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Sampling of Snow and Ice on Lakes

W.P. ADAMS[1] and N.T. ROULET[2]

ABSTRACT. Three years' data, based on unusually large random samples, are combined to characterize the late February snow, white ice, and black ice cover of Elizabeth Lake, Labrador. Similar spatial patterns were found to exist between years with central and marginal locations tending to exhibit consistently above- or below-average thicknesses for particular cover components. It is suggested that maps combining the three years' data and displaying the results in terms of means and standard deviations provide a useful basis for designing ice and snow surveys in medium-sized lakes in snowy environments.

Key words: lake ice, lake snow, ice survey, white ice, black ice, winter limnology, Labrador

RÉSUMÉ. Des données receuillies sur une période de trois ans et fondées sur des échantillons pris au hasard et en nombres nettement plus élevés qu'à l'ordinaire, sont rassemblées en vue de caractériser la neige en fin de février et la glace blanche et noire du lac Élisabeth, au Labrador. Des distributions semblables semblent exister d'année en année, les échantillons centraux et marginaux étant de façon consistante d'un épaisseur au-dessous ou en-dessous de la moyenne quant aux couches particulières. Il est suggéré que les cartes combinant les données des trois ans et indiquant les résultats en termes de moyennes et de déviations standards constituent une base utile pour la conception de levées de glace et de neige pour les lacs de taille moyenne dans des milieux enneigés.

Mots clés: glace lacustre, neige lacustre, levée des glaces, glace blanche, glace noire, limnologie hivernale, Labrador

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INTRODUCTION

During the three winters 1979, 1980, and 1981, the late-winter cover of Elizabeth Lake, Labrador (8 km southwest of Schefferville, Québec) was studied in unusual detail. This is a lake which has received considerable attention in recent years in connection with various biological-limnological and hydrological studies (e.g., Chenard, 1981; Rigler, 1980; Roulet, 1981). In this paper, three sets of data obtained through elaborate late-February surveys of the snow and ice cover of the lake are brought together. These data sets provide an unusual opportunity for generalizing about the spatial variability of snow and ice on lakes in central Québec-Labrador and in other regions in which lake ice develops in a snowy environment.

The general principles of the initiation and evolution of spatial patterns in the winter cover of lakes in regions where snowfall is considerable are now well established. The early work of Andrews (1962), Jones (1969), and others on Knob Lake, Québec, and adjacent lakes, formed the basis for more sophisticated studies in other regions (e.g., Adams and Prowse, 1981) and on Elizabeth Lake, Labrador, which is 20 km southwest of Knob Lake (e.g., Adams and Roulet, 1980).

With various qualifying assumptions (Adams, 1981; Adams and Roulet, 1980), the late-winter pattern of snow and ice on such a lake will include the trends shown in Table 1. This pattern is essentially a response to the persistent redistribution of snow on a lake by wind and to the incorporation of snow into the ice sheet. It has been shown (Adams and Prowse, 1981) that trends of black ice and white ice are established early and become more pronounced as the winter proceeds. Trends of snow tend to be more variable as a result of slushing events, which may dramatically alter the snow cover of some parts of a lake at intervals during the winter.

This spatial variability of the ice and snow components of the lake cover throughout the winter has important implications from various points of view. For example, the variability of snow depth and of the two main components of the ice sheet, which have markedly different strength properties, combine to produce a wide variety of travel conditions for animals and man. Similarly the different properties of snow, white ice, and black ice with respect to light mean that the light regime, upon which photosynthesis in the lake depends, varies widely between different parts of a lake. In terms of the atmospheric loading of a lake, the inputs of precipitation landing on the lake, with its constituent nutrients and pollutants and the wide variety of combinations of snow, white ice (which includes precipitation), and black ice (which does not include precipitation) across a lake need to be known before accurate loading assessments can be made.

