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Areal Differentiation of Land and Lake Snowcover in a Small Sub-Arctic Drainage Basin

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A large, stratified, random sample is used to identify vegetation related patterns of snowcover and patterns of land and lake snowcover properties in the basin of Elizabeth Lake, Labrador, Canada. Spatial patterns of snow depth, density and water equivalent are discussed using analyses of variance and trend surface analyses. Statistically significant relationships are demonstrated between these properties and four distinctive "landscape units," Tundra, Open Lichen Woodland, Close Lichen Woodland and Lake. Special features of a mid-winter lake snowcover are discussed including the amount and type of snow present and the spatial patterns in it. The survey system used appears to be useful for hydrologic work.

Introduction

The identification of distinctive snowcover characteristics for easily identifiable "landscape units" recurs in the literature (e.g., Kuz'min 1960; Payette et al. 1973; Steppuhn 1976; Steppuhn and Dyck 1974 and references). The objective of such work is to enable regional generalizations about snowcover conditions from a few measurements made at selected locations. Relationships between snowcover properties and landscape units defined in terms of vegetation cover are particularly useful (Adams 1976) as the distribution of vegetation types can be quickly and accurately surveyed for large areas thus facilitating regional extrapolations of snowcover measurements.

Results presented here are a contribution to the literature on mesoscale (100m-1,000m linear scale) areal differentiation of snowcover (Gray et al. 1978).

Objective

The purpose of the study was to identify vegetation-related properties of the snowcover of central Labrador-Ungava within easily recognizable vegetation classes. As this is a part of Canada in which lakes occupy more than 20% of the land surface area, a special feature of the study was the inclusion of the Lake as a (vegetation-free) "landscape unit."

Study Design and Methods

The study site selected is part of the catchment area of Elizabeth Lake (54°46'N, 66°54'W, 616m a.s.l.), Labrador, 8 km south-west of Schefferville, Quebec. This NNW/SSE aligned basin provides a sample of conditions in the region which lies in the ridge and valley zone of the Labrador Trough portion of the Canadian Shield. The catchment contains a sizeable lake and it encompasses a cross section of the local range of altitude and vegetation. The topographic basin shown in Fig. 1a was used for the study instead of the entire catchment area of Elizabeth Lake which is greatly extended by deep, narrow, glacial drainage channels. The clearly defined basin has a range of slope and aspect thus providing a range of site situation for each vegetation type.

Elizabeth Lake is in the headwaters of the Churchill River drainage, within the transitional Open Boreal Woodland zone which occupies much of the Labrador-Ungave Peninsula (Hare 1950). In this part of the Peninsula, vegetation zones range from tundra on ridgetops (local relief 400 m) to closely spaced, but not closed crown, spruce woodland in valley bottoms. The region receives a mean annual snowfall of 360 mm, water equivalent. The snowcover is continuous from October to May. Before the onset of melt typical snow depths at bush sites are approximately 130 cm with lower values at more open locations.

In this particular winter the mean monthly temperature/total snowfall in °C/mm water was, October –3.1/74.1, November –12.3/63.1, December –17.7/51.7, January –19.7/60.6 and February –23.9/61.6. Melt before the survey was negligible.

The "landscape units" selected for the study were Open Lichen Woodland (OLW) (trees, 7-12 m apart), Close Lichen Woodland (CLW) (trees, 2-6 m apart), Tundra (shrubs and lichen) and Lake (no vegetation (Fig. 1b)). Each of these units, which are based on the work of Fraser (1956), is easily identified on aerial photographs. In this area, the woodland classes are characterized by black and white spruce (typical mature height 10 m, 20 cm diameter) with a distinctive groundcover of lichens (*Cladonia spp.*) and small shrubs.

The principal focus of the field program was a very large, unaligned, random sample of depth, density and water equivalent undertaken between February 21 and 27, 1979. All measurements were made with Canadian MSC and Federal

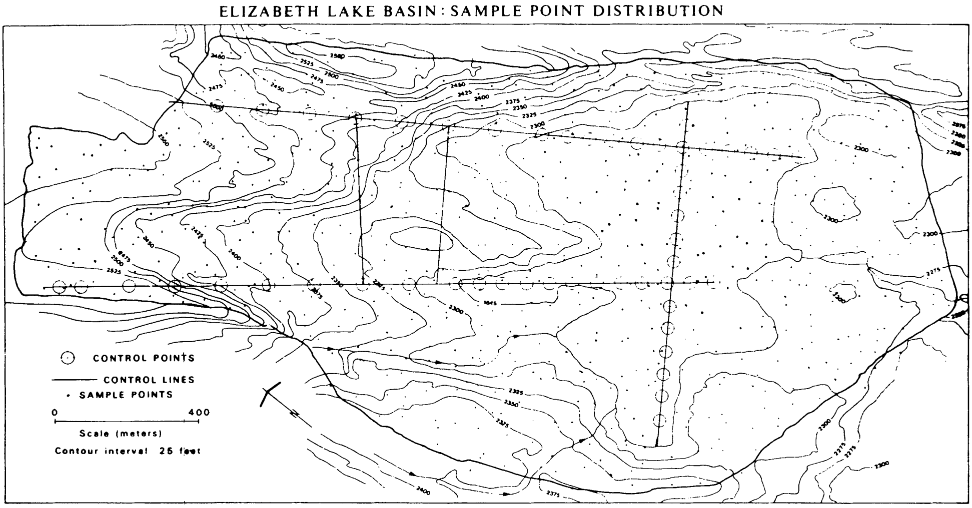

Fig. 1(a). The Elizabeth Lake basin, topography, sample points and control lines used in locating them.

