Environment Canada Environnement Canada

An Approach to Glacier Mass-Balance Analysis Utilizing Terrain Characterization

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SCIENTIFIC SERIES NO. 60
(Résumé en français)

INLAND WATERS DIRECTORATE,
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Abstract

This report describes a method currently being used to produce accumulation, ablation, and net balance maps as part of the mass balance studies on selected glaciers in Western Canada. The method uses associations between snow depth and terrain geometry to extrapolate the measurements made at sampling locations to unvisited parts of the glacier. The grid square technique has proved very efficient for computer manipulation of data bases and for calculations and tabulations of results. The rationale behind the method and instructions for implementation, including a program listing, are presented. Although the system has been developed for Canadian Cordilleran conditions, the approach could be used with equal success on glaciers with substantially different surface geometry characteristics.

Résumé

Le présent rapport traite d'une méthode qui sert actuellement à établir des cartes de l'accumulation, de l'ablation et du bilan glaciaire, dans le cadre d'études du bilan matière de quelques glaciers choisis de l'Ouest du Canada. La méthode utilise les relations établies entre l'épaisseur de la neige et la configuration du terrain pour extrapoler pour les parties du glacier qui n'ont pas été étudiées les résultats des mesures effectuées aux points d'échantillonnage. L'utilisation d'un grillage a donné de très bons résultats lors de l'utilisation par ordinateur des banques de données, ainsi que pour le calcul et la mise en tableaux des résultats. Le rapport explique également les principes de la méthode et donne des instructions concernant son utilisation, y compris l'énoncé d'un programme. La méthode a été mise au point pour les conditions qui prévalent dans la Cordillère du Canada, mais elle peut servir avec les mêmes avantages sur des glaciers très différents pour leur géométrie de surface.

An Approach to Glacier Mass-Balance Analysis Utilizing Terrain Characterization

Gordon J. Young

INTRODUCTION

During the period 1965-1974, the Glaciology Division, Inland Waters Directorate, Environment Canada, has conducted glacier mass-balance studies on five International Hydrological Decade (I.H.D.) representative basins located on an east-west transect through southern Alberta and British Columbia (Figure 1). General outlines of the work carried out on these glaciers have been provided by Østrem (1966), Løken (1970) and Stanley (1970, 1971).

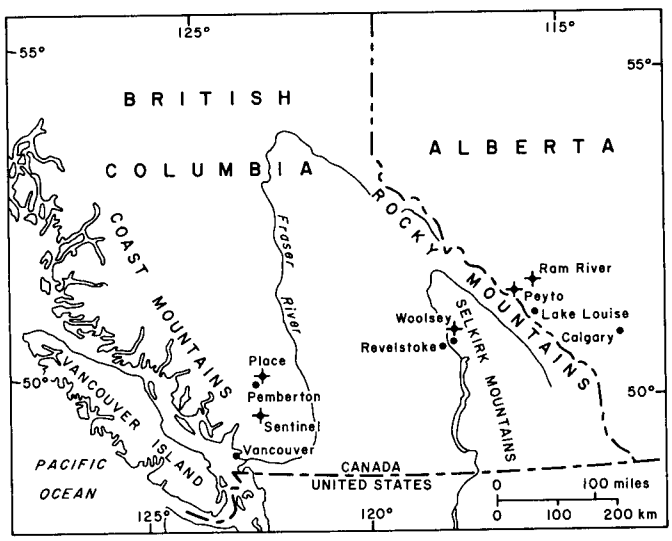

Figure 1. Location of glaciers: Sentinel, Place, Woolsey, Peyto and Ram.

The purpose of this paper is to describe a largely automated system for reducing the snow accumulation and ablation measurements to a readily understandable mapped and tabulated form.

BACKGROUND INFORMATION

Characteristics of the Glaciers Studied

It can be seen from Table 1 and Figure 2 that there is considerable variety within this group of five glaciers. The variety includes: (a) mean elevation and range in elevation above sea level; (b) mean surface slope; (c) size, although no large glacier is included; and (d) regime. Compared with the eastern glaciers, the west coast glaciers are more dynamic with larger winter accumulations and larger summer melts. It should be noted that while there is considerable variety within the group of glaciers, all are small, alpine, valley glaciers lying in temperate latitudes; there are no icecaps represented. Caution should therefore be used in applying the methodology outlined in this paper to glaciers which are very different in size, shape and regime from the glaciers under study.

Nature of the Data

Identical programs of measurement were conducted in all glacier basins during the I.H.D. The procedures have been described in detail in the manual by Østrem and Stanley (1969). A brief summary is given here regarding the collection of data relating to snow accumulation and ablation.

Sampling Network

A network of stakes was established and maintained on each glacier. A typical sampling network is shown for Peyto Glacier in Figure 3. The stake networks were established in a manner as objective as possible, all major

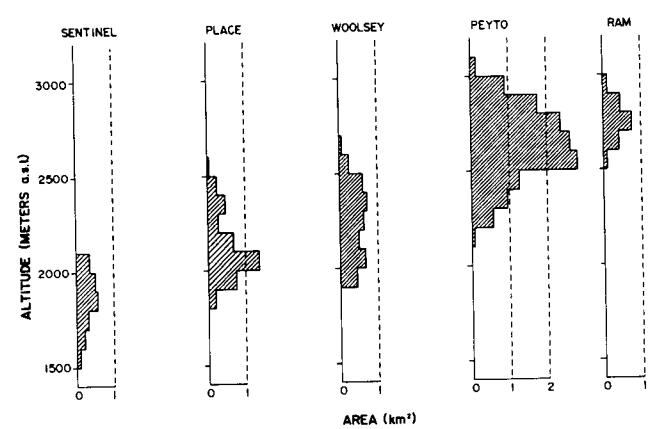

Figure 2. Area/altitude curves for Sentinel, Place, Woolsey, Peyto and Ram glaciers.

Table 1. Comparison of glaciers.

	Sentinel	Place	Woolsey	Peyto	Ram
Area of glacier (km^2)	2.03	4.01	3.92	13.40	1.80
Highest elevation (meters a.s.l.)	2100	2543	2640	3185	2990
Lowest elevation (meters a.s.l.)	1548	1828	1930	2125	2565
Mean slope of surface (degrees)	15.7	10.5	17.5	12.9	13.5
Mean azimuth of surface (degrees)	333	5	22	33	10
Mean net winter accumulation ($m^3 \times 10^6$ w.e.)	6.84**	7.90**	9.85*	19.71***	1.67*
Mean specific accumulation (meters of w.e.)	3.37**	1.97**	2.52*	1.47***	0.93*
Mean net summer loss ($m^3 \times 10^6$ w.e.)	6.92**	10.09**	11.97*	28.11***	2.61*
Mean specific net loss (meters of w.e.)	3.41**	2.52**	3.05*	2.30***	1.45*

* Mean 1966-70 ** Mean 1966-71 *** Mean 1966-72

Table 2. An example of a stake observation form (Peyto Glacier, 1970, stake 90).