TABLE 1. Late winter trends in the snow and ice cover of a lake located in a snowy environment

	Centre → Margins	Upwind → Downwind	Notes
Black Ice[1]	thicker → thinner	thicker → thinner	
White Ice[2]	thinner → thicker	thinner → thicker	
Total Ice[3]	*relatively* even distribution	*relatively* even distribution	patterns will tend to be dominated by the thicker of white ice or black ice
Snow cover	probably thinner → thicker	probably thinner → thicker	This will depend on the extent of redistribution of snow since the last slushing event

[1]Black ice is lake water frozen *in situ*.
[2]White ice is ice formed following the slushing of a snow cover.
[3]Total ice is the combined total of white and black ice.

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[1]Department of Geography and Watershed Ecosystems Program, Trent University, Peterborough, Ontario, Canada K9J 7B8
[2]Department of Geography, McMaster University, Hamilton, Ontario, Canada L8S 4L8

Each of these examples presents a sampling problem. Most regular lake-ice surveys involve measurements at a single site or perhaps at a few sites on a lake. The same is true for most winter limnological studies. The sampling problem can be solved through the use of a large number of sampling sites, as was the case in the surveys discussed here, but this is often not a practicable solution.

How can measurements of one or a few sites be placed in a lake-wide perspective given the diversity of the cover? Is it possible to select one or a few sites which will provide average values for the various lake cover components or which will encompass the range of conditions present on a lake? The fact that systematic trends have been demonstrated in the winter cover of lakes suggests that it should, in priniciple, be possible to generalize about lake-wide conditions from measurements made at a few sites.

This paper addresses the questions posed in the last paragraph with respect to three years' data on the late-winter snow and ice cover of Elizabeth Lake, Labrador, with a view to developing practical and effective sampling procedures for snow and ice on lakes in general.

STUDY LOCATION AND METHODS

Elizabeth Lake (54°46′N, 56°54′W, 616 m asl) has an area of 11.08 ha, a mean/maximum depth of 8.7 m/27.1 m, and a volume of 2.45×10^6 m^3 (Bryan, 1966). The nature of its surrounding topography and vegetation is apparent from Figure 1. The region of Québec-Labrador within which the lake is situated receives an average of 36 cm water equivalent of snow per winter. Its lakes typically develop 110 cm of ice, including 45 cm of white ice. Peak ice thickness occurs in late April.

The snow and ice cover of the lake was surveyed, using standard drilling procedures, in late February 1979, 1980, and 1981. The original sample size, 128, was calculated using an estimated standard deviation and a maximum standard error of 2.5 cm. The estimated standard deviation was based on the literature for lake snow cover in the region as this appeared to be