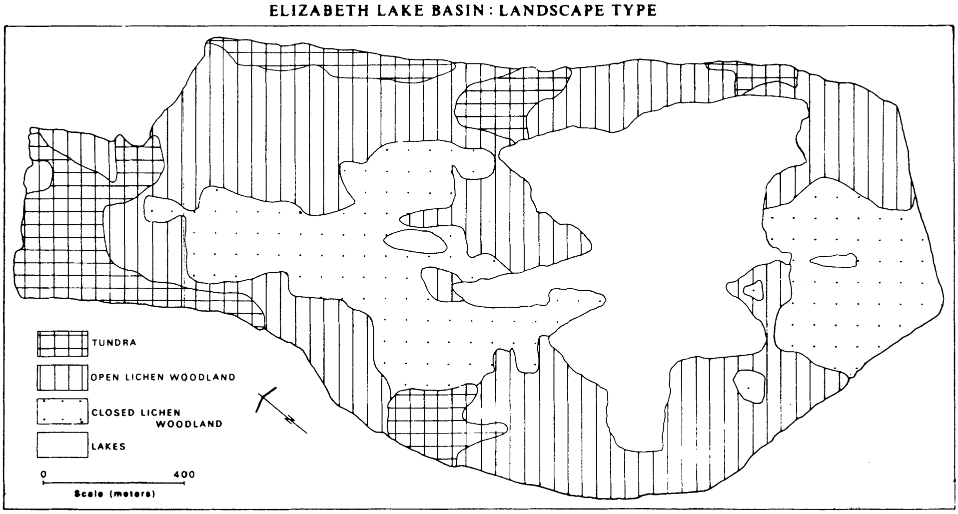

Fig. 1(b). The vegetation-based "landscape units" used in the study.

Table 1 – Actual distribution of sample points.

Landscape Type	Relative Area %	Number of Points	Relative No. of Points %	Density pts/ha
Basin	100.00	522	100.00	10.45
Lake	21.73	129	24.52	11.64
OLW	40.11	216	41.06	10.56
CLW	25.03	107	20.34	8.86
Tundra	13.13	70	13.31	10.46

Table 2 – The standard errors for depth, water equivalent and density for the basin and four landscape types.

	Depth (cm)		W. E. (cm water)		Density (g cm^{-3})	
Landscape Type	σ	S.E.	σ	S.E.	σ	S.E.
Basin	66.67	5.69	19.95	1.70	0.084	0.007
Lake	20.97	3.62	11.43	1.97	0.068	0.012
OLW	60.87	8.12	20.54	2.74	0.079	0.010
CLW	41.11	7.79	14.09	2.67	0.066	0.012
Tundra	60.44	14.15	17.06	3.99	0.092	0.021

The sample was designed on the basis of assumptions about the frequency distribution of snow *depth*. A standard deviation (σ) of 9.31 cm and a standard error of the mean of 2.5 cm were used in calculating sample size.

(Mount Rose) samplers which can be used to a maximum depths of 225 cm. Four sites were eliminated for the sample because they had deeper snow than this.

Full details of the design of the sample, the allocation of sample points and the location of sample points in the field are provided in Adams and Barr (1979). The allocation of points used is shown in Fig. 1a and Table 1. The calculated sample size was 614, the elimination of doubtful data points reduced this to 522 producing the standard errors shown in Table 2.

The data were analysed by means of the SPSS and SYMAP (1976) computer packages. The maps of basin snow depth, density and water equivalent, used here, were drawn and reduced from large format (30 × 55 cm) computer maps produced on the IBM line printer.

Results

Areal Differentiation

Results of the Elizabeth Lake snow survey are summarized and displayed in Fig. 2. Relatively, the greatest variability at the basin level occurred in water equivalent (Fig. 2b), the least in density (Fig. 2c).

The four landscape units of the basin appear to be markedly different in terms of depth (Fig. 2a). Greatest mean depth occurred in CLW with a mean on the Lake which was less than half the next shallowest area, Tundra. The highest coefficient of variation occurred in Tundra, the lowest in CLW.

For mean water equivalent (Fig. 2b), the rank order of the landscape units remains the same with highest values in CLW and lowest on Lake. However, although Lake and Tundra remain distinct, the difference between OLW and CLW is reduced reflecting higher densities in the former. Similarly, relatively low densities on the Lake result in a more marked difference between the two shallower landscape units, Tundra and Lake. For water equivalent there is a change in rank in the coefficient of variation. The two tree-covered units, CLW and OLW respectively, remain least and second least in terms of variability but the Lake is appreciably more variable than Tundra. All coefficients of variation are greater for water equivalent (Fig. 2b) than for depth (Fig. 2a), except in the case of Tundra.

Density exhibits the lowest relative variablity in all cases (Fig. 2c). The coefficient of variation is lowest on the Lake, followed by CLW, Tundra and OLW. Tundra shows the highest mean values followed by CLW, Tundra and OLW. It is interesting that variation in density of the Lake, which shows a highly variable snowcover in terms of depth and water equivalent, should be so low relative to the land-based units. The density characteristics of the Lake here are not atypical in terms of snowcover on other lakes in this region. In part this reflects special features of the evolution of snow on lakes which are discussed below.

From the frequency distribution it is seen that the mode shifts leftward in the case of depth (Fig. 2a) and water equivalent (Fig. 2b), from the most tree covered to the least vegetated unit. The distinctive role of the Lake in the frequency distribution for the region is apparent in all cases.

Analysis of variance showed that the snowcovers of the four landscape units were distinct in terms of depth, density and water equivalent. T-tests on all possible pairs of landscape units, for each property, showed that the snowcovers were distinct at the 90% level except for OLW and CLW in terms of water equivalent. The fact that the pair, OLW and CLW, are similar suggests that they might be treated together for some purposes, including runoff prediction work (see Outerbridge 1980).

