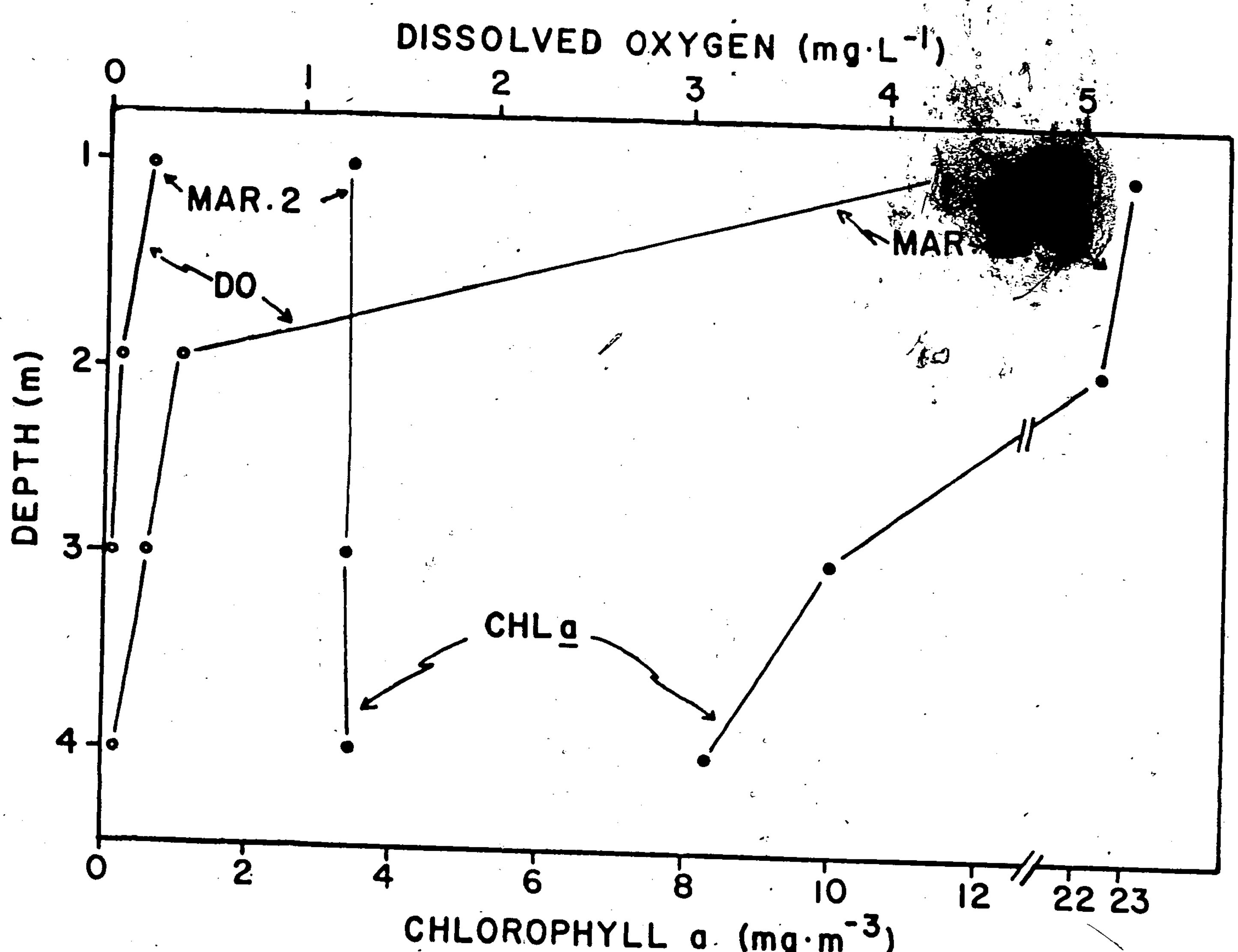

Figure 2: Verical distribution of chlorophyll a (Chl a) ($mg \cdot m^{-3}$) (●) and dissolved oxygen (DO) ($mg \cdot L^{-1}$) (o) in the top 4 m of Sauer Lake on the last two sampling dates (March 2 and March in 1983.

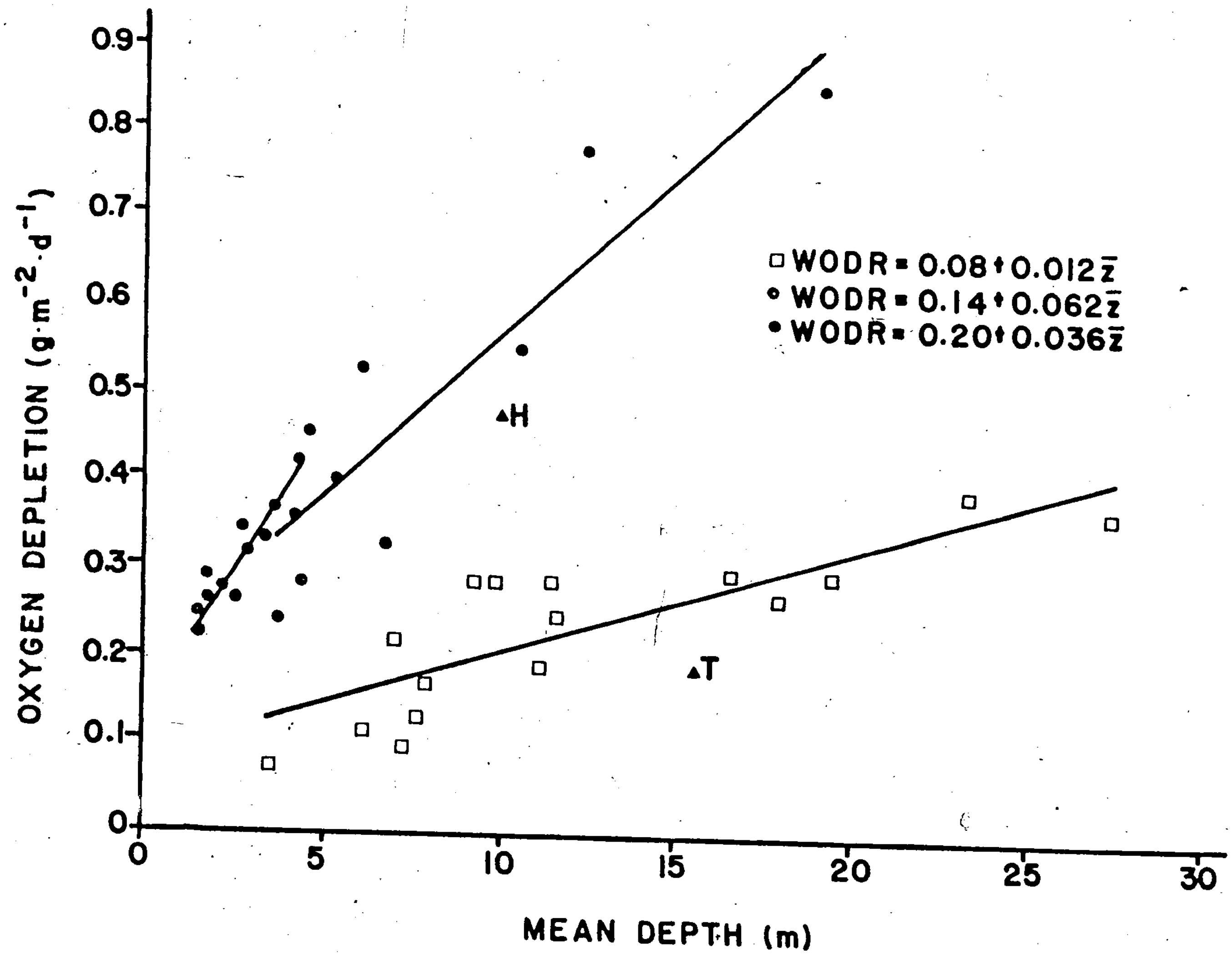

Figure 3: Relationship between winter oxygen depletion rates (WODR) and mean depth ($\bar{z}$) for three sets of temperate zone lakes in Canada: Welch et al. (1976) (□); Barica and Mathias (1979) (○); this study (●). Hubbles Lake (▲H) and Twin Lake (▲T) are part of this study but not included in the regression analysis.

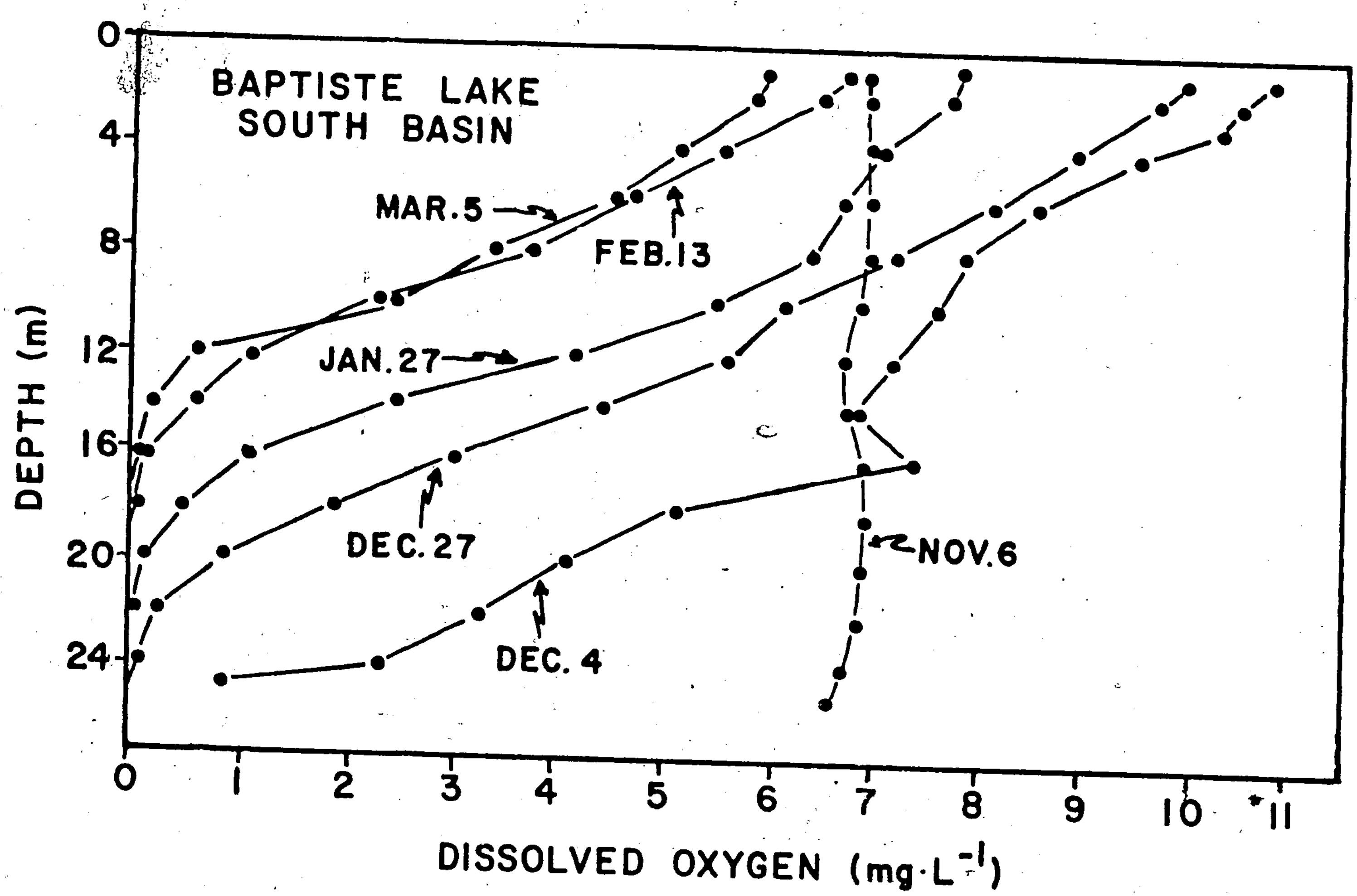

Figure 4: Dissolved *oxygen* profiles from Baptiste Lake, South Basin, during the fall and winter of 1982-83.

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III. General Discussion and Conclusions

(1) One-site sampling

The development of empirical models to predict WODR are based on oxygen profiles obtained from a single site in the lake (Welch et al. 1976; Barica and Mathias 1979; Jackson and Lasenby 1982). I have shown that one-site sampling is not representative of whole-lake oxygen profiles in Albertan lakes. Possible causes of this horizontal heterogeneity may be differential oxygen depletion (Linsey 1981) or localized inputs of oxygen to the lake. Research into the extent, magnitude, and causes of this heterogeneity needs to be performed to obtain better estimates of whole-lake oxygen content under ice-cover.

