A STRATIFIED SAMPLING DESIGN FOR SNOW SURVEYS BASED ON TERRAIN SHAPE

By

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Introduction

Measurements of snowpack water equivalent vary according to the purposes for which the particular studies are designed. A large number of studies, primarily to predict river discharge, use measurements taken at index plots. Although there may be no way of estimating the total volume of snow within the basin from an index plot, empirical associations between measured snow amount and river discharge throughout the following melt season may allow sufficiently accurate predictions of discharge to justify the method. More elaborate point sampling designs have to be implemented if knowledge of the mean depth and variance in depth are desired for the basin-wide snowpack. In this case it must be possible to relate the sample points to the total population (infinite) of points in the basin. The most elaborate designs are required when distribution maps of snow cover are desired as well as mean depth and variance in depth of the pack.

Mean pack depth and variance in depth can be estimated by implementing random designs. However, as indicated by Cochran (1953) higher precision can often be attained by using a stratified sampling design. Cochran has shown that the greatest accuracy (or alternatively the highest accuracy for a given effort) is obtained when the delineation of the strata is based on the snow depth itself. While it is not practically possible to implement a stratification on the variate being measured, this ideal can be approached if strata are delineated according to terrain variables which are known to be closely associated with snow depth. A review by Meiman (1968) shows that there are strong links between terrain characteristics and snow depth. Recently Bartos and Rechard (1973) and Steppuhn and Dyck (1973) have shown how stratified designs, based primarily on vegetation, resulte in greatly increased accuracy in estimation of areal snow cover.

The purpose of this paper is to describe a stratified sampling design based on altitude, local relief and slope angle. By using the design the spatial distribution of the snowpack at the end of winter can be mapped.

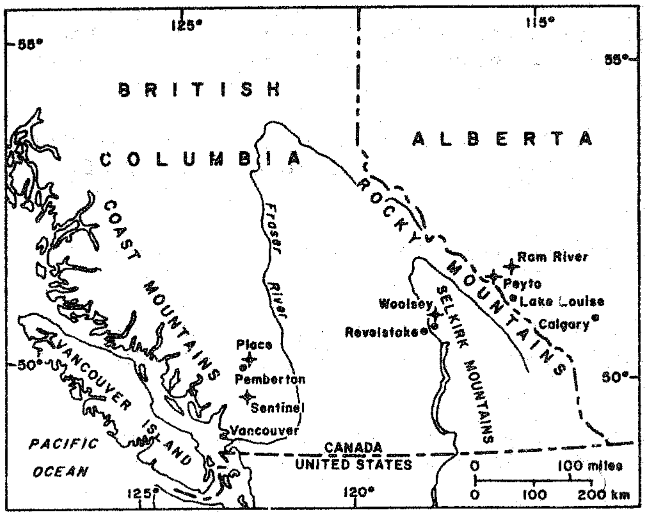

Figure 1. Glacier locations.

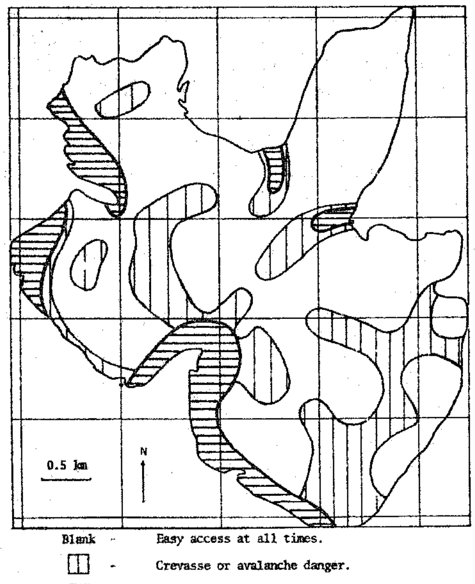

Figure 2. Accessibility over the glacier surface.

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Location of the glaciers -- As part of the International Hydrological Decade (I.H.D.) Program studies of glacier mass balance have been undertaken on several glaciers in the Canadian Cordillera by the Glaciology Division, Department of the Environment, Ottawa. Mokievsky-Zubok (1971); Ostrem (1966); Stanley (1970, 1971) and Young (1970, 1971, 1973a).