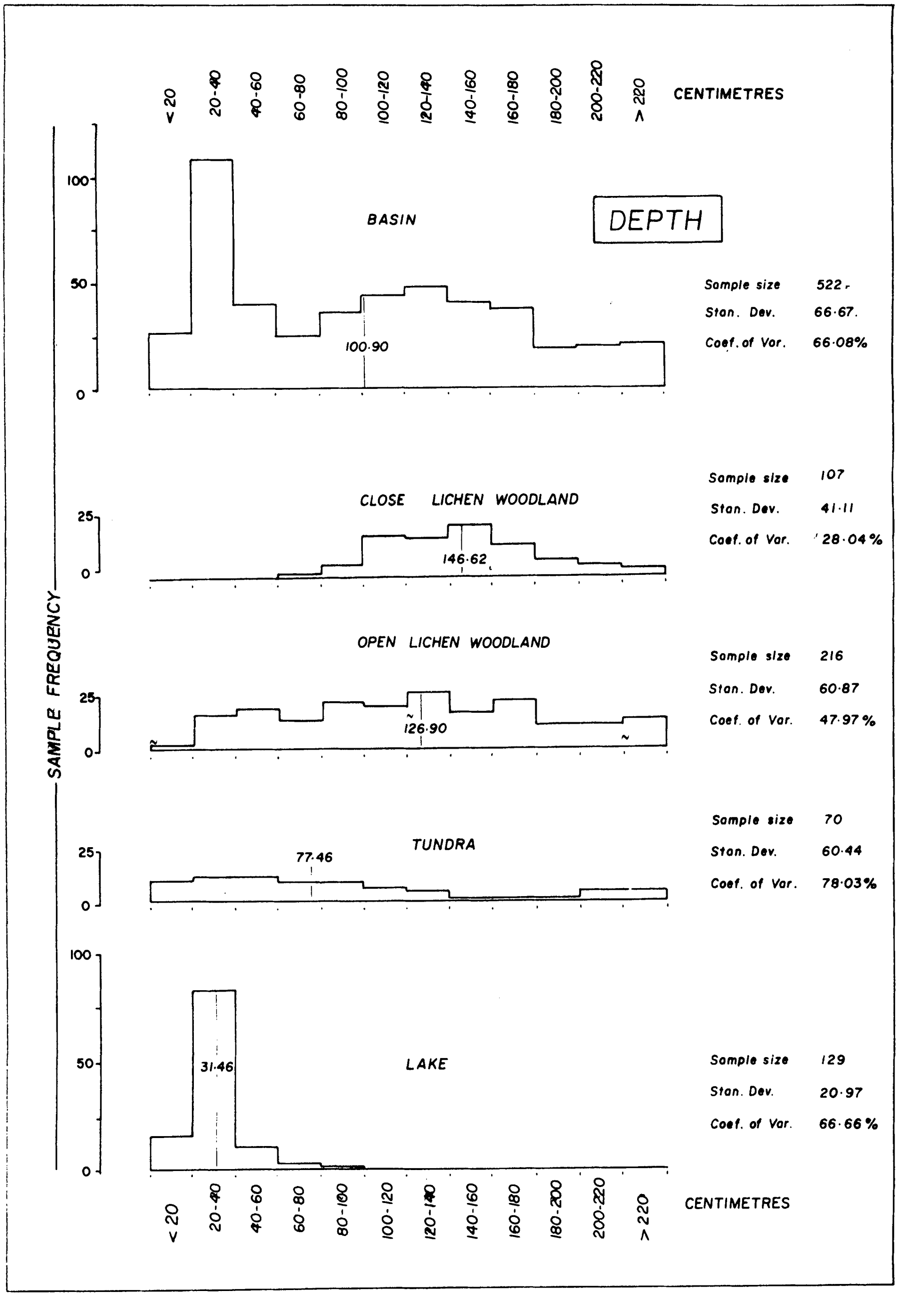

Fig. 2(a). Frequency distribution and sample statistics, snow depth, basin and landscape units. The means are indicated within the diagram.