Date	Top to: Snow (cm)	Top to: Ice (cm)	Snow Sound	Snow Calc.	Snow Dens.	Snow W.eq.	Check	Difference Super ice cm	Difference Super ice w.eq.	Difference Snow	Difference Ice cm	Difference Ice w.eq.	Abl.	Cum. acc.	W.eq. Abl.	Net w.eq.
13 5	33		241		0.41	99	274									+ 99
23 5	49			226	0.45	102	274			3				3		+102
31 5	66		214		0.45	96	280			6			6		3	+ 96
7 6	105		164		0.50	82	269	5	4	14			10		13	+ 86
15 6	158		121		0.49	59	279			23		4	27		40	+ 59
1 7	229		46		0.50	23				36			36		76	+ 23
15 7		354								23	80	72	95		171	- 72
31 7	lost readings inferred from stake 99.										78	70	70		241	-142
31 7		230														
1 8		234									4	4	4		245	-146
2 8		240									6	5	5		250	-151
4 8		260									20	18	18		268	-169
5 8		265									5	5	5		273	-174
6 8		273									8	7	7		280	-181
11 8		295									22	20	20		300	-201
21 8		335									40	36	36		336	-237
25 8		359									24	22	22		358	-259
6 9		400									41	37	37		395	-296

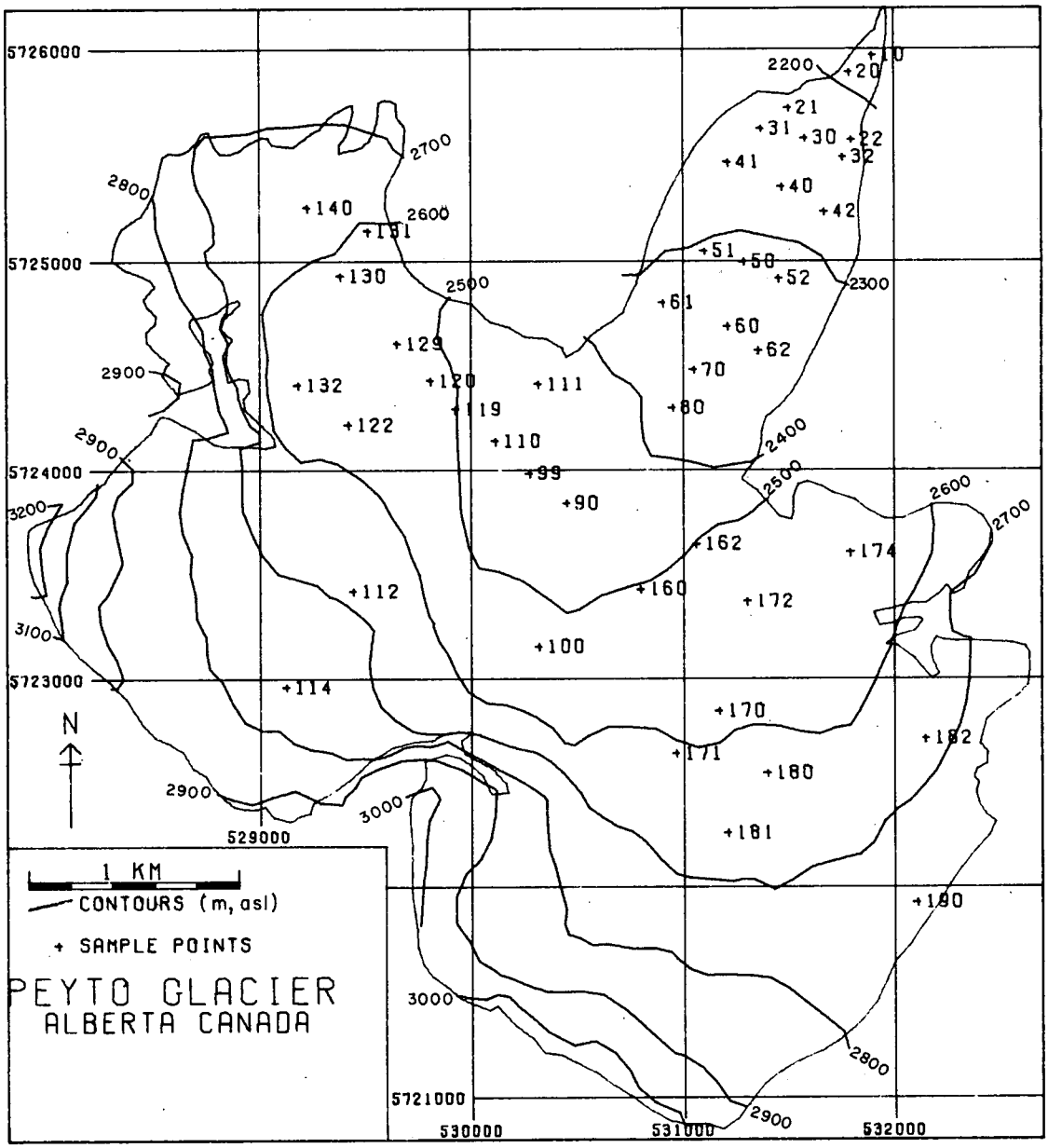

Figure 3. Peyto Glacier – Stake locations in 1970. Note: Maximum movement is about 10 m yr^{-1}; therefore, these positions are all correct to within ±50 m over the I.H.D. period.

areas of a glacier being sampled evenly. It should be noted, however, that on many glaciers large parts of the surface are heavily crevassed or very steep, causing restricted accessibility. A simple map of accessibility for Peyto Glacier is shown in Figure 4.

Surveys

Measurements of snow depth and/or amounts of melt were made at all stakes throughout each melt season. The interval between successive surveys varied from glacier to glacier from once every 10 days to once every month. At each survey, snow depth was measured at each stake location and mean snowpack density was measured at two or three pit locations on the glacier. An example of a typical stake observation form is shown in Table 2. The accuracy of snow depth readings and melt measurements at stakes can vary considerably from one glacier to another. On Peyto, Ram and Place glaciers, where snowfall is relatively light, the overall accuracy of snow depth soundings is high, i.e. ±20 cm in the most difficult parts of the accumulation area. There are very few places on these

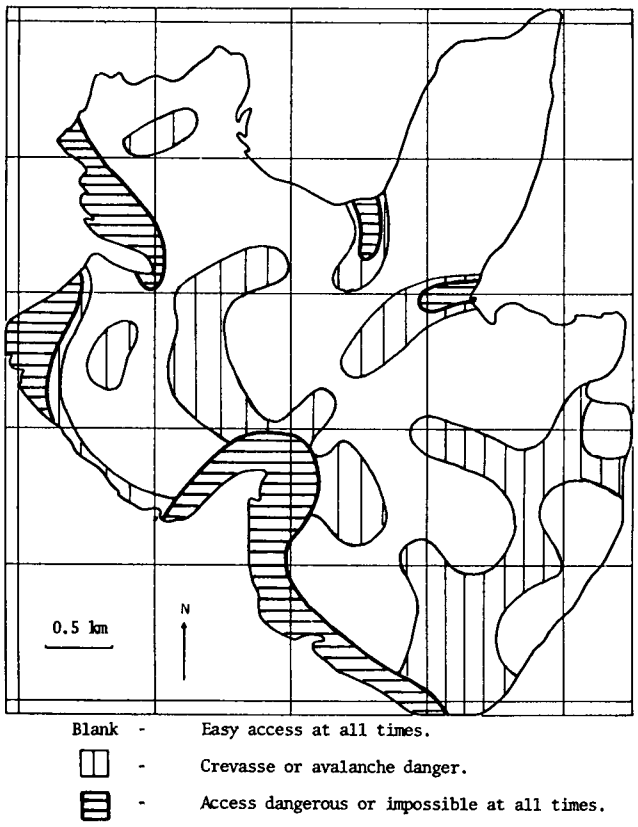

Figure 4. Peyto Glacier – Accessibility over the glacier surface.

glaciers where the measurement would be grossly in error. On Sentinel and Woolsey glaciers, however, where snow depths can be much greater, errors are likely to be larger, especially in the accumulation areas of the glaciers where the firn/new snow contact is often indistinct. On these glaciers, with snow depths of up to 10 m, inaccuracies in snow depth measurement of as much as 1 m may occur. During the surveys of spring accumulation, additional depth soundings were taken between stake locations to produce accumulation maps by the standard method.