Aims -- A major concern of our studies is an evaluation of the processes governing the accumulation of the winter snowpack and the ablation of snow and ice during the summer. These processes are intimately linked to the changing patterns of snow cover through time. As Harvey (1968) has suggested, it can be very profitable to study patterns in considerable detail for insight into the formative processes may thereby be gained. Pattern description is seen, therefore, as an important first step towards process evaluation. Data collection and preliminary analyses have been conducted according to the standard procedures advocated by Ostrem and Stanley (1969).

Problems -- One of the main problems associated with the studies conducted on glaciers is the difficulty of movement over the glacier surface. An important criterion for choosing the five Cordilleran glaciers, in the first place, was that access to them and travel on them was relatively easy. A simple accessibility map for Peyto Glacier is shown in Figure 2. As most other glaciers are more difficult to travel on than the ones under study it is, therefore, questionable whether conclusions representative of the entire population of glaciers are being reached. Furthermore, on any particular glacier there are areas which are always easy to reach, areas which are always 'out of bounds', because of crevasse or avalanche dangers, and areas which are not dangerous at the end of winter but which become ever more dangerous as the melt season progresses. The proportion of each of these three categories varies from glacier to glacier.

In general, the upper parts of Peyto Glacier are much less accessible than the lower parts. This has direct influence on the selection of the network of sampling locations. While a much higher density of sampling locations has been maintained on the lower parts of the glacier, there have been many instances of 'missing data' from the upper parts of the glacier. To a lesser extent the same situation prevails on the other glaciers surveyed despite the fact that there is really more need for a larger number of sampling locations at higher elevations for mean snowpack depth and variability in depth in general increases with increasing altitude.

Further, because of manpower and financial constraints, a much more simple network of sampling locations should be established, but one which would give approximately equal weight to all altitude zones on the glacier.

The Rationale for Stratification

It has been shown in a previous study, (Young, 1973a) that there are close association between accumulation values and various terrain characteristics at sampling locations. While total accumulations vary considerably from one year to another there is nearly always a strong linear association between altitude and snow depth. Within any particular altitude zone (a standard zone is bounded by successive 100 m contour lines) variance in snow depth can be explained largely in terms of slope angle and local relief (for definitions of these terms see the next section). On all the glaciers there is a significant negative correlation between local relief and snow depth, i.e. hollows tend to contain more snow than bumps. On all glaciers, too, there are consistent associations between slope angle and snow depth, although the signs of the correlation coefficients vary from one glacier to another.

It has been found that a very good approximation of total accumulation can be obtained simply by expressing snow depth as a linear function of altitude and mapping the distribution accordingly. Important detail or 'embroidery' on the basic trend derived from altitude can be added to the map by also using the linkages between local relief and slope angle with snow depth.

Consequently, if the altitude/snow depth relationship is derived from a set of measurements made at locations which have lower than average slope angles or atypical local relief then the basic trend map based on altitude will be wrong. It is argued that it is of primary importance to establish as correctly as possible the altitude/snow depth relationship and to this end not only should measurements be made from a wide range of altitudes but also within any altitude zone care should be taken to choose sampling locations typical for the zone in terms of slope angle and local relief. This type of reasoning becomes especially important if it is only possible to take a few measurements. However, it becomes less important if within any altitude zone a sufficiently large number of measurements can be made to establish mean depth and variance in depth with high confidence.

The method outlined below is designed to stratify a basin or area according to altitude, slope angle and local relief and thus define a small number of locations from which good estimates of basin-wide snow cover can be obtained.

Topographic Shape -- A grid square technique similar to that proposed by Solomon et al. (1968) has been adopted here; the computer program used has been described by Young (1973 b) and is illustrated by a series of diagrams for Peyto Glacier (Figures 3-6).