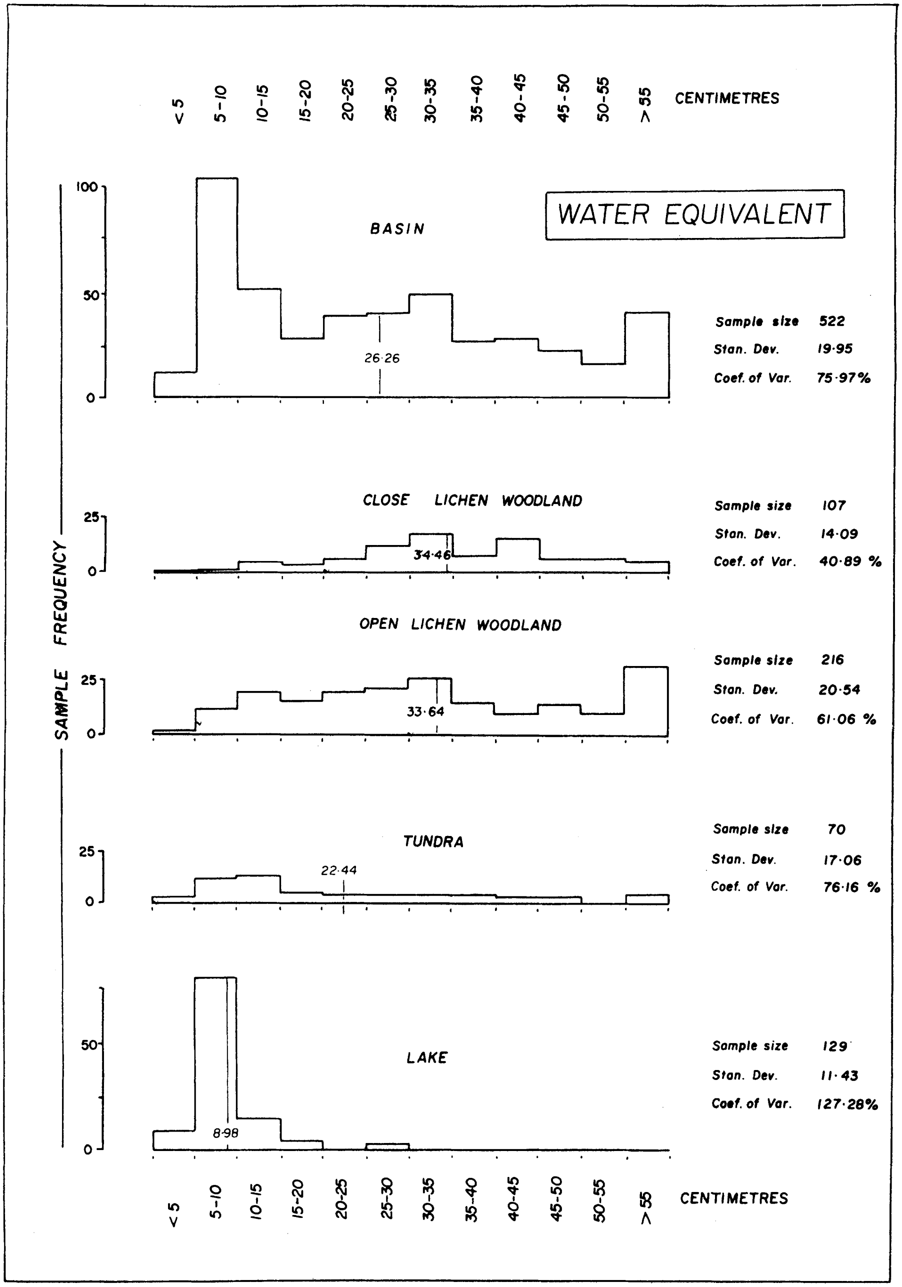

Fig. 2(b). Frequency distribution and sample statistics, snow water equivalent, basin and landscape units. The means are indicated within the diagram.

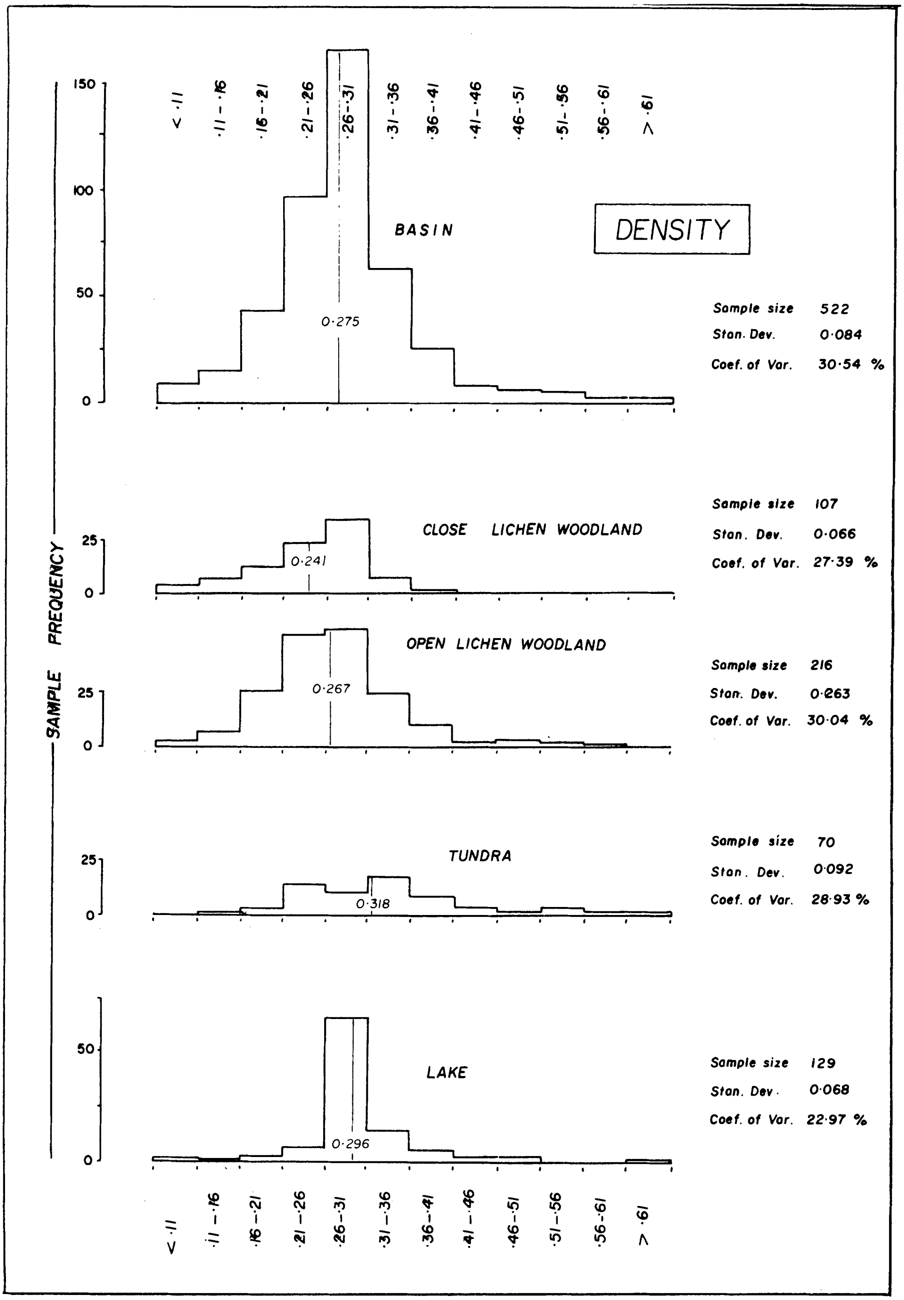

Fig. 2(c). Frequency distribution and sample statistics, snow density (g.cm^{-3}) basin and landscape units. The means are indicated within the diagram.