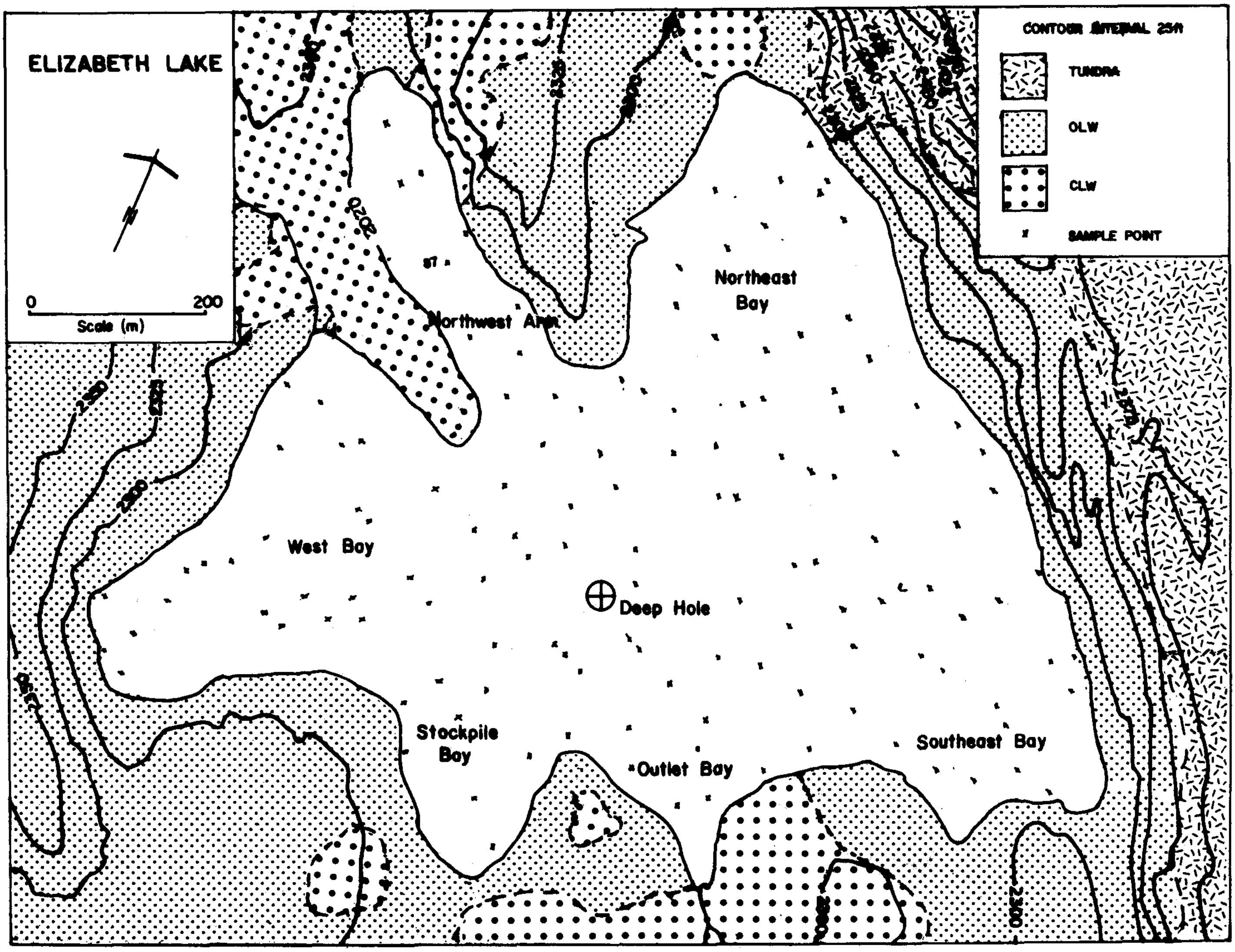

FIG. 1. Elizabeth Lake, surrounding topography and vegetation, and random sample used in the three years of study. The vegetation includes Open Lichen Woodland (OLW), Close Lichen Woodland (CLW) and Tundra. These vegetation types are described by Fraser (1956).

the most variable component of lake winter cover. Points were allocated over the lake surface using a systematic-random procedure. A grid of squares was laid on a map of the lake such that more than 128 squares had more than 50% of that area occupied by lake. A sample point within each square was selected using generated pairs of random numbers and a 10 × 10 coordinate system in the square. The resulting pattern is shown in Figure 1. Points were located in the field by turning right angles and chaining from two control lines of stakes placed on the lake in advance. It is estimated that points were reoccupied in successive years with an accuracy of ±5 m.

For the purposes of this paper, the three annual sets of data were aggregated to provide two- or three-year means for each of the sample sites. Then two- or three-year means and standard deviations were calculated for the lake as a whole. Spatial patterns on the lake were then displayed (Figs. 2-5) using the standard deviations. The idea behind this procedure was to synthesize a number of years of unusually detailed ice and snow data as a basis for generalizing about spatial patterns of winter lake cover and for designing small samples of the cover.

RESULTS

The overall statistical results of the three surveys are presented in Table 2. The values appear to be comfortably within the range of expected snow and ice conditions for this time of year in central Labrador-Ungava. The winters concerned were not exceptional.