A square grid (Universal Transverse Mercator) with a grid interval of 100 m is laid over the topographic map (Figure 3). Altitudes at grid line intersections are stored and used to calculate local relief and slope angle for each grid point. Figure 4 illustrates, for a given point, how the altitudes at that point and latitudes of its four nearest neighbours are used to compute a best fit regression plane, the maximum slope of which is taken as the slope angle at the point in question. Local relief is defined as the extent in meters which the altitude of the center point is above or below the regression plane. Figures 5 and 6 show maps of slope angle and local relief derived by this method.

It is relevant here to discuss the choice 9f a 100 m grid interval rather than any other. Ideally it would have been desirable to have as fine a grid as possible, e.g., a 10 m or a 1 m grid interval. Measurements of snow depth are made within a few meters of sampling locations, i.e. in a very compact area. Processes of accumulation and ablation may well be sensitive to very small scale topographic shapes as well as to larger scale topography. Surface shape measures should be at the same sort of scale as the processes being investigated. As McCarty et al. (1956) has stated: "In geographic investigation it is apparent that conclusions derived from studies made at one scale should not he expected to apply to problems whose data are expressed at other scales. Every change in scale will bring about the statement of a new problem, and there is no basis for assuming that association existing at one scale will also exist at another." The choice of a 100 m grid interval may, therefore, not be the most appropriate choice for the elucidation of the process/pattern interrelationship.

Why, then, was a 100 m grid chosen? Firstly, it was considered the finest scale at which altitudes could be read off the topographic map with confidence. The 1: 10000 maps of the glaciers must be considered very accurate. Contours are at 10 m intervals and are accurate to within ± 2 m over most of the glacier surfaces. At grid locations altitudes can, therefore, probably be read to ± 5 with confidence. It is considered that at horizontal distances of 100 m a 5 m error is tolerable for defining surface geometry characteristics. Secondly, a grid interval of 100 m produces a density of 100 points per km^2; for Peyto Glacier this density translates into 1340 points for the whole glacier, a number which is tolerable for computer manipulation (given that many matrices containing glacier information will be used-in a single computer program). Thirdly, with the sampling interval of 100 m shape measures do not change markedly through time (except for small areas at the extreme snout or edges of the glacier) whereas on a scale of 10 m or especially at 1 m rapid changes in shape may occur over time.

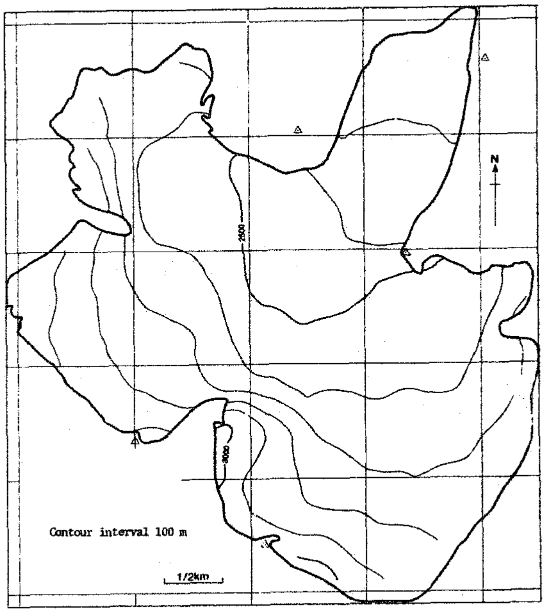
The 100 m grid was then chosen primarily for convenience; results derived by using it should be viewed with appropriate caution.

The Evaluation of an Existing Sampling Network

Before describing the method used to generate a stratified sampling network an example *is* given of how an existing network can be evaluated in terms of altitude, slope angle and local relief.

The method of evaluation is summarized in a number of steps, as follows:

1. The glacier surface is divided into a number of overlapping zones based on altitude. Each zone is centered on a 10 m contour and consists of the area bounded by



PEYTO GLACIER
ALTITUDE

Figure 3.