Table 3 – The correlation coefficients, coefficients of determination and level of variation explained and not explained by the third order trend surface analysis of depth, water equivalent and density.

Parameter	Correlation Coefficient	Coefficient of Determination	Variation Explained by Surface	Variation Not Explained by Surface
Depth	0.43	0.19	49.3%	21.4%
Water Equivalent	0.35	0.12	43.4%	31.8%
Density	0.34	0.11	41.5%	32.6%

Basin-Wide Spatial Patterns

A spatial analysis of the measured properties was undertaken to seek for the spatial expression of the frequency distributions discussed above. Normal, computer-produced, isopleth maps and third order trend surface maps were the principal types of maps used. Table 3 contains correlation coefficients and percentage variation explained by the cubic surfaces.

Figs. 3 and 4 show the variability of *snow depth* in the Elizabeth Lake basin. The shallow snow of the Lake is immediately apparent as is the above average depth of the main areas of woodland. Quite large sections of the rim of the basin also exhibit shallow snow. These are windswept Tundra sites. Locations where the rim has deep snow are characterised by woodland vegetation except in the south east. Greater depths on the south east portion of the rim, at the downwind end of the basin are possibly a result of deposition on the slope.

The residuals from the first order, linear, trend surface for snow depth (Fig. 4) exhibit a topography which includes a round "hill" in the north centre of the basin and a partial oval "depression" in the south centre. The hill seems to result from a combination of the effects of vegetation (CLW) and of deposition in the bottom of the basin as a result of the prevailing NNW-WSW wind. The hill has a particularly steep gradient on its upwind side where there is a rapid transition from exposed Tundra to CLW. The depression, as might be expected from Fig. 3, is firmly based on the Lake with steepest gradients,leading up into the CLW which occupies the southern portion of the Elizabeth Lake basin. This area of vegetation is the best example of CLW in the area. It is interesting that the isopleths which demarcate the depression are open towards the east. If this were a normal topographic map, they might be expected to close forming an enclosed oval hollow, to the right of the diagram. This was one of the rim areas with relatively deep snow mentioned above. This is a good, large scale, example of the way in which both vegetation and topography combine in producing distinctive "landscape units" for snowcover.

Isopleth (Fig. 5) and trend surface maps (not displayed) showed a pattern of

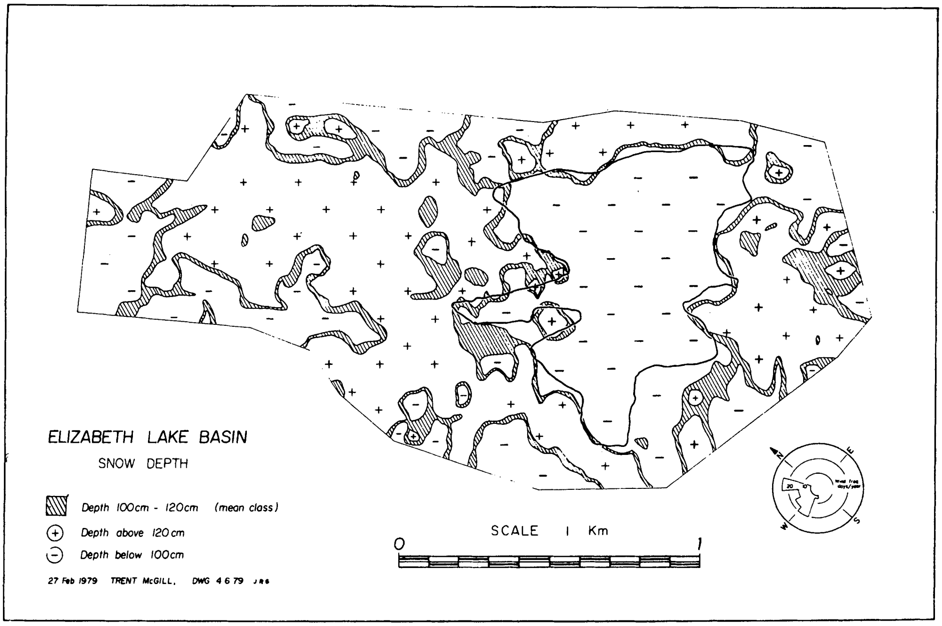

Fig. 3. Snow depth, linear interpolation, drawn from a computer overprint map.