Standard Method of Data Reduction

Maps have been produced and tabulations made for surveys taken at the end of the accumulation and ablation periods. The maps of winter accumulation and summer ablation (and net annual balance as the combination of the two) are produced as follows. Mean pack density measurements are assumed to be valid for large areas surrounding the density pits; these values are applied to the snow depth values at stake locations to give water equivalent values. The snow water equivalent values at stake locations are then plotted on a base map after which isolines of water equivalent are drawn in by hand. Tabulations of specific water equivalent within 100-m altitude zones are derived from the map by planimetry, and graphs of water volume variation with altitude are produced.

In summary, the standard method is subject to three main problems, which vary in their relative importance from one glacier to another: (1) the difficulties in making depth and density measurements at specific locations; (2) the sampling problem of how many measurements to make and exactly where to make them; (3) the difficulties associated with interpolation from the measuring sites to unvisited parts of the glaciers.

The new method, described below, is still subject to the limitations of the first two problems, but the mapping and tabulation procedure is substantially different.

A NEW AUTOMATED METHOD FOR ANALYZING MASS BALANCE DATA

Basic Principles

Background to the Method

The assumption basic to the method is that within a given watershed or research area, spatial variations in the extent and character of the snowpack and variations in the rate of change of the snowpack from place to place are associated with the geometry or shape characteristics of the underlying surface.

The idea that there are associations between terrain variables and snow amounts is not a new one. Meiman (1968) has provided a comprehensive review of the North American literature concerning these associations. Of particular relevance here are papers by Mixsell *et al.* (1951), Grant and Schleusener (1961), Leaf (1962), Court (1963), Anderson and West (1965), Curry and Mann (1965) and Gary and Coltharp (1967). Papers by Salamin (1961) and Martinelli (1965) are also relevant, although not listed by Meiman. Several studies of polar regions have considered the influence of topography on snow accumulation and melt. The Antarctic was the research area for Rubin and Giovinetto (1962), Black and Budd (1964) and Gow and Rowland (1965). Potter (1958, 1965), Jackson (1960), and Benson (1967) deal with general Arctic subjects, while Corbel (1958), Hattersley-Smith (1960), Longley (1960), Müller *et al.* (1963), Arnold (1965) and Mock (1968) perform more detailed studies. Langbein (1965) emphasizes the potential uses of terrain variables as estimators of hydrological variables. Some of the most advanced analysis in this field has been done by H.W. Anderson (1968).

All the investigators mentioned so far have been concerned, in either a quantitative or descriptive way, with associations between snow amount and terrain variables. In particular, they have stressed the increase in snow depth with altitude. While there have been many attempts to show links between terrain shape and snow amount, relatively few studies have gone one step further to use the associations to estimate or predict amounts of accumulation or melt for areas which cannot be visited.

Empirical and semi-empirical formulae have been developed by the U.S. Army Corps of Engineers (1956, 1960). The Stanford watershed studies (Anderson and Crawford, 1964; and Crawford and Linsley, 1966) and the study by E.A. Anderson (1968) have used an energy balance equation approach for snowmelt processes. Range in elevation and simple exposure to solar radiation indices are used to modify energy income over a basin. Hendrick (1971) has shown how an area can be classified by forest type, by slope and aspect and by elevation so that general principles of snowmelt can be deduced; but quantitative estimates of snowmelt at unvisited locations are not made.

Solomon *et al.* (1968) and Pentland and Cuthbert (1971) have used basically the same approach as is taken in the research presented here, but have considered a slightly different problem. In some river basins in Eastern Canada, data were available on river discharge. In all basins, drainage basin characteristics (e.g. size, amount of forest cover, area of lakes, etc.) could be obtained from topographic maps. By associating discharge with basin characteristics within monitored basins and by applying the associations to unvisited basins, for which only basin characteristics were known, discharge could be simulated over very large areas. Grindley (1970) has used a similar method for estimating and mapping evaporation in Britain.

The physics of the processes involved in snow accumulation and ablation are complex. The amount and character of the snowpack at any particular location are associated with such terrain variables as altitude, slope angle, slope azimuth, local relief of the surface, forest characteristics and so on at that location. Variation in snowpack character from place to place is associated with variation in the surface geometry parameters. The nature of the association is usually complex and the main problems in elucidating it are linked strongly with:

(1) being able to measure the snowpack characteristics accurately at well-chosen sampling locations;

(2) being able to choose significant and measurable surface geometry parameters;

(3) the assumption that processes of accumulation and ablation are the same or at least very similar over the entire research area.

Description of the Method

It was found in the many studies quoted by Meiman (1968) that strong associations exist between snow depth and altitude. If within the research area sampling locations are chosen and snow depth measurements made, then altitude versus snow depth can be plotted and an associative equation can be derived which has the form

$$\text{Snow depth} = a + b.\,\text{altitude}$$

where a and b are constants.

This equation can then be applied to any altitude within the research area and so estimates of snow depth at all altitudes can be made. In view of this relationship and the conclusions which could be derived from it, the following points deserve special consideration:

1. It has been assumed that there is a linear relationship between the two variables. A curvilinear or much more complex relationship might be nearer the truth. Although some studies have indicated that snow depth may decrease with altitude above a critical elevation, there is no evidence that this is so on the glaciers under study.

2. The sampling points must be representative of their respective altitude zones.

3. The altitudes of the sampling points within the research area must be well chosen. If the range in altitude within the area is great and if the difference in altitude between sampling points is small—especially if sampling points are either low down or high up within the area—extrapolation below the altitude of the lowest point or above the altitude of the highest point may produce highly erroneous results.

4. Great importance must be attached to the accuracy of the measurements of snow depth (or water equivalent, whichever is being considered) at the sampling points.

More variables than altitude alone may be introduced into the equation to explain snow conditions. Therefore, snow depth might be explained as a function of altitude, slope angle, local relief, etc. Again, multiple linear or more complicated multiple curvilinear relationships can be

assumed. There can be sampling bias, measurement inaccuracy and the problems associated with extrapolation too. If orthogonality cannot be assumed for the variables, transformation of the variables themselves may have to be performed before the associative equations are generated. Confidence in the results, if means and variances are being calculated directly from the samples, is influenced by the type of sampling network and the extent to which the sampling distributions of variables approach the normal frequency distribution.

An associative equation is, then, generated for a particular time and for the sampling locations within the research area under discussion. In the equation snow character (the measure usually being water equivalent) is linked to the surface geometry parameters.

The same surface geometry parameters are also calculated for all points on a square grid covering the entire research area. These parameters do not change through time unless the terrain itself is changing quickly relative to the time difference involved, which is an unusual case. The associative equation can then be successively applied to each point on the square grid and values or estimates of snow amounts returned. Once these values are known, they can be mapped (the square grid, as pointed out by Solomon *et al.*, 1968, being very suitable in this regard), or total volumes or mean depths can be calculated for any given zone within the research area.

Summary

The method outlined above consists of two distinct phases:

1. The description of the surface geometry of the glacier.

2. A program which (a) links accumulation or ablation amounts at point locations to glacier geometry at those locations and (b) uses the associations so produced to make maps and tables of snow amounts.

These two phases are described below.

Description of Glacier Surface Shape

Geometry Measures

A program has been written by the author (Young, 1973) to describe the shape of the surface at a regular array of points within a basin. A square grid (Universal Transverse Mercator) with a grid interval of 100 m is laid over a map of the basin, and altitudes at grid intersections are read and stored. These altitudes are used in the generation of surface shape measures. The maps used were specially compiled by the Glaciology Division at a scale of 1:10,000 with a contour interval on the glacier surface of 10 m. The contours were probably accurate to ±2 m at the time the maps were made; and only in relatively confined areas, near the snouts of the glaciers, could there have been considerable surface change during the decade.