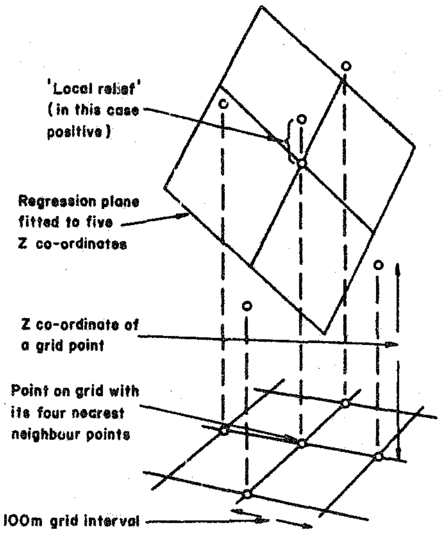
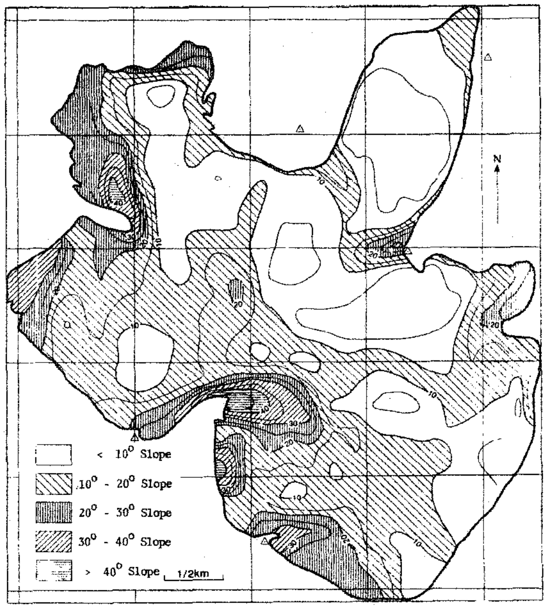
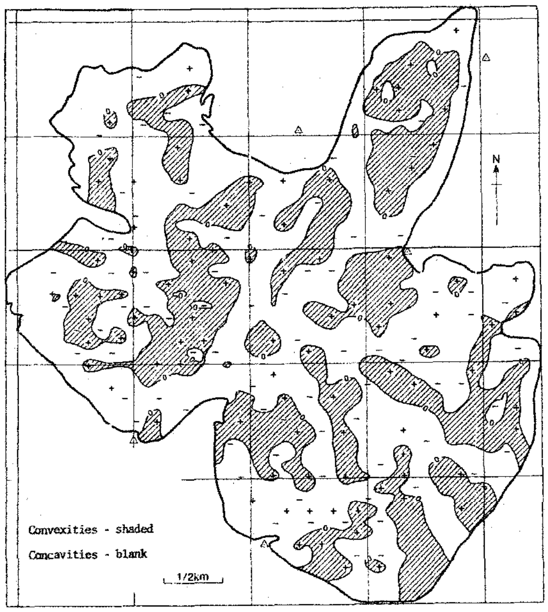


Figure 4. Geometrical relations used to derive local relief.



PEYTO GLACIER

Figure 5. Slope angles.



PEYTO GLACIER

Figure 6. Local relief

contour lines 20 m lower and 20 m higher than the central contour. Two such successive zones are illustrated in Figure 7. A 40 m (vertically) wide zone rather than a zone of any other width is chosen arbitrarily. Each zone contains a sufficiently large number of grid cells so that meaningful statistical measures may be calculated and yet is sufficiently narrow so that the boundary effects at the top and bottom of the glacier are minimized.

2. Within each zone the mean and standard deviation of both local relief and slope angle values are calculated. These values can then be plotted against altitude for each 10 m vertical interval as illustrated in Figure 8. The graphs show clearly how the means and standard deviations for both local relief and slope angle change over the altitude range of the glacier.

3. The values of local relief and slope angle at all stake locations can also be plotted on the graphs (asterisks on Figure 8). It can be seen clearly to what extent the stake locations are typical or atypical, in terms of local relief, and slope angle for the particular elevations, and in terms of altitude range for the glacier.