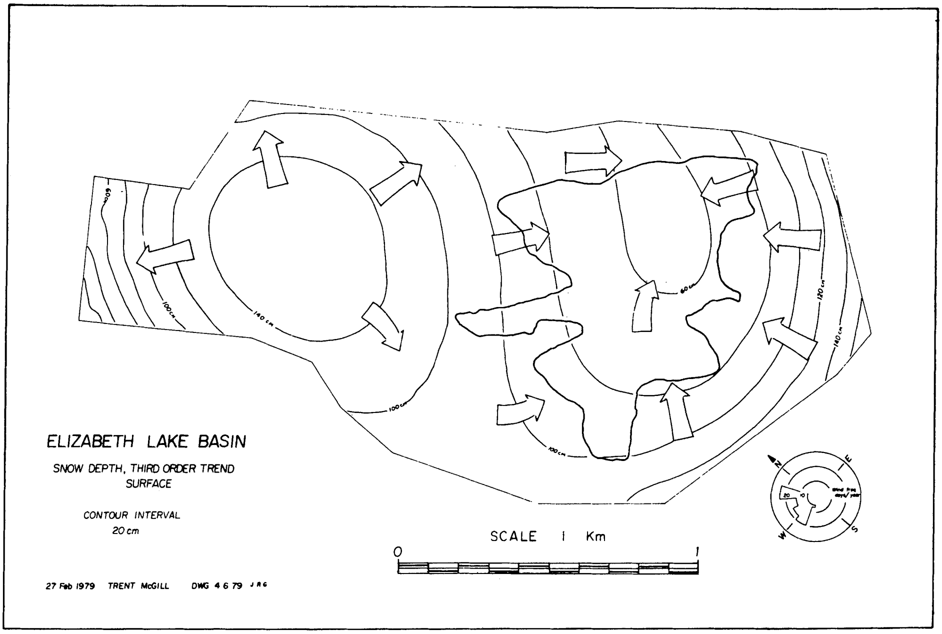

Fig. 4. Snow depth, third order trend surface.

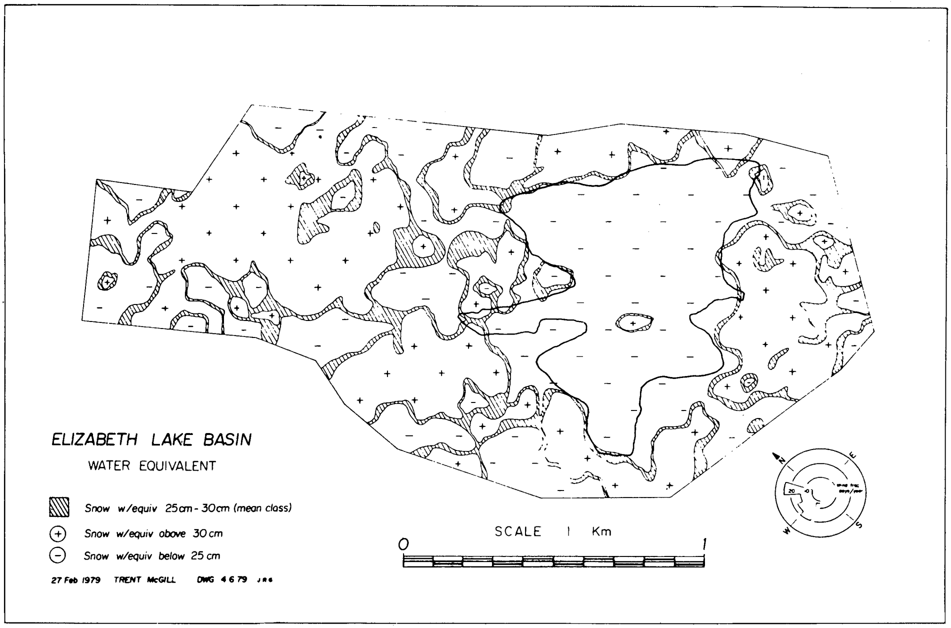

Fig. 5. Snow water equivalent, linear interpretation, drawn from an overprint map.

water equivalent which was broadly similar to that of snow depth. Differences included a low homogeneous distribution pattern in the central woodland area and a somewhat less precise demarcation of Elizabeth Lake itself. The pattern of residuals picked out the Lake more clearly but also produced a more broken pattern in the central woodland zones. This latter effect appears to result from the presence of a small pond north of Elizabeth Lake (Fig. 1). This shows up clearly as an area of overprediction on the trend maps. The CLW area, south of the Lake, persisted as a solid area of high water equivalent (under-prediction), hinting at an upwind-downwind pattern in the basin.

The broad similarity of the patterns of depth and water equivalent, in terms of frequency characteristics and spatial distributions is important for hydrological surveying in that it suggests that depth, which is easily measured, is a good indicator of water equivalent.

The positive skewness of the frequency histograms for depth and water equivalent, which is greatly influenced by the Lake values (see Figs. 2a and 2b) is apparent in maps of those properties. The areal dominance of below average values in Figs. 3 and 5 reflects the dominance of low values in the frequency distributions.

The patterns of density are quite different. The predominance of the class that includes the mean and the classes adjacent to it in Fig. 6 reflects the more normal

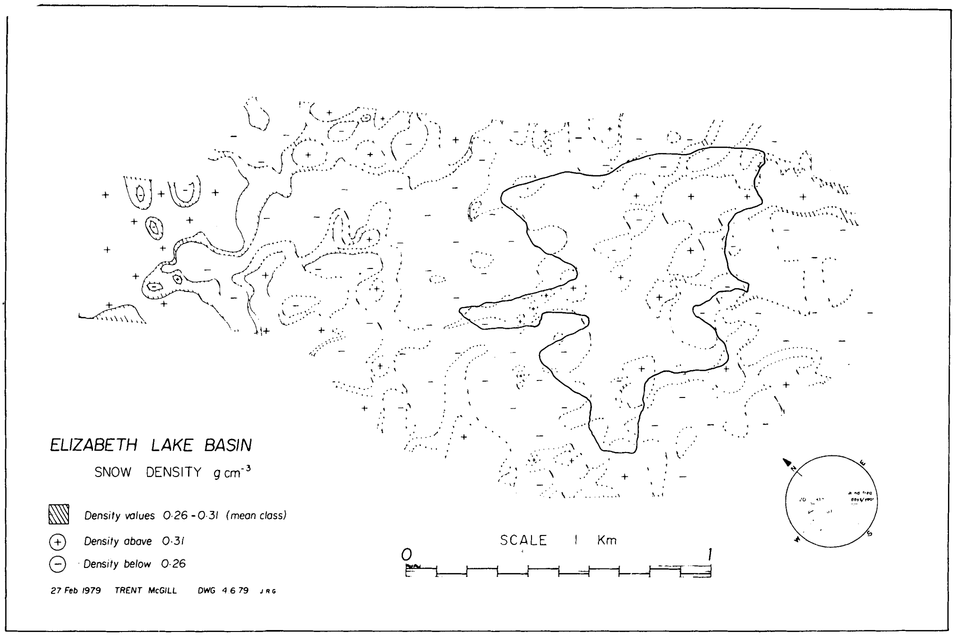

Fig. 6. Snow density, linear interpolation drawn from an overprint map.