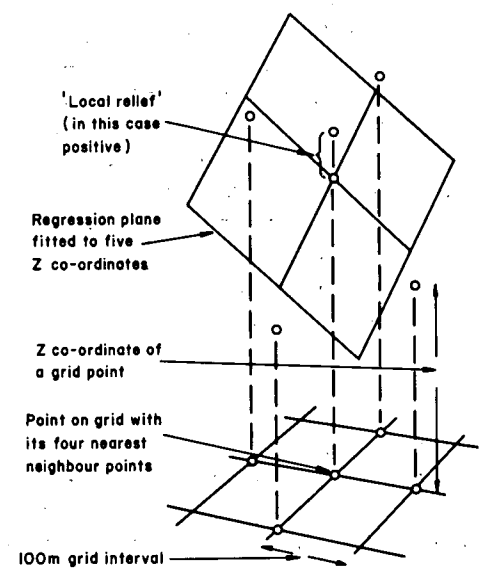

Figure 5. Geometrical relations used to derive geometry measures.

For the purpose of the mass balance analyses, only three measures of surface shape were considered: altitude, slope angle and local relief. These measures are calculated for each grid point by fitting a regression plane to the altitude of the point itself plus the altitudes of the four nearest neighbour points (Figure 5). The angle of maximum slope of the plane is the slope angle for that point and the extent to which the grid point is above or below the plane is taken as the measure of local relief.

Significance of Geometry Measures

As quoted above, many studies of snow accumulation have shown that the amount of snow has often been strongly correlated with altitude, slope angle, and aspect. It may also be connected with local relief of the surface in the sense that, in general, there will be more snow in hollows than on ridges after redistribution by wind has taken place. The situation can be very complicated: for example, some hollows may actually be caused by deflation, whereas hollows of the same size and shape in other parts of the glacier may be snow traps and receive much more accumulation.

It is important to realize that the grid interval of 100 m was subjectively chosen more for convenience than anything else. If a grid interval of 500 m or 10 m had been chosen, then the local relief indices and the slope angles might have been substantially different. It is believed, however, that many characteristics of the glacier surface are adequately described using a grid interval of 100 m.

Processes of ablation are definitely linked to topographic variables. Altitude is especially important through its effect on air temperature. Slope angle in association with azimuth affects greatly the amount of incident incoming direct solar radiation (although albedo may be critical in determining the amount of absorbed, shortwave radiation). Local relief of the surface is also important in that a ridge will, in general, modify the turbulent heat transfer. Ridges on glaciers are often crevassed, i.e. they have large areas of ice exposed to the air and are, therefore, more likely to gain heat from both turbulent and radiative heat transfer processes. Karlén (1965) has suggested that crevassed areas produce 17% more melt than surrounding uncrevassed areas.

The geometry parameters chosen for this study are reasonable because previous studies have shown that similar measures of shape have influenced the processes of accumulation and ablation.

Calculation of Geometry Measures at Stake Locations

Besides knowing the geometry measures at all locations on the square grid, it is necessary to know the geometry measures at each stake location. The positions of all stakes are known to within a few metres at any time, for theodolite surveys of their positions are made at least once a year. Geometry measures have been calculated by the grid square technique for every 100 m on the glacier surfaces. It was initially thought that geometry measures at stake locations should be interpolated between the four nearest neighbour grid points. On further investigation it was found that little was to be gained from an elaborate interpolation routine, for the geometry measures so generated were only slightly different from the values of the nearest grid point to the stake location. Thus the geometry measures for any stake location are simply the measures at the nearest 100-m grid point.

Computer Program MASBAL

Program Description

The basic function of the program is to provide maps and tabulations of accumulation or ablation from a set of measurements made at stake locations at a particular time. The program has been set up to maximize simplicity of operation while retaining flexibility. Problems for a series of times on one glacier can be solved consecutively in one computer run.

For each mass balance problem the user must supply snow depth and bulk density data at as many locations as he likes. Each depth and density must be accompanied either by a stake name or by x and y co-ordinates to locate it on the glacier. The number of depths and densities and the order in which they are given is not restricted. For a typical problem there might be 10 to 50 depth measurements and 1 to 4 density measurements.

A second form of input is automatically supplied by the program: from a data bank containing non-variable information, the appropriate glacier geometry measures (altitude, slope angle and local relief) are abstracted for every point on the square grid and for all stake locations. The structure of this data bank (described below) is of great importance for the smooth running of the program. Although the glaciers vary in size and shape, information is ordered in the same sequence for each glacier.

The first computations of the program are the transformations of snow depths to water equivalents at stake locations. Mean pack density is assumed to vary linearly with altitude; a linear regression equation linking density with altitude is performed and the appropriate density for each stake location is calculated. Water equivalent at each stake location is thereby calculated. The decision to make mean pack density vary linearly with altitude was taken for the following reasons: (a) density pits are usually made over a wide altitude range; (b) at the end of winter, before the pack begins to ripen, there is usually little variation in mean pack density from place to place on the glacier; (c) later in the ablation season the snowpacks low down on the glacier will tend to ripen and become more dense earlier than those at higher elevations and thus there will probably be an inverse relationship between density and altitude; (d) a linear rather than a curvilinear association is assumed, for often only two or three density pits are made.

The second stage in the computation is to link water equivalent at stake locations to geometry measures at those locations. The program provides the user with a choice of three different combinations of predictor variables (In an earlier version of the program the user could choose any combination of predictor variables he desired, but it was found that for convenience the following three options proved sufficient for most routine purposes):

1. The predictions of snow depth can be based on

altitude, slope angle and local relief. The equation will have the form:

$$sd = a + bZ + cR + dS \quad (1)$$

where sd is the snow depth; a is the intercept value; b, c and d are regression coefficients; Z is the altitude of the point; R is the local relief; and S is the surface slope angle.

This is the default option, i.e. if the user does not specify any choice, this first option will be assumed.

2. The user can choose that predictions be made solely as a function of altitude. If there are too few sampling locations to allow the first option to be implemented, there is an automatic default to this second option. The equation will have the form:

$$sd = a + bZ \quad (2)$$

where the same notation as in equation (1) is used.

3. A third option allows a regression of snow depth with altitude, and then user-supplied coefficients for slope angle and local relief can be applied to modify snowpack depth. The main purpose of this third option is to allow the user to simulate better likely patterns of snow distribution, although snow depth measurements may only be available at two or three locations on the glacier. Equation (1) is used again, but "c" and "d" are supplied by the user.

Once the equation has been generated linking snow water equivalent to chosen geometry variables, it is applied to every point on the 100-m grid. An older version of the program has been slightly modified at this stage. Often the slope angles of the terrain at stake locations show a much smaller range in values than for the entire glacier. If a partial regression coefficient generated for slope angles of between, for example, 2° and 15° is applied to slope angles of 40°, usually the results are obviously wrong. To avoid gross errors of this sort, any slope angle greater than the maximum slope angle at stake locations is considered equal to that maximum angle; any slope angle smaller than the minimum slope angle at stake locations is considered equal to that minimum slope angle. The same procedure is applied to the local relief index. It should be noted that this modification has appreciable effect only on small areas of the glaciers with very steep slopes and high local relief. On most glaciers no more than about 10% of the surface is affected and the areas are usually at very high elevations. In these high and steep areas few measurements are taken and processes of accumulation and ablation may be very different from most areas on the glacier (e.g. cornicing and avalanching); and there is least confidence in results no matter which method of data reduction is used.