(2) Chlorophyll *a* under ice

In 12 of the study lakes the average Chl *a* level, during the period WODR were calculated, was 2.9 $mg \cdot m^{-3}$. After this period Chl *a* levels increased and a concommitant rise in DO levels was observed. In the 13th lake, Halfmoon Lake, there was an algal bloom shortly after freeze-up (32 $mg \cdot m^{-3}$ Chl *a*) and, when the algae died, the WODR for this lake increased from 0.373 to 0.448 g $O_2 \cdot m^{-2} \cdot d^{-1}$. Two possible explanations for the increased WODR in Halfmoon Lake after the algae died are: (1) oxygen may have been introduced to the lake via photosynthesis, during the bloom, thereby slowing down the net consumption of oxygen, or (2) when the algae died-off, the consumption of oxygen may have increased since the algae were a fresh supply of organic material available for decomposition. Since primary production was not measured, it is not possible to determine the exact effect algae had on WODR in Halfmoon Lake. Thus, more research is needed to determine what effect(s), both direct and indirect, algae under ice-cover have on WODR.

(3) Nonlinear WODR

In this study, WODR were found to be higher at the beginning of the winter than at the end. Jackson and Lasenby (1982) also found that oxygen was depleted in a nonlinear fashion in lakes under ice-cover in Ontario. Transformed WODR (WODR') are correlated with estimates of open-water productivity, summer TP (TPsu) and Chl *a*, in the Albertan lakes:

$$\text{WODR}' = 0.005 + 0.00047\ \text{TPsu}$$

$$\text{WODR}' = 0.062 + 0.00052\ \text{Chl}\ a$$

Oxygen will be depleted in a nonlinear manner if any of the following conditions are met: (1) the material to be oxidized becomes more resistant to breakdown as the winter progresses (Hargrave 1971); (2) any oxygen depletion taking place in the water column decreases during the winter or; (3) the supply of oxygen to the site where oxidation is occurring decreases to the point where oxygen supply becomes limiting (Mathias and Barica 1980). Since 10 of the 11 study lakes that mixed to the bottom at fall overturn developed anoxic conditions at the bottom by late winter, the supply of oxygen to the bottom sediments could have influenced WODR. The influence which the nature of the material to be oxidized and the supply of oxygen to the sediments have in DO depletion needs further examination.

(4) Linear WODR in lakes

If the WODR in the central Albertan lakes are treated as linear for the 112-days past freeze-up, WODR can be predicted for these lakes if mean depth is known, an observation consistent with the findings of other investigators (Welch et al. 1976; Bariça and Mathias 1979):

$$WODR = 0.20 + 0.036\ \bar{z}$$

Data from other studies (Schindler 1971; Welch et al. 1976; Barica and Mathias 1979) were combined with data from this study and a new model to predict WODR was constructed:

$$WODR = -0.101 + 0.00247\ TPsu + 0.0134\ \bar{z}$$

This equation incorporates both morphometry and estimates of lake productivity as predictors of WODR, demonstrating the interactions of both of these parameters on WODR. This new model is the first model which can predict WODR beyond small geographic regions with specific lake types. More data need to be collected for a wider range of lakes (e.g., shallow and unproductive) to improve the generality of WODR models. These data can also be used to determine if nonlinear models are generally better than linear models to predict WODR.

(5) Predicting oxygen profiles under ice

Existing models to predict oxygen profiles under ice-cover (Jackson and Lasenby, 1982) did not accurately predict DO levels in the Albertan lakes. The model developed for lakes on the Precambrian Shield consistently overestimated DO levels while the model developed for lakes in limestone basins consistently underestimated DO levels in the Albertan lakes. More data on WODR are needed to improve on the existing models. Incorporating an estimate of productivity will likely improve upon the models.

(6) Summer AHOD models vs WODR models

Models developed to predict AHOD (Cornett and Rigler 1980; Charlton 1980) were able to accurately predict WODR in the Albertan lakes. Cornett and Rigler's AHOD models were also able to accurately predict WODR over a wide variety of lake types. These AHOD models incorporated estimates of both productivity and morphometry, illustrating that the magnitude of oxygen depletion in lakes is governed by both morphometry and productivity.

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IV. Appendix A: Chemical data for the study lakes

Table 1: Dissolved oxygen (mg·L⁻¹), snow and ice thickness (cm) and depth sampled (m) for the study lakes during each visit in the fall and winter of 1982-83.

Amisk North

Date	Nov 6	Dec 4	Dec 27	Jan 27	Feb 13	Mar 5	Mar 30
Snow	--	4	11	16	21	22	11
Ice	--	21	37	38	44	45	49
Depth							
1	8.12	8.97	7.72	6.45	6.04	5.89	5.36
2	8.09	8.35	7.58	6.22	5.80	5.50	4.97
3	8.06	7.83	7.56	6.01	5.46	5.11	4.46
4	7.80	7.65	7.64	5.79	5.35	4.87	3.95
5	7.53	7.99	7.63	[illegible]	5.25	[illegible]	3.58
6	7.74	8.32	7.62	[illegible]	4.71	[illegible]	3.12
7	7.94	8.66	7.61	5.15	4.47	[illegible]	2.75
8	7.95	8.56	7.30	4.73	4.23	3.63	2.83
9	7.95	8.46	6.98	4.31	3.52	3.20	1.99
10	8.01	8.37	6.77	3.89	3.08	3.10	1.15
11	8.06	8.15	6.56	3.75	2.64	2.90	0.53
12	8.06	7.92	6.36	3.60	2.45	2.60	0.42
13	8.06	7.70	6.17	3.37	2.25	1.97	0.30
14	8.05	7.49	5.98	3.14	2.05	1.33	0.15
15	8.04	7.28	5.58	2.90	1.82	0.58	0.14
16	8.06	7.08	5.18	2.65	1.44	0.36	0.06
17	8.08	6.88	4.78	2.21	1.05	0.19	0.03
18	8.03	6.69	4.10	1.77	0.73	0.02	0.00
19	7.98	6.49	3.42	1.27	0.40	0.02	0.00
20	8.08	5.88	2.80	0.77	0.31	0.02	0.00
21	8.19	5.27	2.18	0.59	0.22	0.01	0.00
22	8.20	4.66	1.56	0.40	0.18	0.00	0.00
23	8.20	4.51	1.07	0.27	0.13	0.00	0.00
24	8.19	4.35	0.57	0.13	0.07	0.00	0.00
25	8.17	4.01	0.08	0.00	0.00	0.00	0.00
26	8.17	3.66	0.08	0.00	0.00	0.00	0.00
27	8.17	3.41	0.07	0.00	0.00	0.00	0.00
28	8.12	3.15	0.06	0.00	0.00	0.00	0.00
29	8.06	3.14	0.05	0.00	0.00	0.00	0.00
30	8.06	1.92	0.03	0.00	0.00	0.00	0.00

(Table 1 cont'd)

Amisk South

Date	Nov 11	Dec 4	Dec 27	Jan 27	Feb 13	Mar 5	Mar 30
Snow	--	3	6	13	16	18	13
Ice	--	21	34	39	50	52	52
Depth							
1	6.84	9.48	7.96	6.39	5.90	5.53	5.09
2	6.90	8.57	7.64	6.14	5.48	5.07	4.69
3	6.96	8.73	7.39	5.96	5.30	4.93	4.27
4	7.01	8.36	7.09	5.77	5.24	4.67	3.97
5	7.03	7.95	6.94	5.63	5.17	4.40	3.81
6	6.96	7.54	6.80	5.49	5.10	4.36	3.75
7	6.92	7.13	6.65	5.35	4.93	4.31	3.61
8	6.85	7.32	6.53	5.25	4.75	3.90	3.47
9	6.78	7.51	6.42	5.14	4.59	4.11	3.03
10	6.74	7.70	6.30	5.03	4.51	4.05	2.93
11	6.77	7.48	6.18	4.78	4.38	3.88	2.73
12	6.80	7.26	6.06	4.53	4.25	3.34	2.63
13	6.83	7.05	5.84	4.39	3.67	3.16	2.40
14	6.87	6.83	5.62	4.24	3.08	3.33	2.21
15	6.91	6.61	5.49	4.02	2.93	3.13	2.19
16	6.80	6.39	5.37	3.80	2.77	2.93	1.96
17	6.69	6.27	5.24	3.67	2.57	2.70	1.83
18	6.59	6.16	5.03	3.54	2.37	2.77	1.57
19	6.50	6.04	4.81	3.49	2.08	2.46	1.34
20	6.41	5.99	4.60	3.44	1.79	2.04	1.38
21	6.38	5.93	4.45	3.28	1.61	1.93	1.22
22	6.37	5.88	4.30	3.11	1.09	1.36	1.17
23	6.35	5.84	4.06	2.91	0.99	1.30	1.08
24	6.33	5.80	3.82	2.70	1.04	1.24	0.98
25	6.32	5.70	3.59	1.80	0.86	1.13	0.74
26	6.31	5.60	3.35	0.89	0.61	1.01	0.48
27	6.30	5.48	3.29	1.07	0.56	0.60	0.50
28	6.29	5.35	3.22	1.25	0.47	0.18	0.20
29	6.28	5.31	3.15	0.89	0.38	0.10	0.22
30	6.27	5.26	3.23	0.52	0.21	0.02	0.24
31	6.25	5.10	3.30	0.28	0.03	0.00	0.00
32	6.24	4.93	3.38	0.03	0.05	0.00	0.00
33	6.22	4.72	3.01	0.03	0.05	0.00	0.00
34	6.20	4.50	2.63	0.03	0.05	0.00	0.00
35	6.19	4.29	2.16	0.03	0.04	0.00	0.00
36	5.78	4.07	1.69	0.02	0.02	0.00	0.00
37	5.37	4.00	1.75	0.02	0.02	0.00	0.00
38	4.92	3.92	1.81	0.02	0.02	0.00	0.00
39	4.47	3.83	1.59	0.03	0.00	0.00	0.00
40	4.03	3.73	1.36	0.04	0.00	0.00	0.00

(Table 1 cont'd)

Amisk South cont'd

41	3.47	3.43	1.42	0.05	0.00	0.00	0.00
42	2.91	3.13	1.47	0.06	0.00	0.00	0.00
43	2.35	3.02	1.49	0.00	0.00	0.00	0.00
44	2.07	2.91	1.51	0.00	0.00	0.00	0.00
45	1.80	2.77	1.15	0.00	0.00	0.00	0.00
46	1.64	2.64	0.79	0.00	0.00	0.00	0.00
47	1.48	2.64	0.43	0.00	0.00	0.00	0.00
48	1.32	2.63	0.33	0.00	0.00	0.00	0.00
49	1.17	2.55	0.22	0.00	0.00	0.00	0.00
50	1.02	2.47	0.27	0.00	0.00	0.00	0.00
51	0.92	2.22	0.31	0.00	0.00	0.00	0.00
52	0.77	2.12	0.00	0.00	0.00	0.00	0.00
53	0.62	2.02	0.00	0.00	0.00	0.00	0.00
54	0.47	1.85	0.00	0.00	0.00	0.00	0.00
55	0.34	1.67	0.00	0.00	0.00	0.00	0.00
56	0.21	1.50	0.00	0.00	0.00	0.00	0.00
57	0.09	1.32	0.00	0.00	0.00	0.00	0.00
58	0.04	0.09	0.00	0.00	0.00	0.00	0.00
59	0.00	0.00	0.00	0.00	0.00	0.00	0.00
60	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(Table 1 cont'd)

Baptiste Lake

Date	Nov 6	Dec 4	Dec 27	Jan 27	Feb 13	Mar 5	Mar 30
Snow	--	8	6	10	15	17	14
Ice	--	11	37	53	61	63	66
Depth							
1	7.17	10.99	10.11	7.98	6.86	6.12	6.43
2	7.05	10.64	9.90	7.89	6.46	5.97	5.65
3	7.16	10.49	9.51	7.42	6.10	5.71	4.89
4	7.12	9.68	9.09	7.19	5.67	5.27	4.50
5	7.08	9.18	8.70	6.95	5.23	4.83	4.10
6	7.09	8.68	8.30	6.86	4.83	4.64	3.25
7	7.09	8.34	7.91	6.77	4.42	3.68	3.13
8	7.08	8.00	7.33	6.57	3.87	3.45	2.79
9	7.08	7.89	6.74	6.37	3.32	3.09	2.45
10	7.01	7.78	6.37	5.66	2.39	2.55	2.08
11	6.94	7.57	6.00	4.94	1.46	1.12	1.62
12	6.86	7.36	5.71	4.25	1.17	0.69	1.02
13	6.77	7.17	5.41	3.55	1.07	0.26	0.06
14	6.87	6.97	4.51	2.56	0.67	0.21	0.03
15	6.97	7.25	3.60	1.56	0.26	0.24	0.00
16	7.02	7.53	3.09	1.17	0.16	0.26	0.00
17	7.06	6.38	2.57	0.77	0.05	0.13	0.00
18	7.05	5.22	1.94	0.53	0.05	0.00	0.00
19	7.04	4.72	1.30	0.29	0.05	0.00	0.00
20	7.05	4.21	0.89	0.18	0.03	0.00	0.00
21	7.06	3.79	0.48	0.06	.00	0.00	0.00
22	7.00	3.37	0.26	0.05	0.00	0.00	0.00
23	6.95	2.89	0.04	0.04	0.00	0.00	0.00
24	6.87	2.41	0.05	0.02	0.00	0.00	0.00
25	6.78	1.98	0.05	0.00	0.00	0.00	0.00

(Table 1 cont'd)