The variation between years in mean cover values was not large (Table 2). Mean snow depth varied the most between years, and total ice cover the least. In terms of the distribution

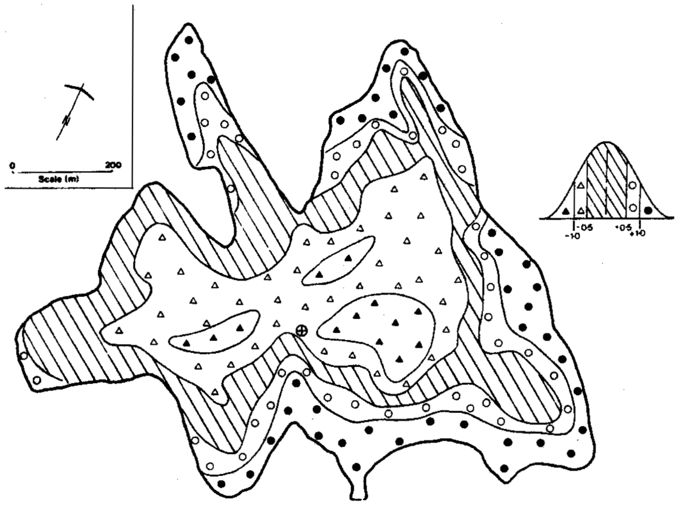

FIG. 2. The spatial pattern of white ice thicknesses on Elizabeth Lake, based on means of values recorded at each of the survey sites for the three study years. The mean thickness ($n=97$), in this case a mean of means, was 21.18 cm with a standard deviation of 13.52 cm. The cross in a circle (also see Figs. 2-4) denotes the "deep hole" of this lake. The legend is designed to allow easy identification of the zone lying within half a standard deviation of the mean.

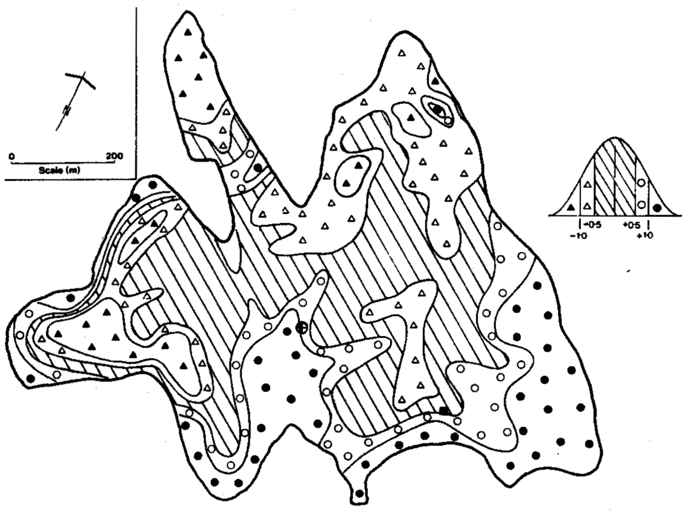

FIG. 3. The spatial pattern of snow depth on Elizabeth Lake, based on three-year mean (1979-1981) at each of the survey sites. The mean depth ($n=98$) was 26.68 cm with a standard deviation of 8.29 cm.

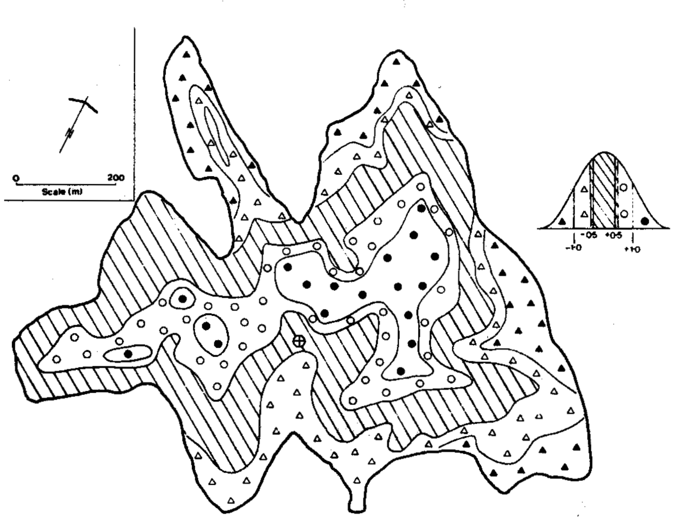

FIG. 4. Spatial pattern of black ice on Elizabeth Lake based on two-year means (1979 and 1981) at each of the survey sites. The mean thickness ($n=109$) was 95.58 cm with a standard deviation of 9.79 cm.