Once the equation linking snow water equivalent to surface geometry has been applied to every point on the 100-m grid, it is a straightforward procedure to tabulate and map the results. The basic tabulation provides the

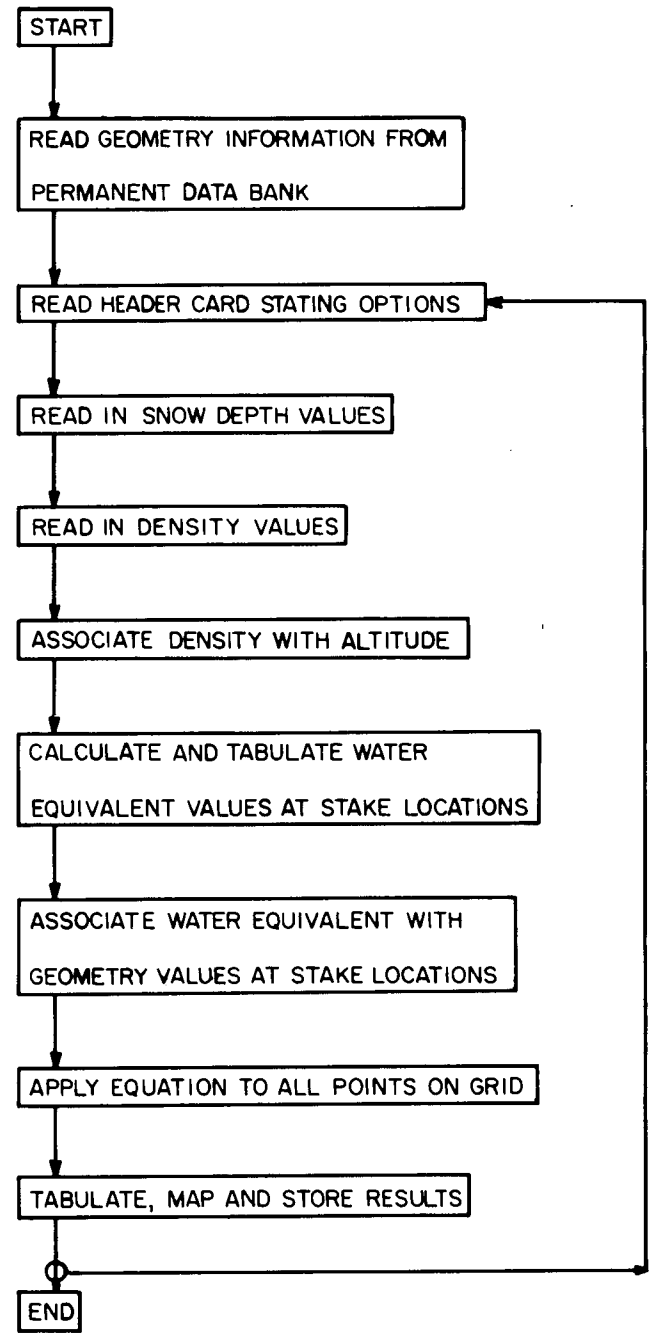

Figure 6. Simplified flow chart for MASBAL program.

following information for the whole glacier and for each 100-m altitude zone: mean, standard deviation, maximum, minimum and range in snow water equivalent. The altitude zone may be changed from 100 m to any size the user desires. The program also provides a line-printer map with a maximum of 10 class intervals for the whole glacier. Map size and class interval may be provided by the user. By default a convenient size and interval are automatically chosen.

The user also has the options of having the tabulations automatically graphed on a CalComp (California Computer Products, Inc.) plotter and/or the final matrix of snow water equivalent values stored on disc in a form that can be taken as a direct input to a contouring package program utilizing a CalComp plotter. The contouring package used in the examples given in the section "Results Obtained by Standard Method Versus those Obtained by New Automated Method" is the CalComp General Purpose Contouring Program (GPCP).

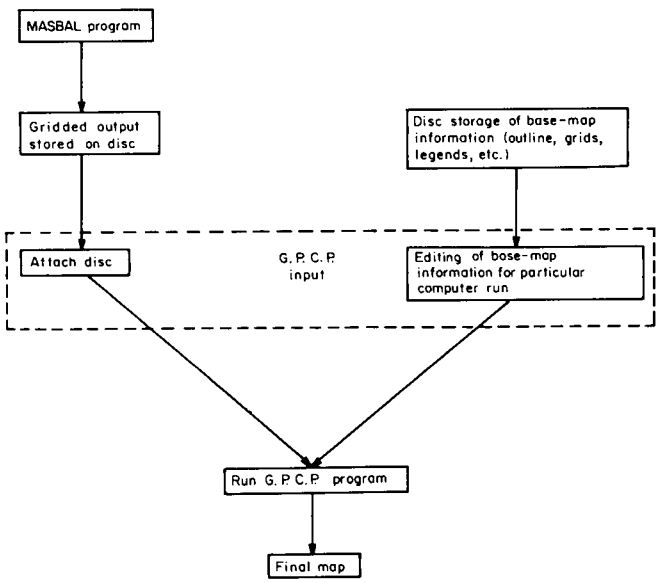

Figure 7. General structure of system to produce final map of the CalComp plotter with the General Purpose Contour Program (GPCP).

Figures 6 and 7 show simplified flow diagrams of the MASBAL program itself and the overall structure of inputs and outputs from the system. Appendix A contains the program listing with input instructions, and Appendix B gives an example of a typical output.

Data Banks and File Structures

Programs and data can be stored and retrieved in many different ways. Several options were tried during this project. Finally, one was chosen which was designed to minimize the number of instructions needed to operate the system.

In the current version of the system, there are three disc files for each glacier, the contents of which are as follows:

FILE 1 contains the MASBAL program. The program is identical for all glaciers except that core storage requirements are tailored to the particular glacier so that the program can run as cheaply as possible. Also, constants to determine map and graph sizes are made unique to the particular glacier. The program is stored in such a way that the user may, if he wishes, make further modifications with little effort.

FILE 2 contains the non-variable geometry measures for all points on the 100-m grid and at stake locations. In detail, the file contains:

M, N, J, (IS (I), (A(I,L), L = 1, 3), I = 1, J), ((ALT(I,K), RE(I,K), SL(I,K), MR(I,K), K = 1,N), I = 1, M)

where

M =number of rows in grid
N =number of columns in grid
J =number of stake locations
IS =stake names
A =altitude, local relief, and slope angle for each stake
ALT =matrix of altitudes for grid
RE =matrix of local relief for grid
SL =matrix of slope angles for grid
MR =matrix containing a mask to blank out non-glacier areas

The size of this file varies considerably between glaciers depending on glacier area.

FILE 3 contains card images of information used to produce the base map for the GPCP. The card images can easily be modified or deleted so that the scale of the final map, the contour interval, legends and so on may be altered for a particular job.

RESULTS OBTAINED BY STANDARD METHOD VERSUS THOSE OBTAINED BY NEW AUTOMATED METHOD

The aim of this section is to compare the results produced by the standard method (i.e. calculated by the procedures outlined by Østrem and Stanley, 1969) with those produced by the new method (i.e. the MASBAL program). This section is divided into two parts. In the first

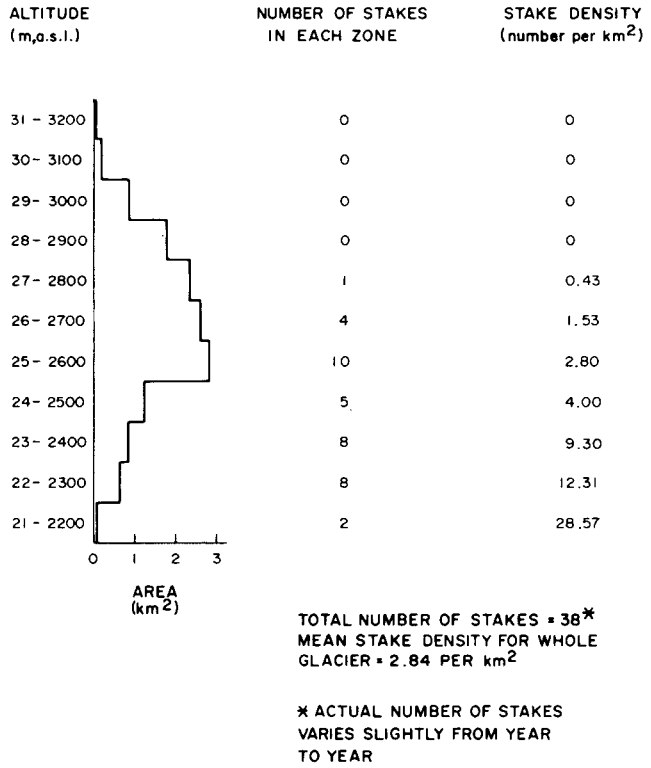

Figure 8. Peyto Glacier – Stake distribution related to altitude.