Lake Eden

Date	Nov 10	Nov 24	Dec 10	Dec 20	Jan. 18
Snow	--	5	3	3	4
Ice	--	16	34	41	42
Depth					
1	9.56	10.40	9.65	9.49	8.70
2	9.36	9.97	9.12	8.86	8.02
3	9.20	9.56	8.97	8.68	7.80
4	9.17	9.33	8.75	8.45	7.72
5	9.10	9.20	8.51	8.25	7.67
6	9.04	8.93	8.47	7.98	6.94
7	9.01	8.55	7.71	7.28	5.55
8	8.99	7.89	6.33	5.75	2.18
9	8.97	7.85	4.95	4.21	0.46
10	8.94	6.90	5.36	2.84	0.65
11	8.89	4.92	3.46	92	0.54
12	8.76	5.36	2.18	65	0.37
13	8.24	4.86	0.65	.41	0.17
14	7.48	2.47	0.32	0.32	0.00
15	0.98	1.38	0.30	0.1[illegible]	0.00

Date	Feb 4	Feb 15	Feb 26	Mar 14	Mar 27
Snow	9	8	0	0	9
Ice	50	54	57	60	63
Depth					
1	7.79	7.38	7.29	7.54	9.21
2	7.27	6.88	6.75	6.74	7.74
3	7.07	6.47	6.48	6.68	7.05
4	6.91	6.45	6.15	6.23	6.27
5	6.80	6.05	5.65	5.58	4.10
6	5.91	4.56	3.29	3.38	3.71
7	4.98	3.90	2.82	3.19	2.37
8	2.76	2.17	0.81	0.51	1.56
9	1.74	1.29	0.52	0.86	0.24
10	0.54	0.59	0.25	0.15	0.22
11	0.36	0.14	0.12	0.07	0.24
12	0.16	0.02	0.03	0.00	0.00
13	0.04	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00

(Table 1 cont'd)

Halfmoon Lake

Date	Oct 29	Nov 18	Dec 2	Dec 14	Dec 24	Jan 9	Jan 25	Mar 10
[illegible]	--	2	6	4	5	4	5	5
Ice	--	18	21	35	39	48	58	60
Depth								
1	5.92	7.66	7.14	6.55	4.81	2.01	0.03	1.72
2	5.82	7.57	6.59	5.47	3.91	1.55	0.00	0.18
3	5.82	7.52	6.38	5.24	3.64	1.31	0.00	0.03
4	5.82	6.76	5.55	4.80	3.31	0.91	0.01	0.00
5	5.81	6.17	4.81	3.60	2.92	0.70	0.01	0.00
6	5.69	5.53	2.38	3.13	1.45	0.17	0.00	0.00
7	5.77	3.11	1.15	1.71	0.87	0.29	0.00	0.00
8	5.63	2.23	0.43	0.29	0.74	0.10	0.02	0.00

Wizard Lake

Date	Nov 1	Nov 26	Dec 15	Jan 15	Jan 31	Feb 17	Mar 7	Mar 22
Snow	--	5	6	3	5	7	13	13
Ice	--	17	35	43	55	52	64	63
Depth								
1	10.39	10.53	9.25	6.44	4.57	3.25	3.22	5.73
2	10.41	10.43	8.86	5.97	4.18	2.65	2.24	2.43
3	10.37	9.82	8.52	5.79	3.99	2.31	1.97	1.77
4	10.37	9.19	8.47	5.56	3.82	2.27	1.89	1.52
5	10.39	9.19	8.03	5.40	2.89	2.02	1.30	1.01
6	10.39	8.53	7.54	5.29	1.39	1.64	0.89	0.81
7	10.33	8.24	6.82	3.02	[illegible]	[illegible]	0.89	0.40
8	10.38	7.46	5.31	2.55	0.68	1.29	0.38	0.33
9	10.39	6.17	4.37	1.83	0.17	0.88	0.22	0.20
10	10.31	6.02	2.16	0.41	0.18	0.53	0.08	0.10
11	10.26	6.15	1.18	0.30	0.03	0.15	0.05	0.12

(Table 1 cont'd)

Hasse Lake

Date	Oct 30	Nov 20	Dec 7	Dec 18	Jan 21
Snow	--	6	5	5	4
Ice	--	17	23	31	45
Depth					
1	11.26	12.40	11.80	10.36	6.09
2	11.37	11.84	11.64	10.14	5.90
3	11.45	12.32	11.46	9.10	5.73
4	11.23	12.20	10.34	8.32	5.38
5	11.37	12.20	9.20	8.02	4.49
6	11.33	[illegible]	8.13	6.38	3.59
7	11.38	[illegible]	7.65	4.75	2.93
8	11.29	7.62	4.94	1.43	2.80
9	11.31	6.76	3.07	0.15	1.31

Date	Feb 6	Feb 16	Mar 2	Mar 14	Mar 27
Snow	9	9	13	11	9
Ice	49	53	57	56	61
Depth					
1	4.82	4.09	3.66	4.26	6.16
2	4.46	3.56	2.96	2.40	3.42
3	4.25	3.18	1.86	1.17	0.86
4	3.73	2.82	1.29	0.66	0.43
5	3.52	2.10	1.40	0.35	0.32
6	2.97	1.90	0.67	0.16	0.06
7	1.56	[illegible]	0.54	0.00	0.00
8	0.53	0.56	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00

(Table 1 cont'd)

Hubbles Lake

Date	Oct 31	Nov 21	Dec 10	Dec 20	Jan 18
Snow	--	4	2	2	2
Ice	--	13	22	35	51
Depth					
1	7.87	7.03	6.76	6.35	5.15
2	7.78	6.94	6.73	6.33	5.13
3	7.75	6.91	6.74	6.34	5.15
4	7.58	6.92	6.78	6.30	5.10
5	7.50	6.92	6.72	6.35	4.98
6	7.43	6.89	6.70	6.26	4.93
7	7.42	6.86	6.66	6.21	4.91
8	7.23	6.84	6.49	6.11	4.88
9	7.23	6.81	6.32	6.15	4.64
10	7.08	6.77	6.16	6.03	4.36
11	7.31	6.55	5.97	5.66	4.18
12	7.26	6.58	5.78	5.35	3.64
13	6.66	6.51	5.60	5.10	3.64
14	6.93	6.43	5.64	5.07	3.51
15	4.38	6.39	5.45	4.62	3.05
16	0.00	6.36	5.49	4.19	2.90
17	0.00	6.26	5.41	4.07	2.78
18	0.00	6.11	5.28	3.66	1.81
19	0.00	6.01	4.38	3.35	1.39
20	0.00	5.61	3.19	2.97	0.59
21	0.00	5.47	2.73	2.38	0.00
22	0.00	1.89	1.88	0.00	0.00
23	0.00	0.00	0.00	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00
25	0.00	0.00	0.00	0.00	0.00
26	0.00	0.00	0.00	0.00	0.00
27	0.00	0.00	0.00	0.00	0.00
28	0.00	0.00	0.00	0.00	0.00
29	0.00	0.00	0.00	0.00	0.00
30	0.00	0.00	0.00	0.00	0.00

(Table 1 cont'd)

Hubbles lake cont'd

Date	Feb 4	Feb 15	Mar 2	Mar 16	Mar 27
Snow	7	8	11	9	8
Ice	54	58	62	65	66
Depth					
1	4.35	3.91	3.34	3.43	3.50
2	4.25	3.72	2.88	2.76	3.07
3	4.25	3.58	2.83	2.60	2.68
4	4.19	3.55	2.77	2.52	2.68
5	4.17	3.50	2.79	2.47	2.08
6	4.08	3.49	2.78	2.02	1.05
7	4.07	3.34	2.67	2.02	0.84
8	3.88	3.09	2.43	2.03	0.40
9	3.75	2.85	2.04	1.38	0.47
10	3.68	2.62	2.05	1.57	0.86
11	2.98	2.28	1.51	1.03	0.44
12	2.69	1.87	1.29	0.73	0.46
13	2.67	1.93	0.86	0.59	0.18
14	2.28	1.32	0.25	0.46	0.21
15	2.01	1.25	0.15	0.38	0.25
16	1.85	0.56	0.10	0.13	0.15
17	1.66	0.53	0.05	0.07	0.15
18	1.32	0.28	0.00	0.00	0.00
19	0.48	0.23	0.00	0.00	0.00
20	0.27	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00
23	0.00	0.00	0.00	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00
25	0.00	0.00	0.00	0.00	0.00
26	0.00	0.00	0.00	0.00	0.00
27	0.00	0.00	0.00	0.00	0.00
28	0.00	0.00	0.00	0.00	0.00
29	0.00	0.00	0.00	0.00	0.00
30	0.00	0.00	0.00	0.00	0.00

(Table 1 cont'd)

Lessard Lake

Date	Oct 20	Nov 24	Dec 11	Dec 22	Jan 10	Jan 22
Snow	--	4	5	8	4	4
Ice	--	25	34	39	48	55
Depth						
1	7.83	11.46	10.25	9.53	8.11	7.26
2	7.79	11.33	9.95	9.15	7.90	7.10
3	8.01	11.18	9.91	8.58	7.62	6.70
4	7.78	8.84	5.88	5.69	5.94	5.00
5	7.71	6.76	4.57	5.29	2.56	4.61
6	7.70	5.96	3.36	4.11	1.35	3.19

Date	Feb 2	Feb 10	Feb 23	Mar 14	Mar 27
Snow	7	7	10	12	13
Ice	56	59	62	65	66
Depth					
1	6.67	6.46	5.71	5.18	5.12
2	6.41	5.79	4.95	5.22	3.70
3	6.02	5.61	4.15	1.83	1.64
4	4.88	3.72	2.47	1.27	1.18
5	4.44	2.82	2.27	0.99	0.79
6	1.66	1.74	1.69	1.13	0.28

Nakamun Lake

Date	Nov 2	Nov 23	Dec 1	Dec 11	Dec 22	Dec 29	Jan 10
Snow	--	4	3	4	6	4	4
Ice	--	18	24	30	36	46	53
Depth							
1	7.13	8.52	8.30	7.58	6.70	5.61	4.59
2	7.32	8.30	7.99	7.03	5.08	4.69	3.88
3	7.30	8.08	7.56	5.95	4.69	3.44	2.60
4	7.26	7.15	3.32	4.40	1.59	1.41	1.05
5	7.23	4.73	2.76	1.62	1.17	0.97	0.41
6	7.21	0.73	0.96	0.95	0.95	0.65	0.25
7	7.22	0.78	0.42	0.43	0.50	0.17	0.22
8	7.07	0.34	0.24	0.04	0.20	0.17	0.09

Date	Jan 22	Feb 2	Feb 10	Feb 23	Mar 14	Mar 27
Snow	6	6	9	6	6	7
Ice	53	62	63	68	71	73
Depth						
1	3.44	2.06	1.74	1.27	0.73	0.85
2	2.95	1.81	1.37	0.87	0.13	0.17
3	2.08	1.61	1.31	0.72	0.02	0.00
4	0.58	1.24	1.01	0.49	0.00	0.00
5	0.51	0.90	0.56	0.30	0.00	0.00
6	0.41	0.42	0.37	0.07	0.00	0.00
7	0.19	0.11	0.10	0.00	0.00	0.00
8	0.08	0.00	0.00	0.00	0.00	0.00

(Table 1 cont'd)

Peanut Lake

Date	Oct 21	Nov 19	Dec 8	Dec 18	Jan 17
Snow	--	8	6	6	5
Ice	--	12	27	30	39
Depth					
1	7.96	8.84	7.72	6.77	4.71
2	7.94	8.91	7.67	6.65	4.58
3	7.94	9.03	7.59	6.63	4.59
4	7.94	9.04	7.43	6.44	4.54
5	7.78	8.90	7.34	6.12	4.40
6	7.92	8.46	6.93	6.51	3.22
7	7.88	7.93	6.14	4.81	2.66
8	7.84	7.33	4.79	2.44	1.53
9	7.86	6.46	3.80	1.72	1.34
10	7.88	5.53	2.27	1.83	0.65
11	7.68	5.18	1.65	1.64	0.34
12	7.38	4.50	1.30	0.61	0.12
13	0.00	3.53	0.70	0.44	0.02
14	0.00	3.50	0.41	0.00	0.00

Date	Feb 2	Feb 10	Feb 23	Mar 14	Mar 27
Snow	8	11	9	8	7
Ice	45	48	55	53	60
Depth					
1	3.51	2.92	2.30	2.19	2.53
2	3.32	2.71	1.96	1.87	1.84
3	3.17	2.63	1.89	1.39	1.23
4	3.05	2.56	1.72	1.09	0.90
5	2.96	2.16	0.74	0.55	0.44
6	2.02	1.43	0.86	0.68	0.13
7	1.04	1.19	0.53	0.23	0.09
8	0.86	0.27	0.33	0.19	0.22
9	0.53	0.26	0.15	0.05	0.06
10	0.32	0.12	0.05	0.00	0.00
11	0.13	0.06	0.00	0.00	0.00
12	0.10	0.03	0.00	0.00	0.00
13	0.02	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00

(Table 1 cont'd)