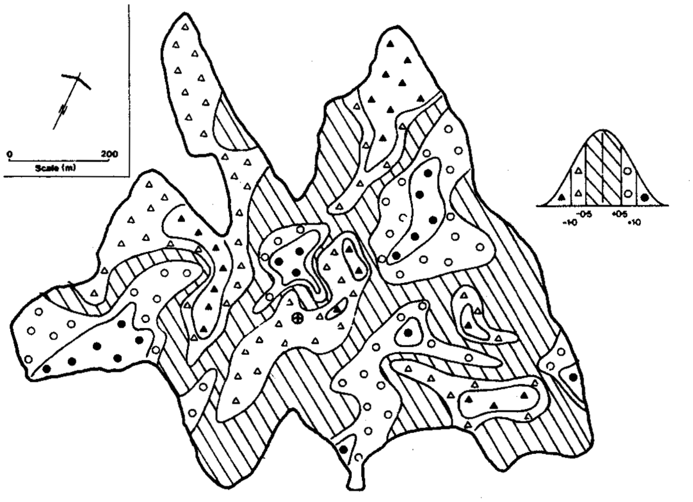

FIG. 5. Spatial pattern of total ice thickness (white ice plus black ice) on Elizabeth Lake based on two-year means (1979 and 1981) at each of the survey sites. The mean thickness ($n=109$) was 95.58 cm with a standard deviation of 9.79 cm.

present on the lake at the time of the surveys, white ice consistently had the highest coefficient of variation, with total ice again having the lowest.

The statistics in Table 2 "represent" the spatial patterns discussed in the introduction. The actual patterns present have been portrayed elsewhere for 1979 (Adams and Roulet, 1980; Roulet, 1981), using normal isopleth maps and trend surface maps. The principal features of the relevant spatial patterns for each of the three dates concerned are summarized in Table 3. Although the magnitude of the ice and snow cover components varied between years, the broad spatial patterns concerned were similar. This shows up clearly when individual-year values are mapped in terms of standard deviations from the mean, rather than in terms of actual values or trends based on actual values (Adams, 1982).

The map of deviations from the three-year lake-wide mean of white ice thickness (Fig. 2) provides an interesting synthesis of the three individual white ice distributions. It should be noted that this averaging procedure results in a loss of data points (as the absence of data for any single year requires the elimination of the point concerned) and a reduction in the range of values for which the three-year spatial mean is a measure of central tendency (Table 2). It is notable, for example, that no site shows zero white ice in the three-year case although several sites were without white ice in individual years. Insofar as three years of data can be assumed to approach the "climatic" norm for this region, this suggests that *some* white ice is normal all over Elizabeth Lake, and that years and sites without white ice are the exception.

Figure 2 illustrates the broad trends outlined in the introduction. The margin→centre, downwind→upwind (i.e., approximately southeast→northwest) pattern of decreasing thickness is clearly apparent. This pattern can be considered as reflecting the persistent tendency for snow to be redistributed in a certain way. The prevailing NW/WNW winds remove snow from exposed upwind and central lake areas and produce accumulations in Southeast Bay. Lee effects at the heads of West and Northeast bays and in Northwest Arm account for drifting and resultant white ice growth there.

The band of values lying within ±0.5 SD of the mean clearly circumscribes the central area reaching the shoreline in part of West Bay and at only two points along the eastern side of the lake. Despite the fact that there are substantial differences between the distribution of white ice as portrayed in Figure 2 and the equivalent three-year map of snow present on the lake in late February (Fig. 3), it can be argued that the white ice pattern provides the best basis for deciding where mean snow depths can be found *throughout* the winter. In this view, the white ice map reflects the persistent tendency for snow to accumulate in certain patterns, whereas the snow map simply reflects conditions since the last major storm or slushing event. In fact, in broad terms, the two distributions are not dissimilar despite the fact that Figure 3 is an attempted synthesis of three quite varied, rather ephemeral, spatial patterns.