distribution of density frequencies which is displayed in Fig. 2c. The Lake no longer appears as a reasonably distinct outline, its general area being occupied by average density values. The Tundra area of the windswept northern end of the basin shows up clearly as a zone a higher density and the main CLW areas tend to exhibit mean to low densities. There is some suggestion of an edge effect in the woodland areas – lower densities towards the centre of stands. There is also some suggestion of an area of higher density at the downwind end of the Lake.

The cubic trend surface for density (not included) showed a slight depression in the west centre area of the basin, in the lee of the western rim, with a rise outwards from this in most directions towards the rims and the Lake but these were very weak.

Lake Snowcover

The Lake unit represents a very significant element in the landscape of the region concerned and indeed of the Canadian Shield as a whole. It also provides a particular environment for snowcover evolution. The nature of this environment affects the properties of the snowcover present on the Lake at the time of the survey and it must be taken into consideration in determining the regional and temporal significance of the survey.

Snow is subject to marked redistribution by wind,on lakes as in a similar open

Table 4 – Comparison of actual snow depth, and snow-plus-white ice depths, compare Fig. 2a.

Mean Depth (cm)		Standard Deviation (cm)		Coefficient of Variation (%)	
Existing Snowcover	Snow-plus-White Ice	Existing Snowcover	Snow-plus-White Ice	Existing Snowcover	Snow-plus-White Ice
31.46	48.80	20.97	20.77	66.66	42.56

space on land, but it is also affected by slushing when the snow load depresses the floating ice sheet below the water surface. This results in the incorporation of snow into the ice sheet so that the snowcover present on a lake at any particular time represents total snowfall receipts less snow deflated and snow consumed by slushing events. The extremely low surface roughness of the lake produces particularly marked upwind→downwind, margin→centre, trends (deep→shallow) of snow depth and water equivalent but this pattern is periodically altered by slushing which has its greatest effect in areas of high water equivalent. Thus a temporal pattern of alternating phases of marked relative variability (associated with pronounced, broad scale, spatial trends) and phases of lower variability (and less marked spatial trends) can be envisaged (Adams and Prowse 1981).

The special characteristics of the Lake in terms of snowcover development account for its generally distinctive position among the landscape units discussed here. The low mean water equivalent reflects both marked deflation and slushing. Even when the thickness of white ice (ice formed from slush) is added to snow depth, the adjusted Lake snow depth is only two thirds that of Tundra (Table 4, cf. Fig. 2a). This suggests that wind removal of snow from the landscape unit as distinct from redistribution within the unit is a marked feature of the Lake environment. However, knowledge of the density of snow, incorporated into the ice would be required to support this hypothesis. In the context of broad scale snow surveying, the Lake has a special significance as it represents a "landscape unit" which is particularly easily defined and the one in which patterns of snow can be predicted most easily. In this case, the Lake snowcover at the time of the survey exhibited quite marked spatial trends, the snow depth pattern (Fig. 7) illustrates this. White ice distribution, which reflects the tendency for snow to be persistently redistributed in a certain pattern normally exhibits even more marked trends which can be explained in terms of prevailing wind directions (Adams and Roulet 1980). It is interesting (Table 4) that "snow depth" produced by combining white ice and snow thicknesses has a lower coefficient of variation than the actual depth of snow lying on the Lake. This, with the quite predictable spatial trends of white ice, eases the problem of designing and obtaining a meaningful sample of the true snow load of a lake.

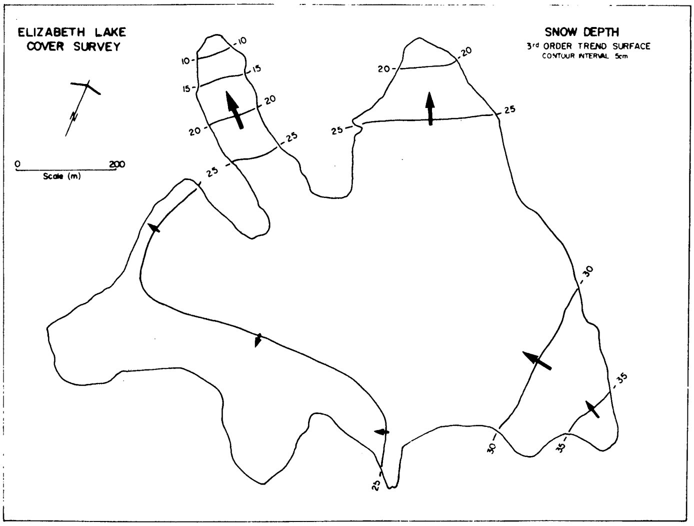

Fig. 7. Cubic trend surface for snow depth on Elizabeth Lake.