part comparisons are made using specific accumulation and ablation for a whole glacier; in the second part comparisons are made on the basis of totals for altitude zones. It would be logical to go one stage further and make comparisons on a point-by-point basis. However, the output from the standard method is not in this form and therefore comparisons at this scale cannot easily be made. All examples are taken from Peyto Glacier. Of the five glaciers in the Western Cordillera which have been studied, Peyto is in size the largest and in shape the most complex. Comparisons between methods on the other four glaciers yielded substantially closer results. In general, the simpler the shape of the glacier and the more evenly spread are the sampling locations, the better is the correspondence between methods and, presumably, the nearer are the results to the truth. Figure 8 shows the considerable bias in stake locations on Peyto Glacier in terms of altitudinal spread. Uncertainty in results and differences in results between methods can largely be explained by this uneven sampling spread. Of particular importance is the lack of any sampling locations above 2800 m.

Whole Glacier Comparisons

Mean specific water accumulation and mean specific net annual balances were calculated for Peyto Glacier for the period 1966-72. Readings on approximately 38 stakes were made at the beginning and end of the ablation season. These measurements formed the bases for all analyses. Additional sounding profiles were used in the analysis of accumulation by the normal method. It should, however, be pointed out that although an additional 100 to 200 measurements of snow depth were thereby provided, these measurements were biased towards lower elevations in a manner similar to the bias exhibited in Figure 8.

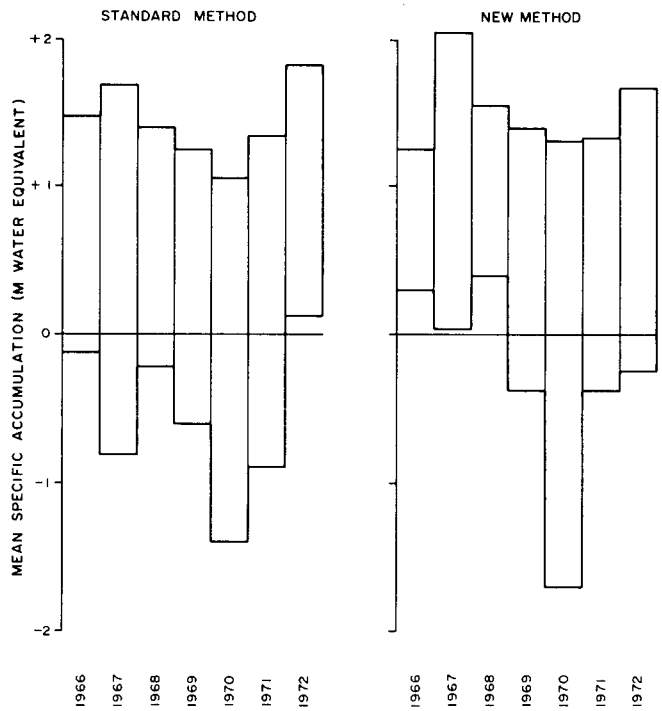

Figure 9. Peyto Glacier – Accumulation and net balance totals calculated by the standard method *vs* the automated method.

Figure 9 shows graphically the comparison of results by two methods. Considering the substantial sample bias, discussed above, the figures for mean specific accumulation are surprisingly close between methods. Figures for mean specific net annual balances are not in such close agreement on a year-to-year basis, but are still remarkably close when the whole 7-year period is considered.

Zone-by-zone Comparisons

The mean specific accumulation and mean specific net annual balance were calculated and plotted for each 100-m altitude zone on the glacier. Figures 10 and 11 show that the greatest discrepancies are in the upper elevation zones of the glacier. Although the areas covered by the upper zones are small in comparison to the areas covered in the middle zones of the glacier, the discrepancies between methods in the upper zones are great enough

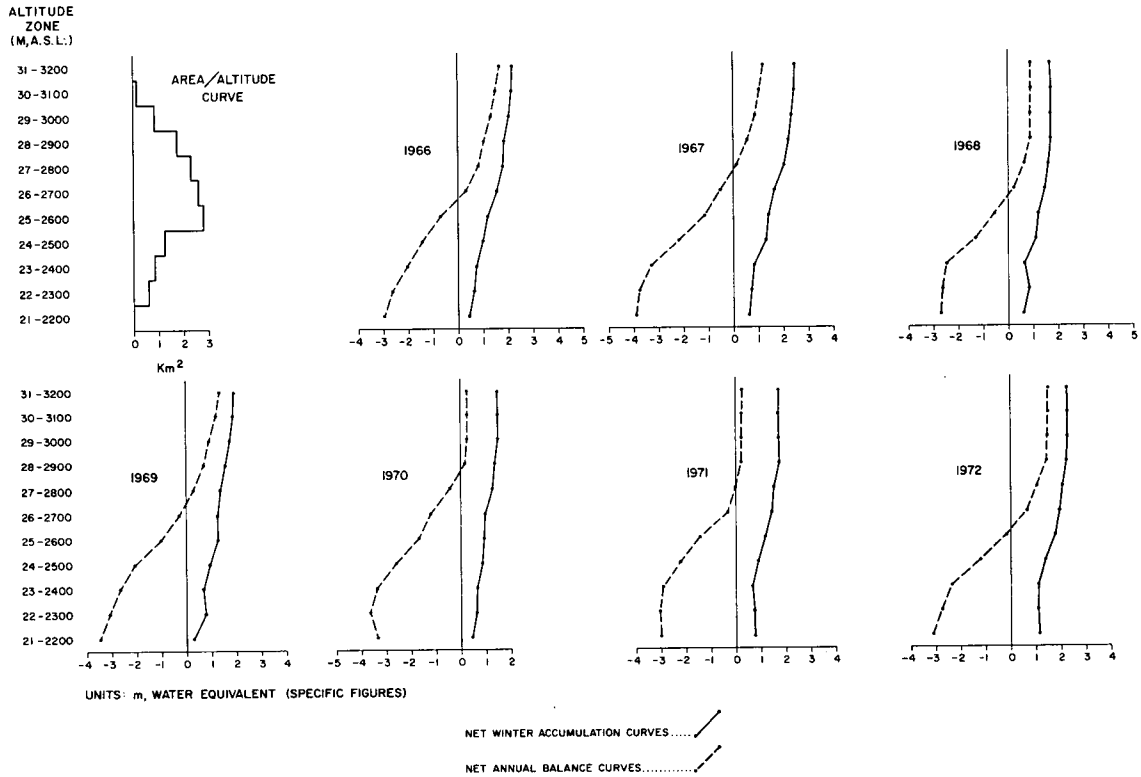

Figure 10. Peyto Glacier – Mass balance curves by the standard method.