The Peyto Glacier example shows that stake locations are usually fairly representative of the glacier in terms of local relief (i.e. values of local relief at stake locations are near to the average for the altitude and are reasonably well dispersed on either side of the mean). However, in terms of slope, there is definite bias towards more gentle slopes, especially on those parts of the glacier where slopes are steepest. This may be of very real importance in making ablation maps for gentle slopes tend to be less well drained than steep slopes and thus there may be considerable bias in the measurements made.

A New Stake Network Based on Stratification According to Surface Geometry

The above described approach can be used to define those parts of a glacier which are representative of slope angle and local relief. The approach is summarized in a number of steps, as follows:

1. For each 100 m grid intersection the procedure is:

    (a) To define the area of the glacier within 20 m of the elevation of the grid point (See Figure 9).

    (b) Calculate the mean and standard deviations of slope angle and local relief for the grid points lying within this area.

    (c) Express the slope angle and local relief of the point in question in terms of standard deviation from the average for the area.

    (d) Classify the point as 'representative' in terms of slope angle and 'representative' in terms of local relief if the values of the point are within ±0.319 a of the mean. The value of 0.319 a has been chosen because if the frequency distributions for slope angle and local relief are normal then about 25% of points should be classed as 'representative'.

2. Map the locations of all points which are classified as representative, first, in terms of local relief, second in terms of slope angle and third in terms of both local relief and slope angle. Figure 10 shows all three maps in one for Peyto Glacier.

3. As shown on Figure 10 about one point in every ten on the square grid is classified as typical in terms of both slope angle and local relief. A subset of these points can now be chosen according to any other criteria the researcher wishes. On the glaciers described in this study the following additional criteria were used:

    (a) Range in altitude was maximized and a similar number of locations were made in each altitude zone.

    (b) Stakes in the original networks which coincided with the 'best' locations, as described above, were used as part of the new stake network, thus minimizing the number of new stakes to be inserted.

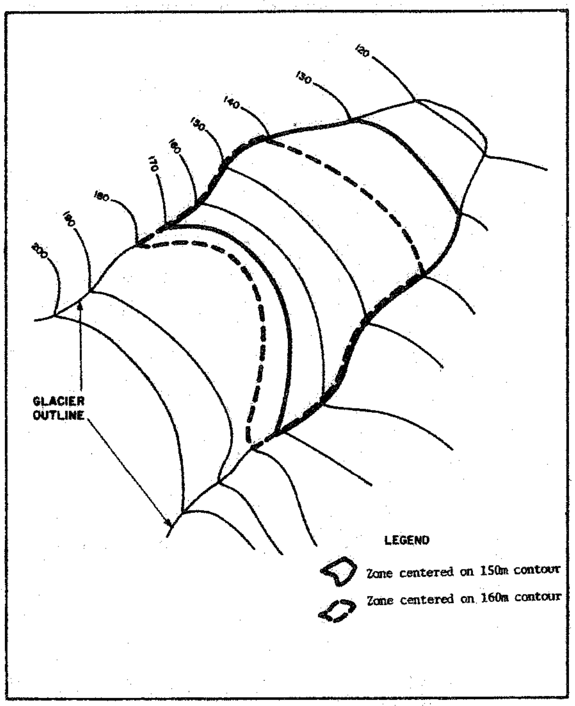


Figure 7. Part of hypothetical glacier showing two successive overlapping altitude zones.