TABLE 2. Elizabeth Lake winter cover statistics 1979-1981 (all values in cm except coefficient of variation)

		23-25 Feb. 1979	20-21 Feb. 1980	21-25 Feb. 1981	Two- or three-year value*
SNOW DEPTH	Mean	26.88	19.50	34.74	26.68
	Std. Deviation	9.07	10.80	17.29	8.29
	Coeff. of Var. (%)	33.75	55.38	49.77	31.10
	Maximum	65.00	53.00	91.50	57.00
	Minimum	2.50	0.50	13.00	14.00
	Range	62.50	52.50	78.50	43.00
	n	126	112	115	98
WHITE ICE DEPTH	Mean	20.65	19.63	25.50	21.18
	Std. Deviation	13.82	19.93	18.08	13.52
	Coeff. of Var. (%)	66.94	101.53	70.90	63.80
	Maximum	67.00	83.00	92.00	72.50
	Minimum	0.00	0.00	0.00	5.00
	Range	67.00	83.00	24.00	67.50
	n	116	110	121	97
BLACK ICE DEPTH	Mean	73.66		68.42	72.82
	Std. Deviation	17.82		24.34	16.74
	Coeff. of Var. (%)	24.18		35.57	22.99
	Std. Error	3.11		2.22	
	Maximum	103.50		118.00	110.00
	Minimum	40.00		0.00	21.00
	Range	63.50		118.00	89.00
	n	126		121	109
TOTAL ICE DEPTH	Mean	94.23		96.89	95.56
	Std. Deviation	12.89			9.79
	Coeff. of Var. (%)	13.68			10.25
	Maximum	118.00		155.50	117.00
	Minimum	66.00		76.50	76.00
	Range	52.00		79.00	41.00
	n	126		122	109

*Calculation based on average of 1979+1981 or 1979+1980+1981 (see text). The *n* values are lowest in this column because the omission of a site in any of the years results in an omission here.

The pattern for black ice (Fig. 4) forms an interesting reversal of the white ice pattern (cf. Fig. 2) with thinner ice around the margins and downwind. This illustrates the point that these two types of ice tend to be compensatory. Again, the zone of near mean values is found to encircle the central area of the lake, reaching the margins in West Bay and along the eastern shore.

The total ice thickness map (Fig. 5) does not contain similar, easily described, lake-wide patterns. The range of values shown is much less than in the preceding maps — a coefficient of variation of only 10% — reflecting the compensatory nature of white ice and black ice growth. This is a much less dramatic distribution. In this case a full range of thickness values can be found at both marginal and central sites.

DISCUSSION

Although there are clear limitations to generalizations based on only two or three years of data, the patterns of ice and snow depths displayed here appear plausible in terms of previous experience in subarctic and temperate areas. A less detailed survey of Elizabeth Lake in 1983 produced similar results. There are broad patterns in the way thicknesses vary across the lake which can be "explained" in terms of prevailing winds, redistribution of snow, and white ice formation. Although particular features of the environment of Elizabeth Lake, such as the location and nature of its bays and its surrounding topography and vegetation (Fig. 1), complicate the detailed pattern, the broad trends are clear. There is a substantial central zone which has black ice of above-average thickness and white ice and snow of below-average thickness; there is a marginal zone of thin black ice and above-average white ice and snow. The marginal zone tends to be more complex than the central one. Between these two zones is a zone of white ice and black ice of near-mean values.