Sauer Lake

Date	Oct 29	Nov 20	Dec 1	Dec 17	Jan 21
Snow	--	8	6	6	5
Ice	--	12	19	35	40
Depth					
1	8.68	9.46	8.69	7.07	3.93
2	8.61	9.11	8.47	6.86	3.52
3	8.53	8.99	8.18	6.60	3.22
4	8.49	8.77	7.87	6.22	2.84
5	8.49	8.41	7.49	5.83	2.67
6	8.49	8.35	7.00	5.41	1.79
7	8.54	8.24	6.46	4.94	0.89
8	8.49	7.71	5.88	5.02	0.48
9	8.46	7.59	5.17	3.13	0.47
10	8.49	6.83	4.00	1.83	0.27
11	8.62	6.13	2.97	0.51	0.23
12	[illegible]	2.93	1.92	0.41	0.12
13	8.56	2.46	0.77	0.28	0.00
14	8.50	1.93	0.42	0.00	0.00

Date	Feb 6	Feb 16	Mar 2	Mar 25
Snow	10	9	14	13
Ice	48	47	48	56
Depth				
1	2.51	1.10	0.20	4.26
2	1.95	0.66	0.05	0.33
3	1.63	0.44	0.00	0.19
4	1.35	0.18	0.00	0.19
5	0.86	0.10	0.00	0.00
6	0.42	0.08	0.00	0.00
7	0.30	0.04	0.00	0.00
8	0.24	0.00	0.00	0.00
9	0.19	0.00	0.00	0.00
10	0.06	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00

(Table 1 cont'd)

Twin Lake

Date	Nov 1	Nov 17	Dec 15	Jan 15	Jan 31	Feb 17	Mar 9	Mar 22
Snow	--	1	3	7	13	11	18	11
Ice	--	10	37	47	47	51	50	50
Depth								
1	9.36	8.46	7.96	7.62	7.37	7.21	7.91	8.11
2	9.32	8.35	7.75	7.53	7.23	7.05	6.83	6.98
3	9.31	8.39	7.67	7.46	7.26	6.97	6.80	6.63
4	9.03	8.35	7.75	7.42	7.25	6.94	6.75	6.53
5	9.22	8.31	7.73	7.38	7.03	6.95	6.77	6.46
6	9.26	8.28	7.70	7.30	7.12	6.89	6.65	6.45
7	9.18	8.31	7.72	7.29	7.09	6.81	6.63	6.35
8	9.21	8.31	7.65	7.29	6.96	6.78	6.54	6.25
9	9.22	8.14	7.50	7.23	6.89	6.78	6.53	6.07
10	9.31	7.96	7.52	7.20	6.88	6.65	6.27	6.00
11	9.02	7.81	7.40	7.02	6.72	6.57	6.19	5.94
12	9.02	7.66	7.38	6.93	6.49	6.51	6.14	5.92
13	3.60	7.54	7.00	6.80	6.31	6.30	6.00	5.67
14	2.38	7.42	6.97	6.55	6.15	6.30	5.81	5.63
15	2.36	7.38	6.88	6.17	5.76	5.64	5.68	5.19
16	1.18	7.34	6.75	6.11	5.47	5.62	5.39	5.13
17	0.30	6.95	6.66	5.73	5.57	5.70	5.31	4.85
18	0.16	6.55	6.47	5.58	5.60	5.43	5.29	4.76
19	0.11	6.20	6.26	5.70	5.46	5.23	5.23	4.54
20	0.00	5.84	6.25	5.37	5.00	5.15	4.76	4.08
21	0.00	3.83	5.01	4.45	4.01	4.67	2.12	4.09
22	0.00	2.19	3.94	3.89	2.73	3.37	2.52	3.30
23	0.00	0.72	0.95	0.99	1.31	2.25	1.45	2.59
24	0.00	0.26	0.68	0.47	0.54	0.[illegible]	0.37	1.29
25	0.00	0.33	0.34	0.15	0.35	0.[illegible]	0.20	0.73
26	0.00	0.56	0.15	0.20	0.19	0.23	0.02	0.19
27	0.00	0.08	0.15	0.14	0.04	0.09	0.00	0.00
28	0.00	0.03	0.07	0.07	0.04	0.09	0.00	0.00
29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 2: Dissolved oxygen ($mg \cdot L^{-1}$) profiles for the five lakes sampled to determine if one-site-sampling is representative of the whole lake.

Lake Eden, Feb 26, 1983

	SITE						
Depth	1	2	3	4	5	6	7
1	7.29	6.97	6.74	5.30	6.13	6.97	5.20
2	6.75	6.62	6.57	5.24	5.83	6.91	5.08
3	6.48	6.15	6.46	5.33	5.71	6.82	3.[illegible]3
4	6.15	5.68	6.37	5.04	5.48	6.50	
5	5.65	4.89	5.89	4.71	5.08		
6	3.29	5.02	4.94	4.52			
7	2.82	4.29	3.51				
8	0.81	1.68					
9	0.52	0.72					
10	0.25	0.21					
11	0.12	0.06					
12	0.03	0.03					
13	0.00						
14	0.00						
15	0.00						

Halfmoon Lake, Jan 9, 1983

	SITE					
Depth	1	2	3	4	5	6
1	2.01	2.07	2.34	2.43	2.77	0.95
2	1.55	1.67	1.96	2.04	1.88	
3	1.31	1.39	1.66	1.53	1.52	
4	0.91	1.37	1.58	0.74		
5	0.70	1.13	1.18	0.52		
6	0.17	0.60	0.71	0.64		
7	0.29	0.50				
8	0.10	0.04				

Hasse Lake, Feb 6, 1983

	SITE						
Depth	1	2	3	4	5	6	7
1	4.82	4.62	4.92	4.56	0.98	0.00	4.24
2	4.46	4.44	4.51	4.20	0.00		
3	4.24	3.99	3.62	3.78			
4	3.73	3.56	1.72	2.76			
5	3.52	3.16	2.42				
6	2.97	3.01	2.37				
7	1.56						
8	0.53						
9	0.00						

(Table 2 cont'd)

Lessard Lake, Jan 22, 1983

Depth	SITE 1	2	3	4	5	6
1	7.26	8.06	7.63	7.72	8.22	9.61
2	7.10	7.53	7.60	7.42	8.06	
3	6.70	6.96	6.83	6.86		
4	5.00	3.28	5.27			
5	4.61	2.84				
6	3.19					

Wizard Lake, March 7, 1983

Depth	SITE 1	2	3	4	5	6
1	3.22	5.95	2.75	4.82	5.15	4.16
2	2.24	3.91	2.25	3.89	4.16	3.50
3	1.97	3.73	2.04	3.59	[illegible]	
4	1.89	3.37	1.24	3.21	3.35	
5	1.30	3.25	1.11	2.86	3.22	
6	0.89	2.00	0.90	2.75		
7	0.89	2.11	0.69			
8	0.38	1.41	0.87			
9	0.22					
10	0.08					
11	0.05					

Table 3: Chlorophyll *a* ([Chla]) ($mg \cdot m^{-3}$) in the study lakes during the winter of 1982-83.

Amisk North

Dec 4		Dec 27		Jan 27	
Depth	[Chla]	Depth	[Chla]	Depth	[Chla]
1	13.44	1	2.01	1-4	1.18
2	6.25	2	1.92	7-12	0.46
3	4.03	3	1.49	14-18	0.47
4	2.77	4	1.10	20-26	0.61

Feb 13		Mar 5		Mar 30	
Depth	[Chla]	Depth	[Chla]	Depth	[Chla]
1-3	0.65	1-5	0.54	1-4	0.85
5-8	0.29	7-9	0.24	6-8	0.24
9-13	0.31	10-12	0.22	10-13	0.21
15-19	0.33	14-18	0.35		

Amisk South

Dec 4		Dec 27		Jan 27	
Depth	[Chla]	Depth	[Chla]	Depth	[Chla]
1	5.74	1	1.90	1-4	0.82
2	3.82	2	2.60	7-12	0.26
3	3.09	3	1.47	14-18	0.30
4	2.50	4	0.92	20-26	0.34

Feb 13		Mar 5		Mar 30	
Depth	[Chla]	Depth	[Chla]	Depth	[Chla]
1-3	0.72	1-3	0.56	1-3	0.95
4-8	0.23	5-8	0.20	4-6	0.30
9-12	0.22	9-11	0.20	8-10	0.25
14-18	0.22	12-14	0.29	11-13	0.17

Baptiste South

Dec 4		Dec 27		Jan 27	
Depth	[Chla]	Depth	[Chla]	Depth	[Chla]
1	7.27	1	2.52	1-3	1.52
2	3.42	2	2.21	4-6	1.20
3	2.54	3	2.32	8-10	1.28
4	2.42	4	2.12	12-14	1.01

Feb 13		Mar 5		Mar 30	
Depth	[Chla]	Depth	[Chla]	Depth	[Chla]
1-3	0.98	1-5	0.72	1-3	1.24
5-9	0.53	6-8	0.64	5-7	0.99
11-13	0.57	9-11	0.55	8-10	0.78
15-19	0.32	13-16	0.38	11-13	0.64

(Table 3 cont'd)

Lake Eden

Nov 24

Depth	[Chla]
1	7.51
2	4.64
3	2.56
4	3.08

Dec 12

Depth	[Chla]
1	8.53
[illegible]	2.34
[illegible]	2.69
4	1.69

Dec 20

Depth	[Chla]
1	3.81
2	2.45
3	1.35
4	1.20

Jan 18

Depth	[Chla]
1-3	1.13
4-6	0.65
7-9	1.12
10-12	2.05

Feb 4

Depth	[Chla]
1-3	1.01
4-6	0.52
7-9	0.52
10-12	3.78

Feb 15

Depth	[Chla]
1-3	1.20
4-6	0.56
7-9	[illegible].07
10-12	5.32

Feb 26

Depth	[Chla]
1-3	3.09
4-6	1.57
7-9	2.00
10-12	8.44

Mar 14

Depth	[Chla]
1-3	5.56
4-6	3.74
7-9	4.83
10-12	10.46

Mar 27

Depth	[Chla]
1-3	7.53
4-6	6.95
7-9	8.17

Halfmoon Lake

Nov 18

Depth	[Chla]
1	9.42
2	9.25
3	7.80
4	6.79

Dec 2

Depth	[Chla]
1	15.46
2	5.34
3	5.91
4	5.38

Dec 14

Depth	[Chla]
1	31.57
2	8.00
3	4.14
4	4.56

Dec 24

Depth	[Chla]
1	3.37
2	2.21
3	1.79
4	1.58

Jan 9

Depth	[Chla]
1-2	2.52
3-4	1.31
5-6	2.19

Jan 25

Depth	[Chla]
1-2	2.07
3-4	0.90
5-6	1.19

March 10

Depth	[Chla]
1-3	16.41
4-6	3.07
7	2.30

(Table 3 cont'd)

Hasse Lake

Nov 20		Dec 7		Dec 18	
Depth	[Chla]	Depth	[Chla]	Depth	[Chla]
1	14.72	1	6.56	1	3.54
2	12.81	2	7.49	2	3.84
3	13.76	3	7.88	3	3.03
4	13.47	4	6.27	4	3.25

Jan [illegible]		Feb 6		Feb 16	
Depth	[Chla]	Depth	[Chla]	Depth	[Chla]
1-2	1.41	1-3	3.30	1-3	1.17
3-4	0.67	4-6	0.58	4-6	0.32
5-6	0.48	7-8	0.90		
7-8	0.67				

March 2		March 14		March 27	
Depth	[Chla]	Depth	[Chla]	Depth	[Chla]
1-3	2.65	1-3	4.10	1-3	7.28
4-6	0.73	4-6	1.30	4-6	3.56

Hubbles Lake

Nov 21		Dec 10		Dec 20		Jan 18	
Depth	[Chla]	Depth	[Chla]	Depth	[Chla]	Depth	[Chla]
1	9.50	1	9.58	1-2	8.77	1-3	4.48
2	9.62	2	9.48	3-4	7.74	4-6	4.02
3	9.34	3	9.13	5-6	7.48	7-9	3.48
4	9.34	4	9.13	7-8	7.19	10-12	2.18

Feb 4		Feb 15		Mar 2		Mar 16	
Depth	[Chla]	Depth	[Chla]	Depth	[Chla]	Depth	[Chla]
1-3	4.19	1-3	4.57	1-3	3.34	1-3	3.23
4-6	3.18	4-6	3.40	4-6	3.61	4-6	4.02
7-9	2.81	7-9	2.50	7-9	2.63	7-9	2.37
10-12	1.47	10-12	1.40	10-12	1.47	10-12	1.17

(Table 3 cont'd)