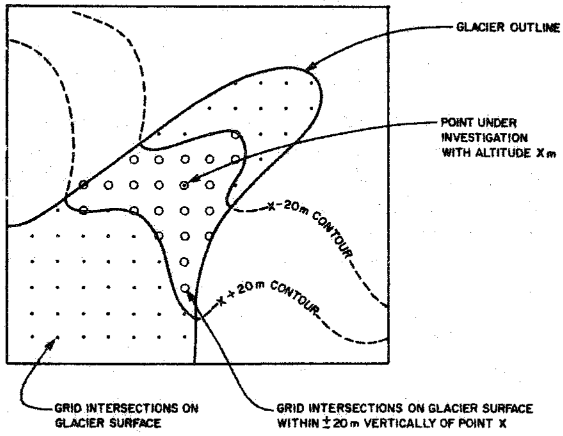
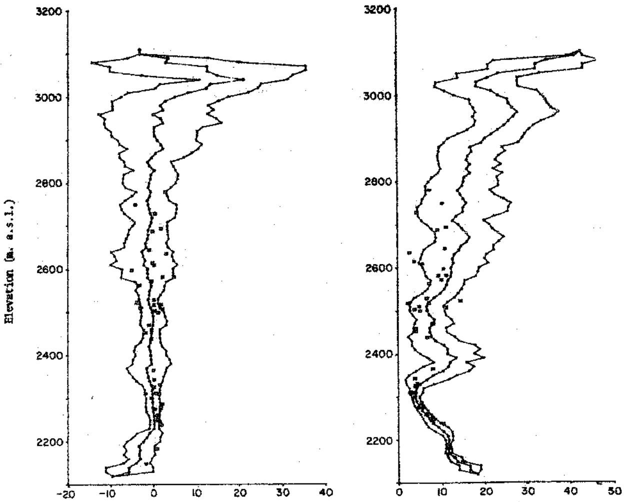


Figure 9. Part of hypothetical glacier showing the definition of a 40 m altitude zone centered on a given point.



(a) Elevation/local relief relationship.

(b) Elevation/slope angle relationship

Figure 8.

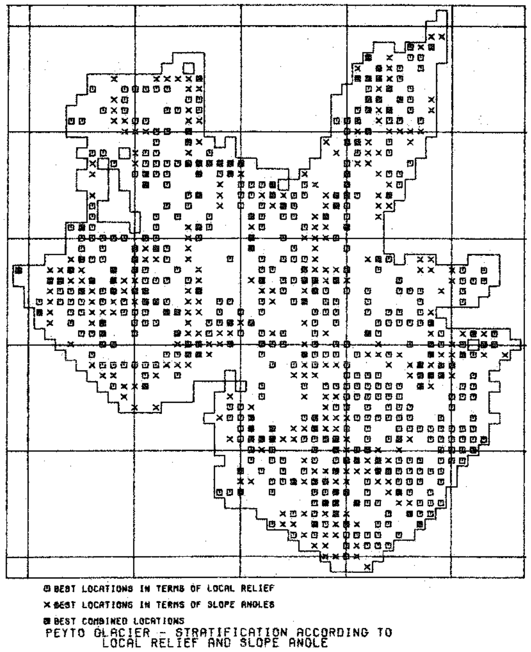


Figure 10. Map of 'best' sampling locations.

(c) Possible new stake locations which fell in highly crevassed areas had to be eliminated for practical reasons.

(d) New locations were also chosen away from moraines or valley walls which might have had significant effects on processes of accumulation and ablation.

(e) Within the constraints described above, variation in azimuths of new locations was maximized.

Results of a Standard vs. the Stratified Technique on Peyto Glacier

On 25 May 1973 snowpack water equivalent measurements were taken at 25 locations which have been visited each year as part of the regular survey and at 10 locations which have been positioned in accordance with the stratified design. Five of the stratified locations coincided with 5 of the normal sampling locations (all low down on the glacier). The distributions of these two sets of sampling locations are shown in Figure 11. It can be seen from the map and from the accompanying scatter diagrams that the normal stakes are clustered toward the lower parts of the glacier, the stratified set is more evenly spread both spatially and altitudinally.

The following analyses were performed on the two sets of data.

1. Accumulation was associated with altitude. The scatter diagrams, linear regression equations and correlation coefficients (shown in Figure 11) are remarkably similar for the two sets of data.

2. Accumulation was associated with altitude (A), local relief (R) and slope angle (S). While the multiple correlation coefficients are both very high, the linear regression equations are markedly different. Standard partial regression coefficients are given so that the relative importance of the three predictor variables within each equation may be seen. It is noticeable that altitude is relatively less important in the second equation (stratified sample) than in the first while slope angle is more important. In other words, slope angle is the dominant predictor variable in the stratified sample.