Discussion

Analysis of variance suggested that the four "landscape units" selected, CLW, OLW, Tundra and Lake, did exhibit distinct snowcovers in late February, 1979. Trend surface analyses reinforced the importance of the units, particularly CLW and Lake, as basic controls of snowcover. However, t-tests indicated that the mean water equivalents for the two tree-covered units were *not* significantly different. If it is normal for these two classes, which occupy 65% of the basin but which contain 80% of the water present as snow, to be similar in this particular respect, it would not be necessary to differentiate between them for snow surveys designed for hydrologic purposes. However, it would be necessary to treat them separately for other purposes – for example, a survey of snow properties designed to predict skiing conditions or travel conditions for large mammals. The distinctive patterns of snow density indicate that surveys of it must be quite purposefully designed.

It is interesting to note that surveys of depth and water equivalent in this vicinity during previous winters do suggest that Tundra and Lake develop distinctive snowcovers but that OLW and CLW are similar in terms of both properties (Adams et al. 1966; Fitzgibbon 1976; and Granberg 1975). This earlier work suggests that it is OLW, rather than CLW, which usually contains the greater amount of snow in terms of water equivalent. Differences between winters or in criteria used to define vegetation classes could, of course, account for this difference. Granberg (1975) suggests that removal of samples from boundary zones can eliminate differences between cover types.

It should be noted that interception of snow by trees was considerable in some parts of the basin in both OLW and CLW. The snow values for these classes are, presumably, somewhat low on account of this. The matter of snow in trees at the time of a survey is not considered in detail in the literature on this region.

The earlier surveys cited, like the one in 1979 (see also Granberg 1972, 1973, Nicholson 1975) were undertaken relatively late in the winter when accumulation patterns are well established. Granberg (1978) develops the important point that terrain roughness, which controls the wind-induced pattern of snow accumulation typical of this cold environment, changes during the accumulation season. The accumulating snow smoothens minor surface irregularities which inhibit snow drifting in the early winter. In relatively open areas, he envisages an early season of fairly uneven snow distribution, a transitional season in which some areas have been smoothed and a final phase in which drift transport is least inhibited. He suggests the spatial variability in snow depth is greatest in the second phase. It is to be expected that spatial variability of snowcover will vary over time for reasons such as these and on account of areal differences in metamorphism (see Adams 1976). Thus the timing of a survey and the nature of the winter concerned have to be taken into account when generalizing about the snowcover of landscape units. However, it is felt that points made here are valid for most winters in the Elizabeth Lake area in the third (late winter) of Granberg's phases. They are therefore of value in designing peak, pre-melt, snowcover surveys which are the focus for most hydrologic programs. The matter of the particular significance of timing in the case of the Lake is addressed in a somewhat different context below.

It is also possible to comment on the areal or regional as well as the temporal validity of results obtained. In generalizing from the small study basin to the region within which it lies, it is interesting to note the approximate proportions of the selected landscape units in the drainage basin of Knob Lake (34.95 km^2) which is topographically a characteristic segment of the Labrador Trough. The proportions concerned, with Elizabeth Lake values in parentheses, are Lake 23% (22), OLW 20% (40), CLW 10% (25) and Tundra 47% (13). The differences in each category except Lake reflect in large measure the under-representation of ridges in a single, selfcontained basin as distinct from a drainage area which, like the Trough itself, contains a series of ridges and valleys. The fact that the two snow surveys cited above (Adams et al. 1966) in the Knob Lake drainage area indicated broadly similar snowcover patterns does suggest that the snowcover of the Elizabeth Lake basin might be quite representative for the region.

It is clear that factors other than vegetation control snowcover in the basin including topography, altitude, aspect and non-vegetative surface roughness. The trend surface analyses hinted at some of these effects, including upwind→downwind patterns in the basin, but marked broad scale wind effects were only present on the Lake. A topographic basin was selected as the site for the study so that the "landscape units" involved would subsume a reasonably characteristic range of slope, aspect, etc. It would appear that the snowcover units used here have merit as easily identified bases for surveys of snow depths and winter equivalent, which also encompass some of the other controls of snow distribution.

However, the approach has its limitations, the data produced here do not provide a good basis for study of patterns *within* the landscape units including "edge effects" which are a marked feature of snow distribution in a cold, windy, area such as this. For such detailed work, rate of change with distance becomes an important criterion in calculating sample size. It is worthy of note that wind-induced patterns of accumulation will be different in a case where there is an abrupt change of terrain roughness (e.g., Lake→Tundra→OLW→CLW) than where there is an abrupt change of terrain roughness (as where Lake and CLW are juxtaposed). This accounts for some of the variations in gradient on the trend surface maps. This point is also important with respect to the regional representativeness of this basin which is downwind of an extensive area of Tundra and which contains a Lake which is relatively sheltered. It can be argued that Tundra densities presented here, are relatively high and that Lake densities are relatively low (cf. Adams et al. 1966; Findlay 1966; Granberg, pers.comm.).

The timing of a Lake snow survey has particularly important implications in terms of regional extrapolation of results. In this case, the survey was undertaken at a time when approximately 16 cm of white ice was present on the lake, including at least 5 cm, water equivalent, of snow incorporated into the ice (see Granberg 1975). This represents an increase of 55% of snow present on the Lake or an increase of 1 cm, water equivalent to snow covering the entire basin. Adams and Rogerson (1968) suggest that snow incorporated into the 78.9 ha of ice in the Knob Lake basin in March of 1966 amounted to 2.5 cm, water equivalent, in a 31.0 cm water equivalent, snowcover. The incorporation of snow into lake ice sheets is a normal feature of snowcover evolution in regions such as this but the amount incorporated clearly must vary considerably within and between winters and, because slushing phases need not be in phase within a region, even between lakes. Where a regional survey is designed to provide estimates of total snow receipts, a partial solution to this problem is to extrapolate on the basis of Lake snowcover values which include an estimate of snow incorporated in white ice. The role of this snow in spring melt is quite different from that of snowcover lying on land or even snow lying on top of the ice (see, for example, Fitzgibbon 1976).

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