Lessard Lake

Nov 24

Depth	[Chla]
1	8.68
2	6.95
3	4.42
4	3.55

Dec 11

Depth	[Chla]
1	2.97
2	2.05
3	1.87
4	1.10

Dec 22

Depth	[Chla]
1	1.13
2	0.70
3	0.44
4	0.38

Jan 10

Depth	[Chla]
1	0.72
2	0.55
3-4	0.25
5	0.49

Jan 22

Depth	[Chla]
1-2	0.85
3-4	0.38

Feb 2

Depth	[Chla]
1-3	0.56
4-5	0.38

Feb 10

Depth	[Chla]
1-3	0.62
4-5	0.33

Feb 23

Depth	[Chla]
1-3	0.69
4-5	0.24

Mar 14

Depth	[Chla]
1-3	1.38
4-5	0.53

Mar 27

Depth	[Chla]
1-3	2.26
4-5	1.19

Nakamun Lake

Nov 23

Depth	[Chla]
1	2.44
2	1.21
3	0.73
4	0.59

Dec 1

Depth	[Chla]
1	2.47
2	0.91
3	0.54
4	0.29

Dec 11

Depth	[Chla]
1	1.89
2	1.03
3	0.55
4	0.35

Dec 29

Depth	[Chla]
1	1.27
2	0.56
3	0.33
4	0.22

Jan 10

Depth	[Chla]
1-2	0.88
3-4	0.20
5-6	0.28
7	0.27

Jan 22

Depth	[Chla]
1-3	0.57
4-5	0.22
6-7	0.30

Feb 2

Depth	[Chla]
1-3	1.07
4-6	0.24
7	0.31

Feb 10

Depth	[Chla]
1-3	2.3[illegible]
4-6	0.2[illegible]
7	0.85

Feb 23

Depth	[Chla]
1-3	0.80
4-6	0.32

Mar 14

Depth	[Chla]
1-3	1.0[illegible]
4-6	0.44

Mar 27

Depth	[Chla]
1-2	2.99
3-5	1.20

(Table 3 cont'd)

Sauer Lake

Nov 20 Depth	[Chla]	Dec 1 Depth	[Chla]	Dec 17 Depth	[Chla]	Jan 21 Depth	[Chla]
1	3.10	1	5.41	1	1.61	[illegible]	0.74
2	3.43	2	5.03	2	1.15	4-6	0.32
3	2.75	3	4.21	3	0.99	7-9	1.39
4	2.11	4	2.58	4	0.81	10-12	5.18

Feb 6 Depth	[Chla]	Feb 16 Depth	[Chla]	Mar 2 Depth	[Chla]	Mar 25 Depth	[Chla]
1-3	0.53	1-3	0.71	1-3	3.27	1	22.86
4-6	0.37	4-6	1.19	4-6	3.33	2	22.28
7-9	2.09	7-9	4.36	7-9	6.51	3	9.88
10-12	6.73					4	8.25

Wizard Lake

Nov 26 Depth	[Chla]	Dec 15 Depth	[Chla]	Jan 15 Depth	[Chla]	Jan 31 Depth	[Chla]
1	9.18	1	3.37	1-3	1.88	1-3	3.07
2	8.07	2	2.96	4-6	1.45	4-6	1.57
3	7.34	3	2.82	7-9	1.08	7-9	1.27
4	6.35	4	2.65	10	2.26	10	1.95

Feb 17 Depth	[Chla]	Mar 7 Depth	[Chla]	Mar 22 Depth	[Chla]
1-3	1.87	1-3	3.19	1-3	7.59
4-6	1.14	4-6	1.55	4-6	2.94
7-9	0.97	7-9	1.12	7-9	1.64

(Table 3 cont'd)

Peanut Lake

Nov 19

Depth	[Chla]
1	4.81
2	6.31
3	5.85
4	6.36

Dec 8

Depth	[Chla]
1	3.50
2	3.52
3	3.34
4	3.11

Dec 18

Depth	[Chla]
1	2.52
2	2.27
3	1.96
4	1.96

Jan 17

Depth	[Chla]
1-3	3.67
4-6	1.85
10-12	1.38
10-12	1.38

Feb 2

Depth	[Chla]
1-3	4.16
4-6	1.59
7-9	1.18
10-12	1.15

Feb 10

Depth	[Chla]
1-3	4.77
4-6	1.29
7-9	1.23

Feb 23

Depth	[Chla]
1-3	1.12
4-6	0.63
7-9	1.18
10-12	

Mar 14

Depth	[Chla]
1-3	1.46
4-6	1.59
7-9	2.79

Mar 27

Depth	[Chla]
1-3	3.14
4-6	8.29
7-9	7.10

Twin Lake

Dec 15

Depth	[Chla]
1	0.45
2	0.31
3	0.32
4	0.18

Jan 15

Depth	[Chla]
1-3	0.33
4-6	0.07
7-9	0.02
10-12	0.03

Jan 31

Depth	[Chla]
1-3	0.54
4-6	0.12
7-9	0.08
10-12	0.06

Feb 17

Depth	[Chla]
1-3	1.10
4-6	0.27
7-9	0.22
10-12	0.06

Mar 9

Depth	[Chla]
1-3	1.37
4-6	0.68
7-9	0.31
10-12	0.19

Table 4: Mean loss on ignition (LOI) of sediment samples, and standard deviations (s) of the means, from 12 of the study lakes

Lake	LOI	s
Amisk N	39	3.1
Amisk S	41	3.6
Baptiste S	29	2.5
Halfmoon	30	7.7
Hasse	35	10.1
Hubbles	38	8.3
Lessard	63	2.4
Nakamun	46	3.9
Peanut	30	9.1
Sauer	28	4.7
Twin	30	1.6
Wizard	30	7.3

Table 5: Productivity estimates of Hubbles Lake for the ice-free season of 1982. Depth of the euphotic zone (EZ), chlorophyll *a* concentration ([Chla]) and total phosphorus (TP) ($mg \cdot m^{3}$)

Date	EZ	[Chla]	TP
May 14	4	15.3	38
June 3	5	2.8	16
June 24	9	2.3	13
July 15	8.5	3.5	19
Aug 26	8	3.4	16

V. Appendix B: Morphometric data for the study lakes

Table 1: Morphometric characteristics of the study lakes

Amisk North
Surface area=1,893,823 m^2
Volume=20,293,770 m^3
Maximum depth=30 m
Mean depth=10.7 m

Amisk South
Surface area=2,270,461 m^2
Volume=44,089,070 m^3
Maximum depth=60 m
Mean depth=19.4 m

STRATUM (m)	VOLUME (m^3)	STRATUM (m)	VOLUME (m^3)	STRATUM (m)	VOLUME (m^3)
0-1	1,840,738	0-1	2,205,350	41-42	267,418
1-2	1,736,590	1-2	2,077,667	42-43	245,707
2-3	1,635,476	2-3	1,953,793	43-44	224,916
3-4	1,537,395	3-4	1,833,727	44-45	205,043
4-5	1,442,347	4-5	1,717,468	45-46	186,378
5-6	1,337,055	5-6	1,636,558	46-47	168,881
6-7	1,222,893	6-7	1,588,929	47-48	152,247
7-8	1,113,826	7-8	1,542,004	48-49	136,475
8-9	1,009,854	8-9	1,495,782	49-50	121,566
9-10	910,976	9-10	1,450,264	50-51	106,534
10-11	823,109	10-11	1,401,966	51-52	91,561
11-12	745,423	11-12	1,351,048	52-53	77,723
12-13	671,589	12-13	1,301,072	53-54	65,018
13-14	601,605	13-14	1,252,039	54-55	53,447
14-15	535,472	14-15	1,203,947	55-56	42,225
15-16	483,479	15-16	1,157,561	56-57	31,619
16-17	444,169	16-17	1,112,842	57-58	22,547
17-18	406,526	17-18	1,069,003	58-59	15,009
18-19	370,549	18-19	1,026,047	59-60	9,005
19-20	336,240	19-20	983,970		
20-21	285,001	20-21	945,492		
21-22	221,143	21-22	910,465		
22-23	165,380	22-23	876,100		
23-24	117,718	23-24	842,397		
24-25	78,158	24-25	809,345		
25-26	57,403	25-26	773,783		
26-27	50,359	26-27	735,878		
27-28	43,776	27-28	698,925		
28-29	37,655	28-29	662,923		
29-30	31,994	29-30	627,874		
		30-31	589,450		
		31-32	548,021		
		32-33	508,102		
		33-34	469,692		
		34-35	432,793		
		35-36	402,749		
		36-37	379,034		
		37-38	356,039		
		38-39	333,764		
		39-40	312,208		
		40-41	290,048		

(Table 1 cont'd)

Baptiste South

Surface area=4,429,196 m^2
Volume= 55,856,240 m^3
Maximum depth=25 m
Mean depth=12.6 m

STRATUM (m)	VOLUME (m^3)
0-1	4,302,718
1-2	4,054,674
2-3	3,813,995
3-4	3,580,679
4-5	3,354,728
5-6	3,180,733
6-7	3,055,464
7-8	2,932,712
8-9	2,812,476
9-10	2,694,758
10-11	2,580,463
11-12	2,469,541
12-13	2,361,056
13-14	2,255,007
14-15	2,151,396
15-16	1,979,002
16-17	1,745,935
17-18	1,527,472
18-19	1,323,610
19-20	1,134,349
20-21	913,514
21-22	675,351
22-23	473,160
23-24	306,939
24-25	176,688

Hubbles

Surface area=395,820 m^2
Volume=3,997,871m^3
Maximum depth=30 m
Mean depth=10.1 m

STRATUM (m)	VOLUME (m^3)
0-1	385,989
1-2	364,628
2-3	335,173
3-4	302,402
4-5	271,333
5-6	246,914
6-7	231,310
7-8	211,708
8-9	195,982
9-10	178,566
10-11	159,490
11-12	145,941
12-13	133,786
13-14	122,562
14-15	112,056
15-16	101,636
16-17	91,684
17-18	81,162
18-19	70,228
19-20	59,202
20-21	48,613
21-22	39,756
22-23	31,781
23-24	24,311
24-25	18,833
25-26	13,451
26-27	8,958
27-28	5,718
28-29	2,914
29-30	1,757

(Table 1 cont'd)

Lake Eden

Surface area=161,460 m²
Volume=1,122,598 m³
Maximum depth=15 m
Mean depth=6.95 m

STRATUM (m)	VOLUME (m³)
0-1	153,076
1-2	138,547
2-3	124,490
3-4	111,938
4-5	103,527
5-6	96,177
6-7	88,096
7-8	79,673
8-9	69,953
9-10	56,546
10-11	42,786
11-12	30,314
12-13	18,516
13-14	7,992
14-15	967

Wizard Lake

Surface area=2,440,500 m²
Volume=14,791,400 m³
Maximum depth=11 m
Mean depth=6.2 m

STRATUM (m)	VOLUME (m³)
0-1	2,334,250
1-2	2,144,250
2-3	1,999,400
3-4	1,829,300
4-5	1,619,450
5-6	1,418,250
6-7	1,197,950
7-8	941,050
8-9	681,500
9-10	398,150
10-11	227,850

Halfmoon Lake

Surface area=412,347 m²
Volume=1,956,646 m³
Maximum depth=8 m
Mean depth=4.8 m

STRATUM (m)	VOLUME (m³)
0-1	381,465
1-2	337,753
2-3	311,386
3-4	276,113
4-5	228,022
5-6	175,877
6-7	127,158
7-8	82,935

Hasse Lake

Surface area=898,000 m²
Volume=3,276,550 m³
Maximum depth=9 m
Mean depth=3.6 m

STRATUM (m)	VOLUME (m³)
0-1	800,500
1-2	627,000
2-3	501,950
3-4	409,150
4-5	318,350
5-6	238,950
6-7	179,150
7-8	126,750
8-9	74,700

(Table 1 cont'd)

Lessard Lake

Surface area=3,207,083 m^2
Volume=12,492,882 m^3
Maximum depth=6 m
Mean depth=3.9 m

STRATUM (m)	VOLUME (m^3)
0-1	3,001,477
1-2	2,643,990
2-3	2,376,802
3-4	2,038,836
4-5	1,568,604
5-6	863,173

Nakamun Lake

Surface area=3,542,528 m^2
Volume=15,768,015 m^3
Maximum depth=8 m
Mean depth=4.5 m

STRATUM (m)	VOLUME (m^3)
0-1	3,309,864
1-2	2,928,830
2-3	2,628,576
3-4	2,246,214
4-5	1,776,314
5-6	1,376,030
6-7	992,537
7-8	512,650

Peanut Lake

Surface area=226,885 m^2
Volume=1,247,507 m^3
Maximum depth=14 m
Mean depth=5.5 m

STRATUM (m)	VOLUME (m^3)
0-1	215,874
1-2	196,884
2-3	181,091
3-4	162,859
4-5	140,825
5-6	116,727
6-7	82,820
7-8	49,639
8-9	33,425
9-10	24,801
10-11	17,220
11-12	11,821
12-13	7,942
13-14	4,246

Sauer Lake

Surface area=84,688 m^2
Volume=351,850 m^3
Maximum depth=14 m
Mean depth=4.2 m

STRATUM (m)	VOLUME (m^3)
0-1	76,804
1-2	60,776
2-3	47,239
3-4	40,547
4-5	34,006
5-6	26,125
6-7	20,728
7-8	15,245
8-9	10,740
9-10	7,527
10-11	5,080
11-12	3,401
12-13	2,311
13-14	1,321