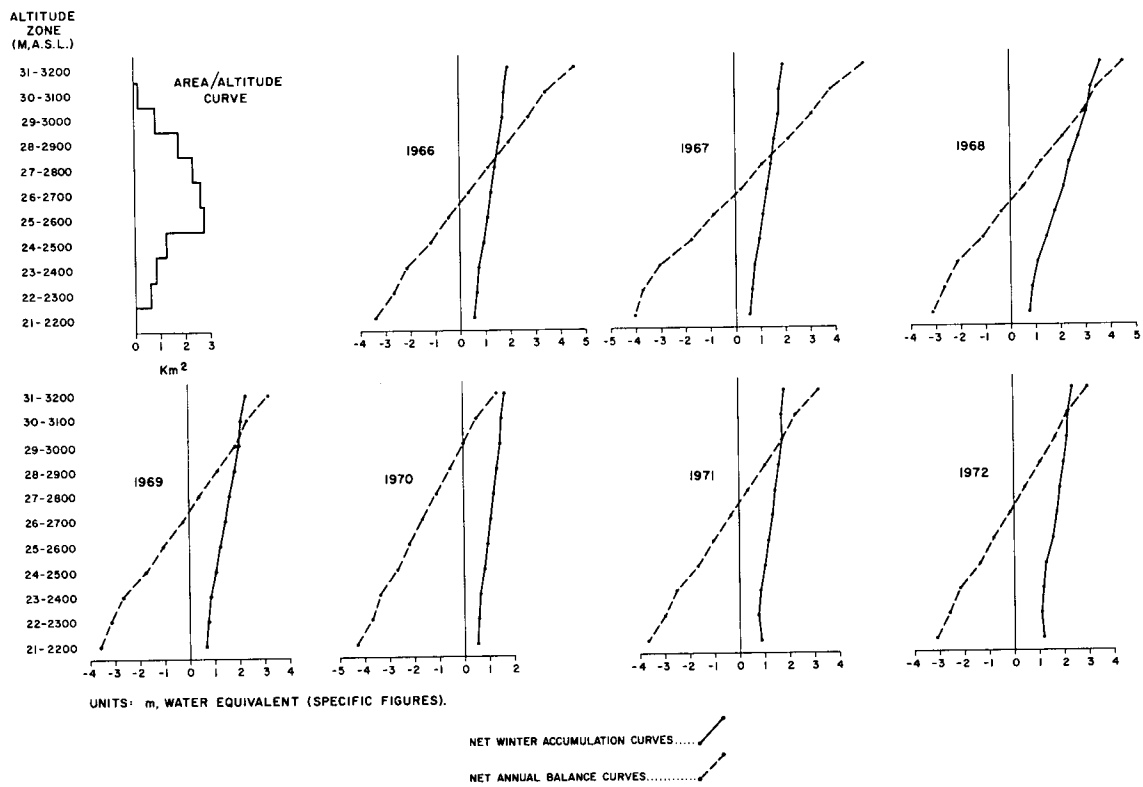

Figure 11. Peyto Glacier – Mass balance curves by the automated method.

to explain the differences in overall results shown in Figure 9.

The automated method almost certainly underestimates summer ablation in the higher parts of the glacier. The standard method may be nearer the truth in these higher zones, although the procedure used does not take into account the possibility of internal alimentation (i.e. meltwater from the annual snowpack being trapped in lower layers of firn and thereby not being lost from the glacier). Therefore the true values for upper parts of the glacier probably lie somewhere in between the values obtained by two methods.

Conclusions

(i) It is encouraging that there is fairly close agreement between a standard and an automated method on a glacier as complex as Peyto. There is much better agreement on less complex glaciers.

(ii) Discrepancies between methods can be almost entirely attributed to differences in estimates within the highest zones on the glacier.

(iii) Both methods suffer from sampling bias. Almost certainly, there would be better agreement if samples could be taken in the highest zones of the glacier.

(iv) The main advantage of the new method lies in speed of data reduction.