Equation 1 (using 25 normal locations).

$$\text{Accumulation} = -533.4 + 0.250 \times A + 3.76 \times R + 4.78 \times S$$

Standard partial regression coefficients are: A 1.02; R 0.15; S 0.36; multiple correlation coefficient = 0.95.

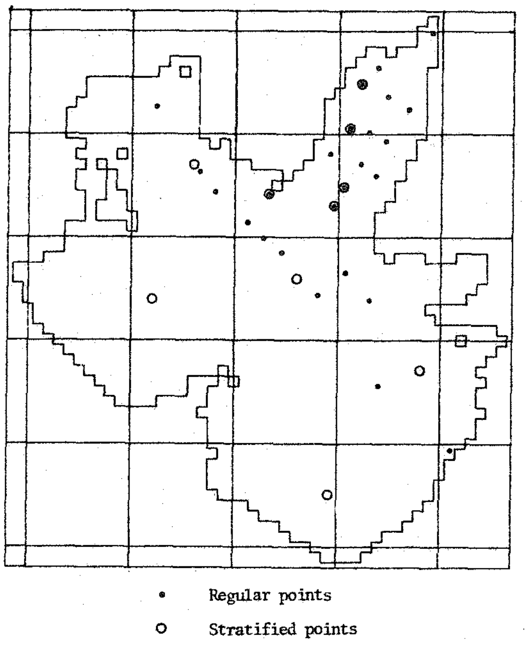
Equation 2 (using stratified sampling design).

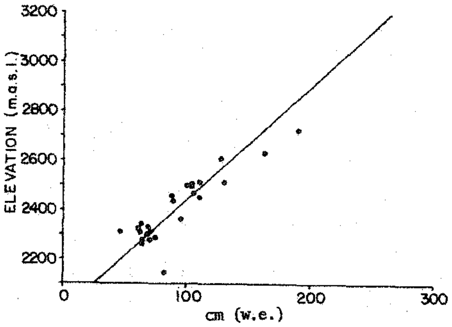
$$\text{Accumulation} = 43.2 + 0.035 \times A + 0.51 \times R + 6.84 \times S$$

Standard partial regression coefficients are: A 0.18; R 0.01; S 0.81; multiple correlation coefficient = 0.98.

3. Volumes of total accumulation and maps of snow depth distribution were produced by substituting in equation 1 and 2 the values of A, R and S for each grid point and mapping these results. Total volumes were substantially different ($24.7 \times 10^6 m^3$ by equation 1, $10.5 \times 10^6 m^3$ by equation 2) Figure 12 shows these differences when the distributions are mapped. Additional information gathered after 25 May suggests that the snow depths in the upper parts of the glacier predicted by equation 1 are unrealistically high. The depths generated by equation 2 are probably much more realistic.

This example of using the stratified sampling design in one situation for one survey cannot be taken as a complete test of the method. However, it indicates that the method seems to produce realistic results and if in addition it means a saving in effort then it may be worthy of implementation on other areas.





Regular sample
W.E. = -432.5 + 0.22 *ALT
r = 0.89

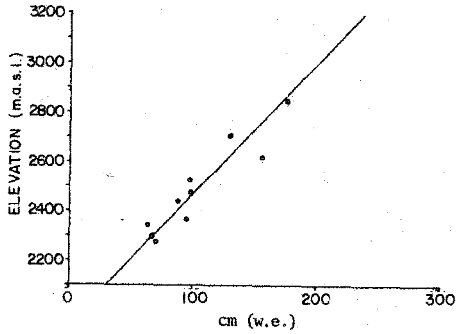


Figure 11. Peyto : accumulation by two different methods.

Stratified sample
W.E. = -365.6 + 0.19 *ALT
r = 0.94

PEYTO ACCUM 25 MAY 73 ALT+LR+SL

PEYTO ACCUM 25 MAY 73 STRATIFED SAMPLE ALT+LR+SL

Figure 12. Maps of accumulation.

ACKNOWLEDGEMENTS

The author would like to thank Mr. K. C. Arnold and Dr. A. D. Stanley of the Glaciology Division, Inland Waters Directorate, Ottawa, Ontario for their helpful comments.

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