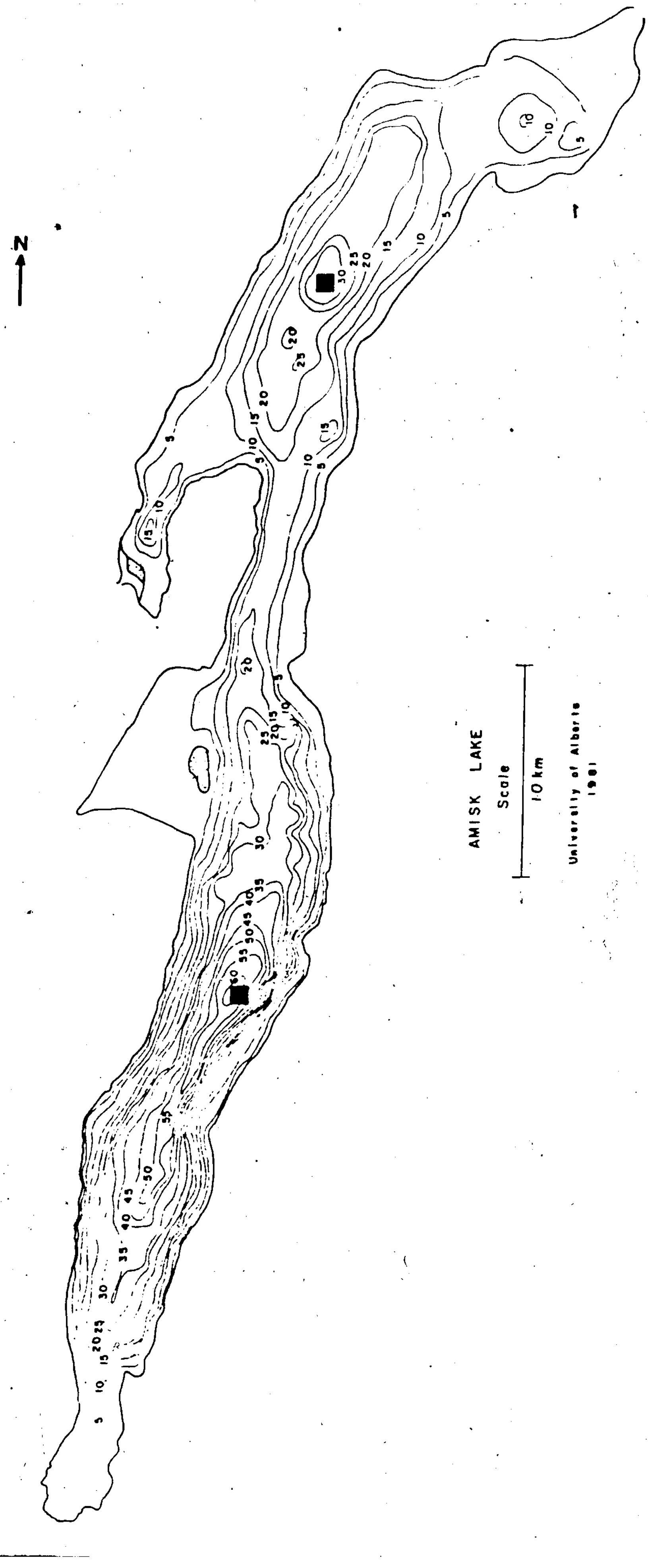
(Table 1 cont'd)

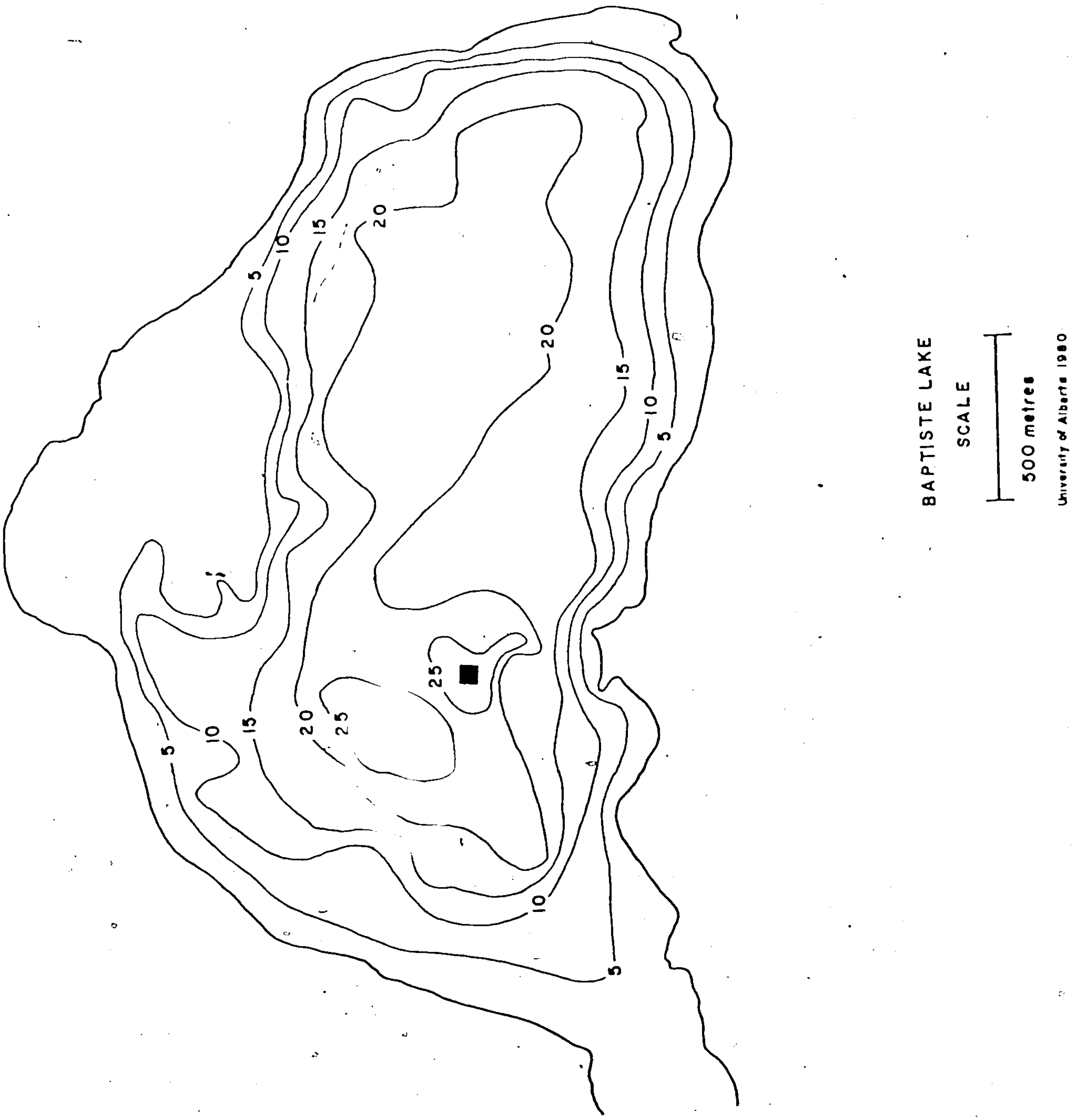
Twin Lake

Surface area=235,823 m^2
Volume=3,691,504 m^3
Maximum depth=35 m
Mean depth=15.7 m

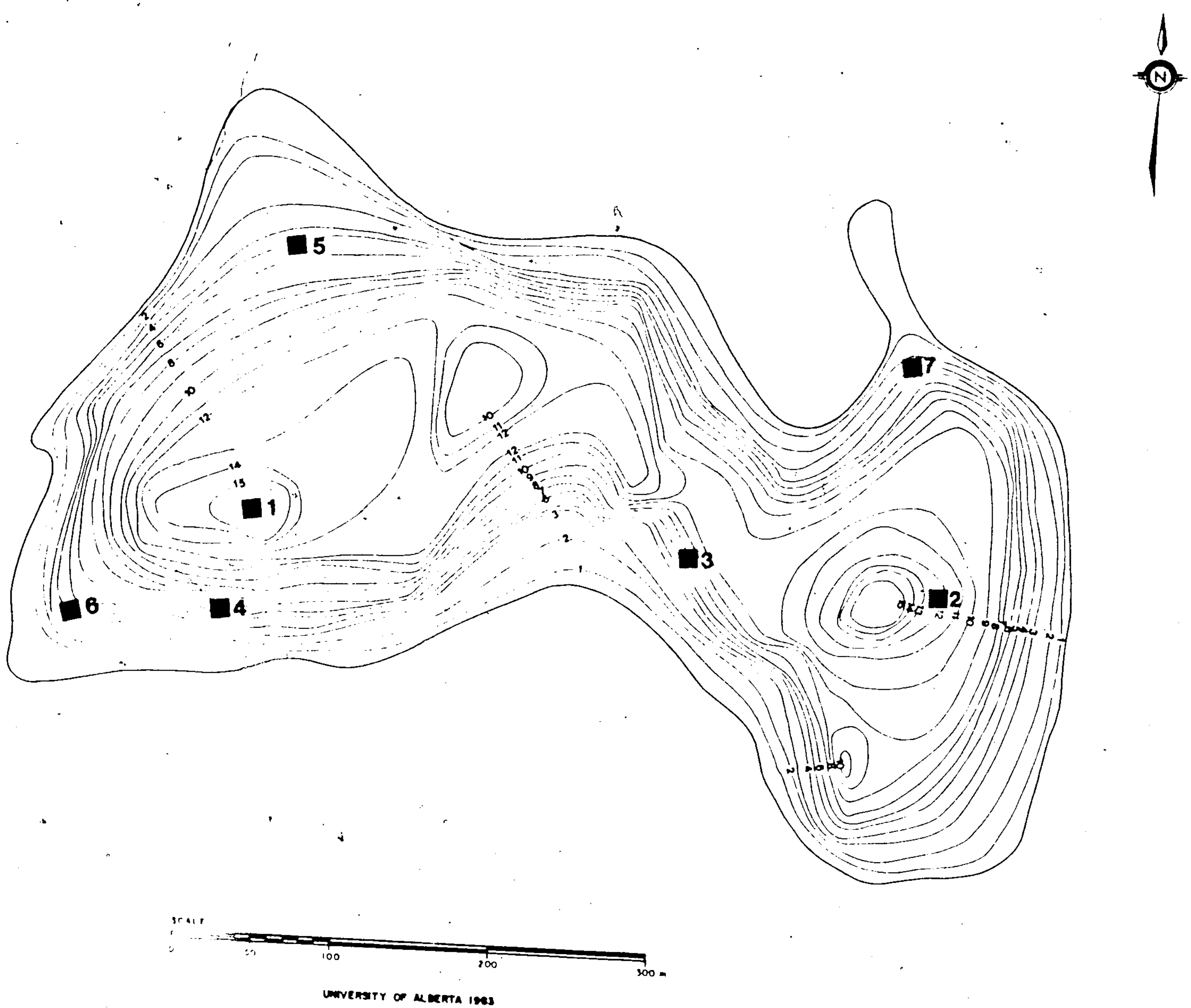
STRATUM (m)	VOLUME (m^3)
0-1	229,288
1-2	216,464
2-3	204,010
3-4	191,924
4-5	180,207
5-6	170,438
6-7	162,629
7-8	154,960
8-9	147,476
9-10	140,178
10-11	134,309
11-12	129,797
12-13	125,363
13-14	121,005
14-15	116,725
15-16	112,178
16-17	107,383
17-18	102,694
18-19	98,108
19-20	93,628
20-21	89,243
21-22	84,955
22-23	80,771
23-24	76,694
24-25	72,722
25-26	67,224
26-27	60,637
27-28	53,896
28-29	47,748
29-30	42,040
30-31	33,014
31-32	21,963
32-33	13,164
33-34	6,617
34-35	2,322

Figure 1: Bathymetric maps of the study lakes. The sampling sites on each lake are indicated by (■). For lakes where more than one site was sampled, the main site is indicated by (■1), site number two is indicated by (■2), etc. Only the south basin of Baptiste Lake is shown. Contour intervals are in m.