The three "ice" distributions discussed here, white ice, black ice, and total ice, can, on the basis of previous studies (notably Adams and Prowse, 1981), be assumed to represent a culmination of the evolution of distinct patterns established early in the ice season. These patterns can be assumed to persist until the cover begins to decay, i.e., in this region, for another two months or so. The patterns thus give an indication of the variability that can be expected across the lake for a considerable portion of the winter. The significance of this is illustrated by (among other things) the implications of the white ice pattern shown as the "deep hole" of this particular lake (see Figs. 1 and 2). On this lake the deep hole, which is commonly used by limnologists as the sole site for routine sampling programs, is located close to the centre of the lake on a zone of consistently low white ice. As white ice and the snow which it "represents" are effective barriers to light (in contrast to black ice which is effectively transparent), the deep hole here appears to receive consistently more light than most of the lake. (Indeed, Roulet and Adams [1983] calculated that sites near the centre of Elizabeth Lake received, in the 1979-80 winter, several hundred percent more light than the margins.) Chenard (1980) draws attention to this same point with respect to studies of lake oxygen.

Although the width of, e.g., the marginal zones identified here will vary for different topographical, vegetational, and wind situations (a matter which we hope to address in future work), we believe that the patterns shown here are useful generalizations for all lakes in snowy locales. This general conclusion has been reached elsewhere using different arguments (e.g., Adams, 1977; Adams and Brunger, 1975; Adams and Prowse, 1981). The patterns form a useful basis for the design of winter-long sampling programs for any snow- and

TABLE 3. Summary of trends observed in the three survey years

	1979*		1980		1981		2 or 3 Year Pattern**		
	High	Low	High	Low	High	Low	High	Low	Notes
SNOW DEPTH	SE Bay, margins of W and NE Bays	NW Arm, Outlet Bay	SE Bay	N central and S central	SE Bay, Outlet Bay, Stockpile Bay	Central area notably W of centre	SE Bay, S Shore, margin of W Bay	NE Bay, tip NW arm W Bay	
WHITE ICE DEPTH	Margins, including heads of bays	Central area, notably W centre	Marginal areas including heads of bays	Central area	Marginal areas except side of SE Bay	Central area, plus E side of SE Bay	Marginal areas, including heads of bays	Central area	Marked centre-margin pattern
BLACK ICE DEPTH	Central area, notably W of centre	W Bay, tips of NW Arm and NE Bay	N/A	N/A			Central area notably E of centre	Marginal areas except W Bay	Marked centre-margin pattern
TOTAL ICE DEPTH	Central and marginal areas	NE Bay	N/A	N/A			W Bay, strip E of centre	NE Arm, NW Bay	The most broken pattern

* See Adams and Roulet (1980) for displays of the 1979 patterns.
**Based on average of 1979+1981 or 1979+1980+1981 (see text).

ice-covered lake or for placing in some perspective one or a few measurements obtained from a lake.

At the present time, official routine ice surveys are deliberately based on measurement at a single site located close to a lake's margin (Environment Canada, 1980). It is important that interpreters of such survey data realize that, in snowy locales, they are from a zone in which values will generally be 0.5 SD, often 1.0 SD, from the lake-wide mean. Furthermore, as the marginal zone itself is typically very variable, a single site is likely to provide values which are not very representative of it!

A practicable routine alternative to the very large random samples discussed here would be a lake-based equivalent of the snow course which is now the standard means of obtaining snowpack data on land. A snow course is essentially a transect of 5 or 10 points in the vicinity of which regular snowpack measurements are made. A "snow and ice course" along a line running through the centre of the lake and perpendicular to the prevailing winter wind could provide a useful coverage of the lake-wide zones identified here. Variations along such a line are likely to be more clear-cut than those along a line parallel to the prevailing wind.

Where only one or a few measurements can be made, site selection will naturally vary with the objectives of the work. Where water column sampling is the principal objective, the ice-measuring site will be dictated by the location of the "deep hole." In such cases, the generalizations presented here, perhaps supplemented by one or a few sets of measurements along a "snow and ice course" provide a useful perspective on the lake-wide representativeness of data obtained.

However, where mean values of all components are desired and where only a single measurement can be made, rules of thumb for site selection should include the following. The site should be selected away from the lake margin (beyond the influence of shoreline snowdrifting) and yet well clear of the centre of the lake. Here again, more precise definition of the marginal and central zones might be easily obtained from a set of measurements along a "snow and ice course" used in conjunction with the maps presented in this paper.

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