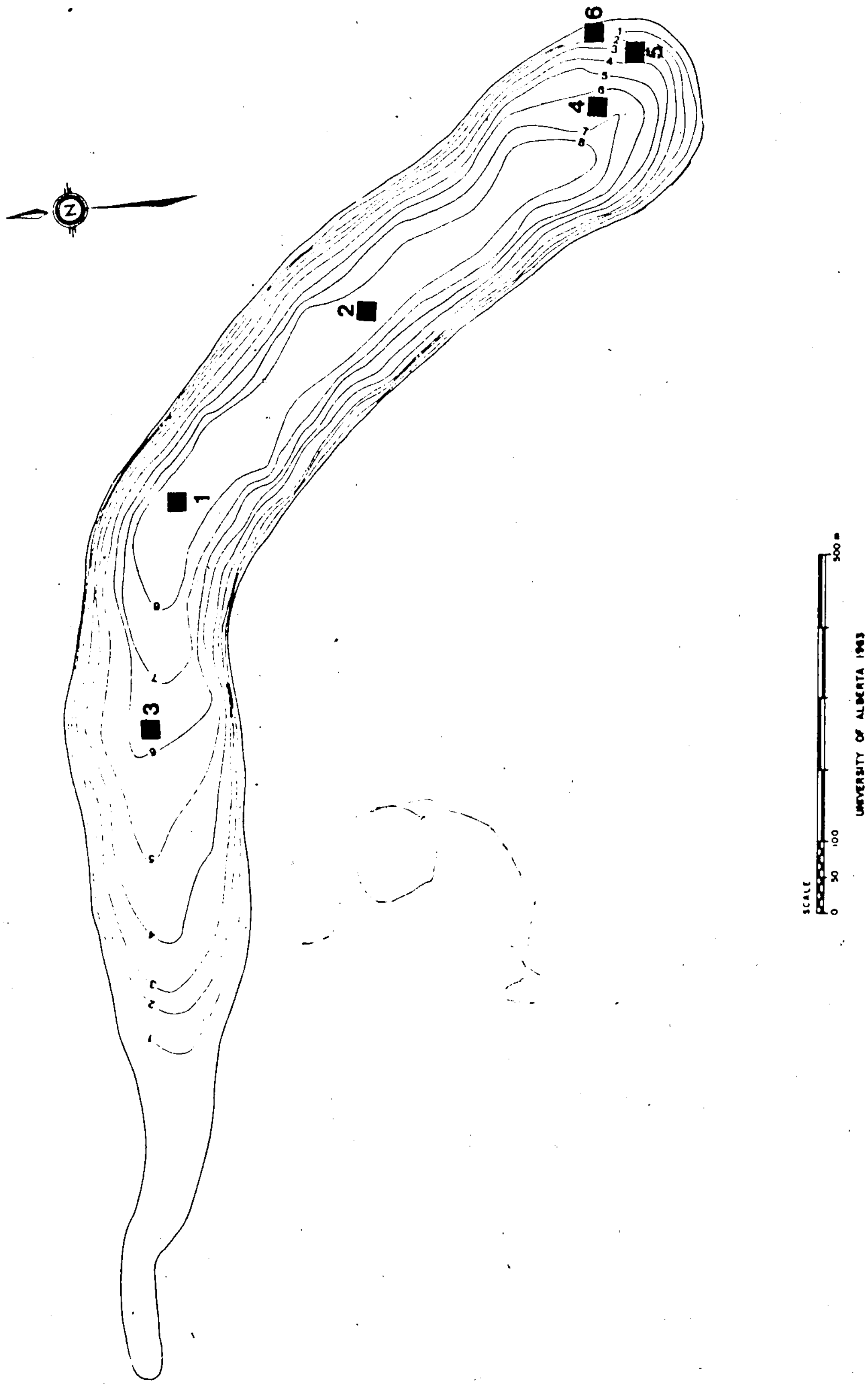

N
AMISK LAKE
Scale
1.0 km
University of Alberta
1981


BAPTISTE LAKE
SCALE
500 metres
University of Alberta 1980
5
10
15
20
25

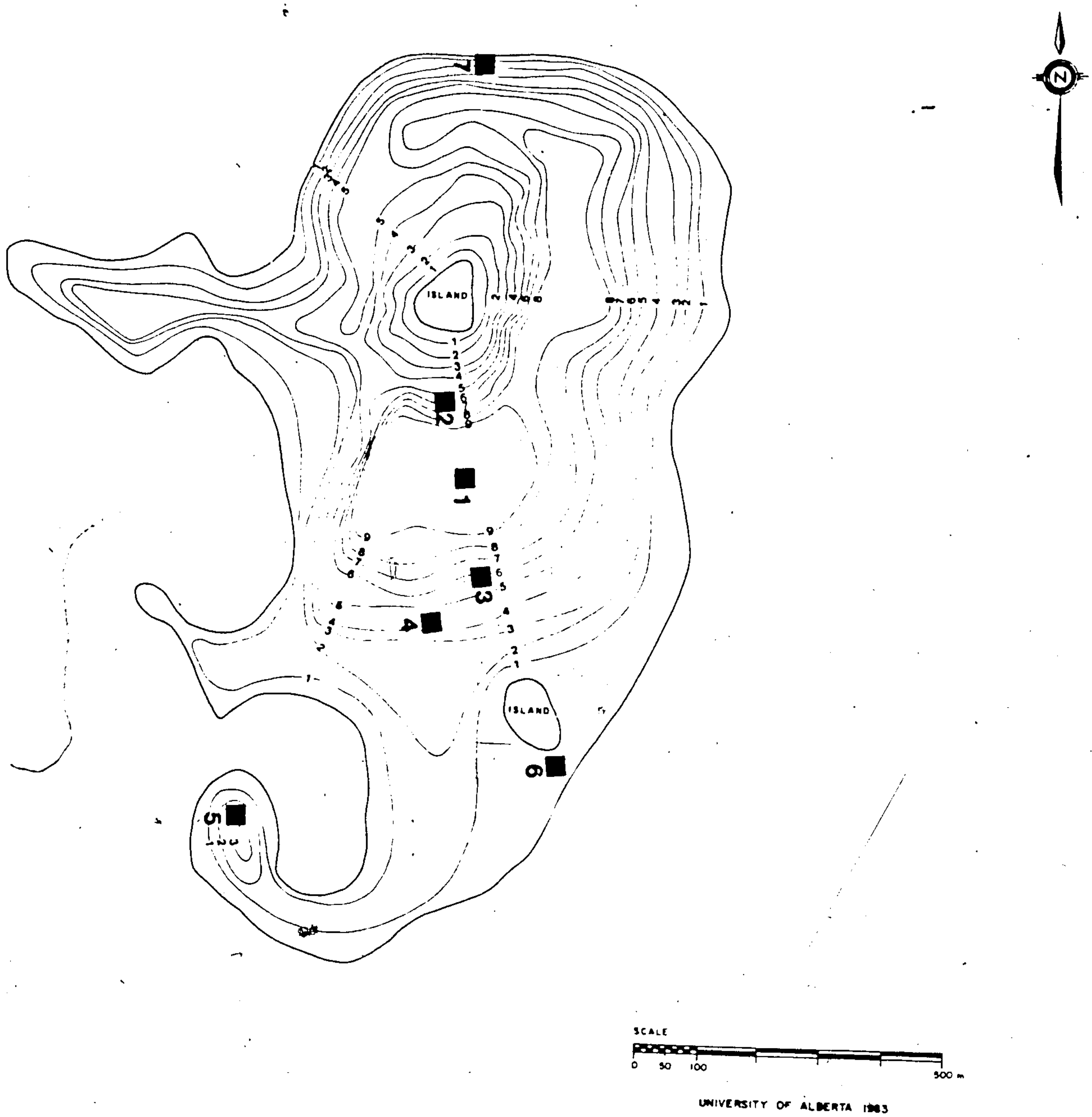
EDEN LAKE

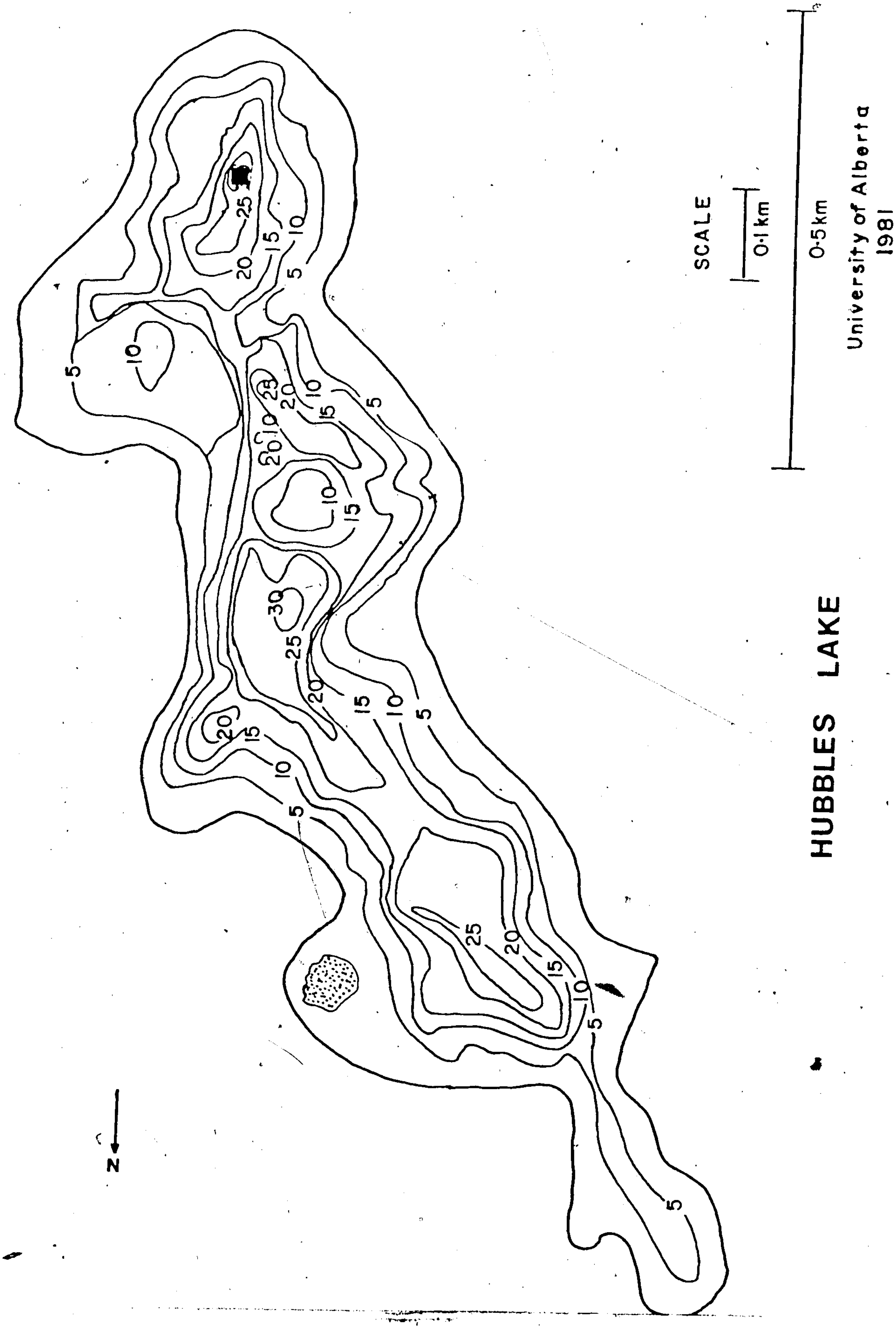


HALFMOON LAKE

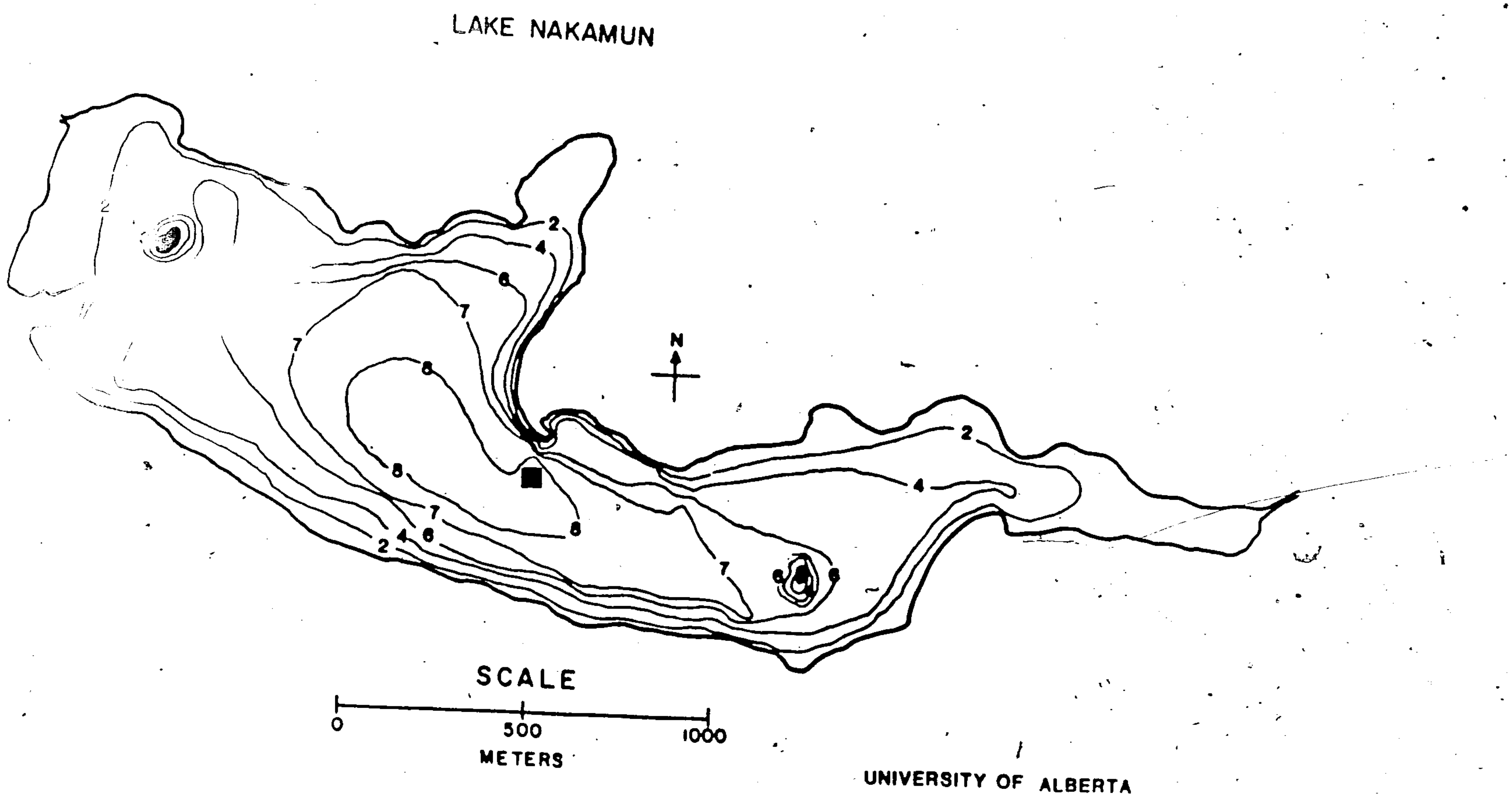


HASSE LAKE

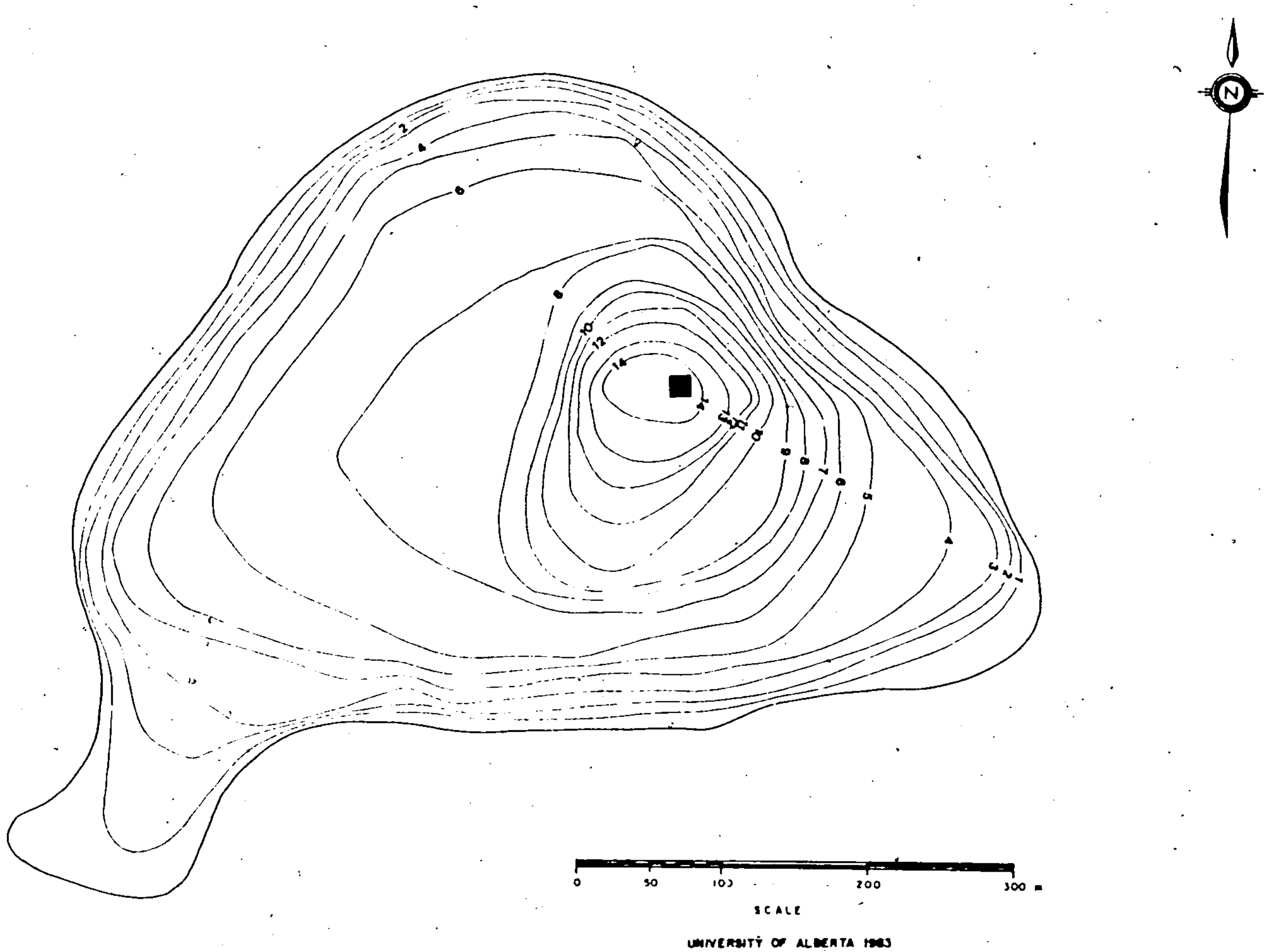

ISLAND
ISLAND
1
2
3
4
5
6
7
SCALE
0 50 100
500 m
UNIVERSITY OF ALBERTA 1983

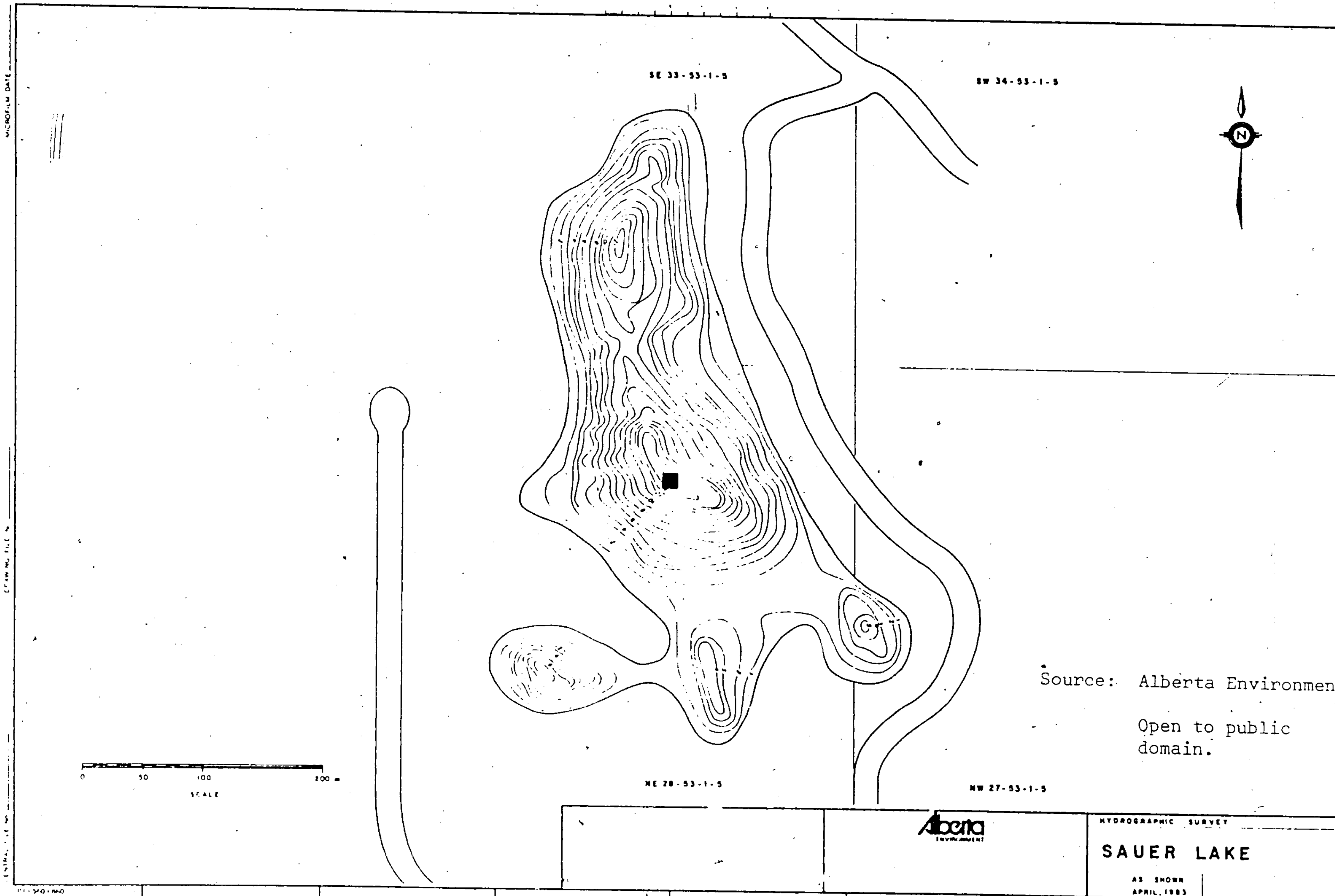

HUBBLES LAKE
SCALE
0·1 km
0·5 km
University of Alberta
1981
N
5
10
15
20
25
30

LESSARD LAKE


LAKE NAKAMUN
N
2
4
6
7
8
SCALE
0
500
1000
METERS
UNIVERSITY OF ALBERTA

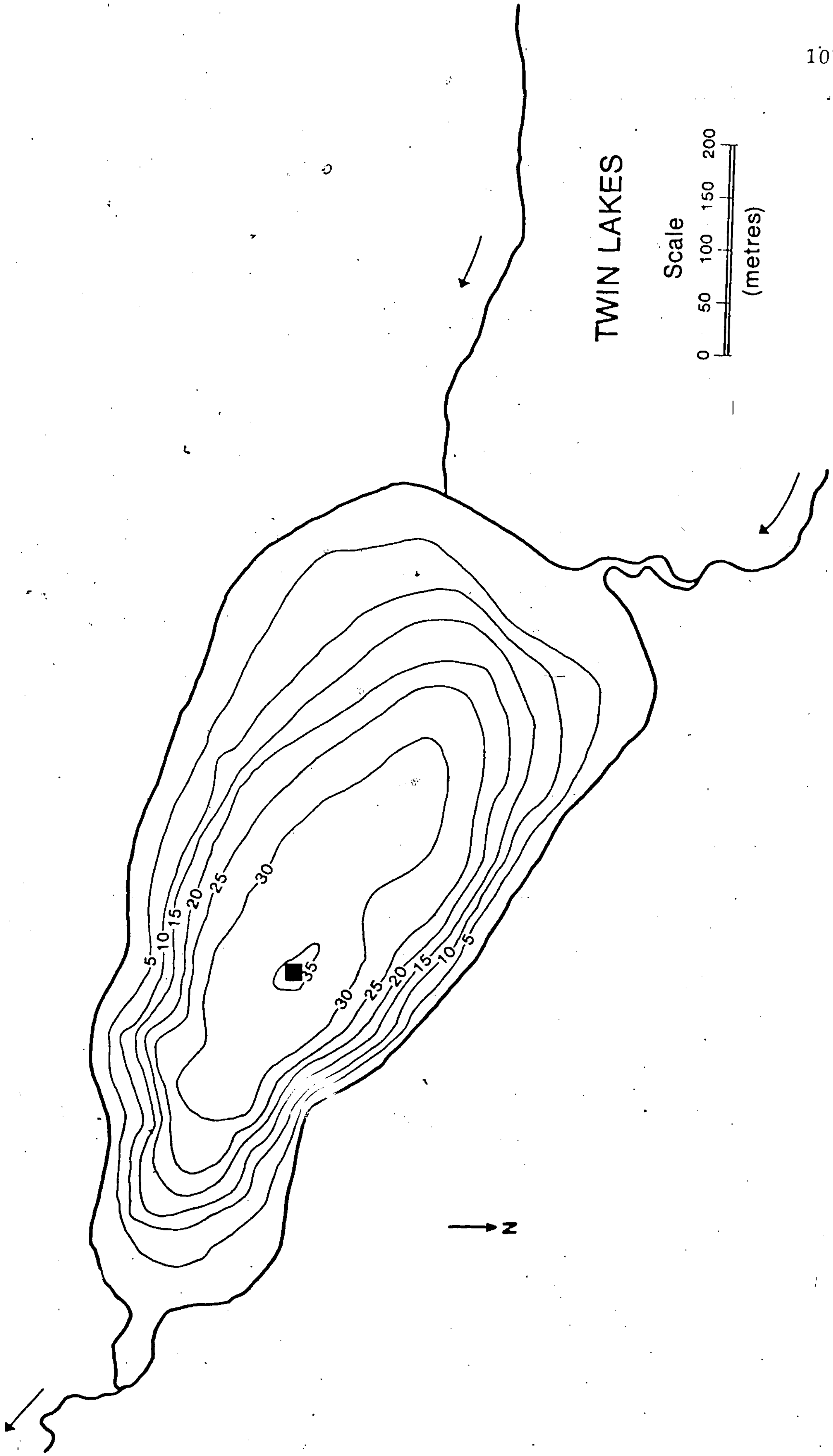
PEANUT LAKE


1
2
3
4
5
6
7
8
9
10
12
13
14
0
50
100
200
300 m
SCALE
UNIVERSITY OF ALBERTA 1983



Source: Alberta Environment

Open to public domain.


TWIN LAKES
Scale
0 50 100 150 200
(metres)
N
5
10
15
20
25
30
35
30
25
20
15
10
5

WIZARD LAKE