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Appendix A
Program Listing

APPENDIX A. Program Listing.

```
      PROGRAM MASBAL(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE1,TAPE2)
C
C     PROGRAM BY G.J.YOUNG 1974
C
C     CARD INPUT
C
C  1 HEADER CARD
C
C      PARAMETER    TYPE       POSSIBLE  COLUMNS
C                               VALUES
C        J1         INT.       0,1,2          1
C        J2         INT.       0,1            2
C        J3         INT.       0,1            3
C        J4         INT.       0,1            4
C        JSCALE     INT.       0 TO 9         5
C        BASE       REAL       ANY         6-10
C        AJUMP      REAL       ANY        11-15
C        BB(2)      REAL       ANY        16-20
C        BB(3)      REAL       ANY        21-25
C        Z          REAL       ANY        26-30
C        TITLE      ALPHA.     ANY        31-80
C
C    EXPLANATION OF PARAMETERS
C
C    J1   0  PREDICTIONS BASED ON ALTITUDE, LOCAL RELIEF AND SLOPE ANGLE
C         1  PREDICTIONS BASED ON ALTITUDE ALONE
C         2  PREDICTIONS BASED ON ALTITUDE AND FORCED COEFFICIENTS,
C            BB(2) FOR LOCAL RELIEF AND BB(3) FOR SLOPE ANGLE
C    J2   0  NO DENSITY VALUES GIVEN
C         1  DENSITIES GIVEN
C    J3   0  NO GRAPHICAL OUTPUT
C         1  GRAPHICAL OUTPUT GIVEN
C    J4   0  MAP NOT STORED ON DISC
C         1  MAP STORED ON DISC FOR CONTOURING
C    JSCALE  0  DEFAULTS TO A CONVENIENT MAP SIZE FOR LINE PRINTER
C            1-9  AS VALUE OF JSCALE INCREASES, LINE PRINTER MAP
C                 BECOMES SMALLER
C    BASE   VALUE OF LOWEST CLASS LIMIT FOR MAP
C    AJUMP  CLASS INTERVAL FOR MAP
C           IF AJUMP=0 A CONVENIENT CLASS INTERVAL IS CHOSEN FOR MAP
C    BB(2),BB(3)   COEFFICIENTS FOR LOCAL RELIEF AND SLOPE ANGLE
C                  WHICH ARE FORCED INTO EQUATION IF J1=2
C    Z   SIZE OF ALTITUDE ZONE FOR SUMMARY TABLES  DEFAULTS TO 100M
C    TITLE   ANY 50-CHARACTER TITLE FOR JOB
C
C  2 ANY NUMBER OF CARDS, ONE FOR EACH STAKE LOCATION CONTAINING
C    STAKE NAME,SNOW DEPTH  FORMAT(6X,I4,F6.0)
C
C  3 END OF RECORD CARD
C
C  4 ANY NUMBER OF CARDS, ONE FOR EACH LOCATION CONTAINING X AND Y
C    COORDS. AND SNOW DEPTH  FORMAT(2I2,F6.0)
C
C  5 END OF RECORD CARD
C
C  6 ANY NUMBER OF CARDS, EACH CONTAINING X AND Y COORDS. AND
C    DENSITY  FORMAT(2I2,F6.0)
C
C  7 END OF RECORD CARD
C
C     LIBRARY SUBROUTINES USED
C     IBM NAME    EMR NAME
C     CORRE       ACS001
C     ORDER       ACS002
C     MINV        GBS002
C     MULTR       ACS003
C     TALLY       AAS003
C
```

```
      DIMENSION ALT(53,48),RE(53,48),SL(53,48),R(53,48),MR(53,48),
     *ISS(124),X(124),IS(124),V(124,4),A(124,3),CB(1340),Y(124)
      DIMENSION TITLE(5),BUFF(1024),VMAX(4),VMIN(4),VDEN(10,2),S(3,10),
     *VA(4),SD(4),AVER(4),TOT(4),VMI(2),VMA(2),BB(3),ISAVE(4),RX(16),
     *RR(10),D(4),
     *T(4),B(4),RY(4),ANS(10),SB(4),PRC(4),D1(100),D2(100)
    1 FORMAT(1H1*    PEYTO GLACIER -- BASIC STATISTICS*/1X*ALTITUDE INFO
     *RMATION*)
    2 FORMAT(1H0*LOCAL RELIEF INFORMATION WITHIN ALTITUDE ZONES*)
    3 FORMAT(1H0*SLOPE ANGLE INFORMATION WITHIN ALTITUDE ZONES*)
   10 FORMAT(5I1,5F5.0,5A10)
   11 FORMAT(1H15I4,5F12.4,5X,5A10//1X*STAKE*4(4X,A4)/)
   12 FORMAT(6X,I4,F6.0)
   13 FORMAT(1H *STAKE*I5* NOT IN SYSTEM*)
   14 FORMAT(1H I5,6F8.1)
   22 FORMAT(1H0*COORDINATE MISTAKE*)
   23 FORMAT(1H0*TOTAL NUMBER OF STAKES CONSIDERED =*I4)
   24 FORMAT(1H0*  COORDS.    ALT.    DENSITY*)
   30 FORMAT(1H *MEANS*4F8.1/3X*STD*4F8.1/2X*MINS*4F8.1/2X*MAXS*4F8.1)
   31 FORMAT(1H0*NO DENSITIES GIVEN*)
   32 FORMAT(2I2,F6.4)
   33 FORMAT(1H02I4,F9.0,F10.4)
   34 FORMAT(1H0*1 DENSITY VALUE =*F5.3)
   35 FORMAT(1H0I4* DENSITY VALUES*)
   36 FORMAT(1H *DENSITIES -- MEAN*F6.3* STD*F7.3* MIN*F6.3* MAX*F6.3)
   37 FORMAT(1H *ALTITUDES -- MEAN*F6.0* STD*F7.1* MIN*F6.0* MAX*F6.0)
   38 FORMAT(1H *DENSITY =*F10.2* + *F10.3* X ALTITUDE*)
   39 FORMAT(1H0*STAKE   N.E.*)
   40 FORMAT(1H1*SELECTION =*I2* OBSERVATIONS =*I4*  3 INDEPENDENT VARIA
     *BLES*//1X*CORRELATION MATRIX*//10X4(4X,A4)/)
   41 FORMAT(1H 2X,A4,4X,4F8.3)
   42 FORMAT(1H029X*INTERCEPT*3(6X,A4)/21X*AMOUNT =*4F10.3/1X*STANDARD D
     *EVIATIONS OF REGRESSION COEFFS.*F7.3,2F10.3/1X*T-VALUES*30X3F10.3/
     *1X*STANDARD PARTIAL REGRESSION COEFFS.    *3F10.3/1X*MULTIPLE CORRE
     *LATION COEFFICIENT*F27.3)
   43 FORMAT(1H029X*INTERCEPT*6X,A4/21X*AMOUNT =*2F10.3/1X*STANDARD DEVI
     *ATION OF REGRESSION COEFF.*F9.3 /1X*T-VALUE*F41.3/1X*CORRELATION C
     *OEFFICIENT*F36.3)
   44 FORMAT(1H *STANDARD ERROR OF ESTIMATE*F33.3/1X*SUM OF SQUARES ATTR
     *IBUTABLE TO REGRESSION*F18.3/1X*DEGREES OF FREEDOM ASSOCIATED WITH
     * SSAR*F20.3/1X*MEAN SQUARE OF SSAR*F40.3/1X*SUM OF SQUARES OF DEVI
     *ATIONS FROM REGRESSION*F15.3/1X*DEGREES OF FREEDOM ASSOCIATED WITH
     * SSDR*F20.3/1X*MEAN SQUARE OF SSDR*F40.3/1X*F-VALUE*F52.3)
   45 FORMAT(1H0*ONLY*I2* OBSERVATIONS*/30X*INTERCEPT*6X*ALT.*/
     *21X*AMOUNT =*2F10.3)
   46 FORMAT(1H1*SUMMARY OF DEPTH VALUES FOR WHOLE GLACIER *5A10)
   47 FORMAT(1H0*RANGE IN ALTITUDES OF STAKES*)
   48 FORMAT(1H0*RANGE IN LOCAL RELIEF OF STAKES*)
   49 FORMAT(1H0*RANGE IN SLOPE ANGLES OF STAKES*)
   50 FORMAT(A4,1X,3F10.2,45X)
   51 FORMAT(A4,76X)
      DATA((S(J,K),K=1,10),J=1,3)/1H.,1H-,1H+,1H*,5(1H0),1HI,5(1H ),
     *1H-,1H+,2(1HX),1HM,8(1H ),1H+,1HW/
      DATA(VA=4HALT.,4HREL.,4HSLO.,4HSNOW),(ISAVE=1,2,3,4),
     *(CNTL=4HCNTL),(BEND=4HBEND)
```

```
C
C     READ GLACIER INFORMATION
C
      READ(2)M,N,JK,(IS(I),(A(I,N1),N1=1,3),I=1,JK),((ALT(I,J),RE(I,J),S
     *L(I,J),MR(I,J),J=1,N),I=1,M)
      WRITE(6,1)$CALL ZONE(M,N,ALT,MR,ALT,100.,VV,VX,D1,D2,KK,0)
      WRITE(6,2)$CALL ZONE(M,N,ALT,MR,RE ,100.,VV,VX,D1,D2,KK,0)
      WRITE(6,3)$CALL ZONE(M,N,ALT,MR,SL ,100.,VV,VX,D1,D2,KK,0)
      JX=0
   60 READ(5,10)J1,J2,J3,J4,JSCALE,BASE,AJUMP,BB(2),BB(3),Z,TITLE
      IF(EOF(5))1000,61
   61 WRITE(6,11)J1,J2,J3,J4,JSCALE,BASE,AJUMP,BB(2),BB(3),Z,TITLE,VA
      IF(J3)72,72,71
   71 JX=JX+1$IF(JX.EQ.1)CALL PLOTS(BUFF,1024)
   72 NUM=1
C
C     READ IN AND COUNT DATA CARDS
C
   90 READ(5,12)ISS(NUM),V(NUM,4)$IF(EOF(5))100,92
C
C     CHECK THAT STAKE INFORMATION IS IN THE DATA BANK
C
   92 DO 95 J=1,JK
      IF(IS(J).EQ.ISS(NUM))GO TO 96
   95 CONTINUE$WRITE(6,13)ISS(NUM)$GO TO 90
   96 DO 97 JJ=1,3
   97 V(NUM,JJ)=A(J,JJ)
      WRITE(6,14)ISS(NUM),(V(NUM,JJJ),JJJ=1,4)
      NUM=NUM+1$GO TO 90
  100 NUM1=NUM
C
C     READ DATA CARDS REFERENCED BY X,Y COORDINATES
C
  101 READ(5,32)IR,IC,V(NUM,4)$IF(EOF(5))110,102
  102 IF(IR.LE.M.OR.IC.LE.N)GO TO 103
      WRITE(6,22)$GO TO 101
  103 V(NUM,1)=ALT(IR,IC)$V(NUM,2)=RE(IR,IC)$V(NUM,3)=SL(IR,IC)
C
C     V NOW CONTAINS ALL THE RELEVANT STAKE INFORMATION
C     TABULATE DATA CARD INPUT
C
      WRITE(6,14)ISS(NUM),(V(NUM,JJJ),JJJ=1,4)
      NUM=NUM+1$GO TO 101
  110 NUM=NUM-1$WRITE(6,23)NUM
      DO 111 J=1,NUM
      X(J)=CB(J)=V(J,1)$CB(J+NUM)=V(J,2)$CB(J+NUM*2)=V(J,3)
  111 CB(J+NUM*3)=V(J,4)
      CALL AAS003(CB,X,TOT,AVER,SD,VMIN,VMAX,NUM,4)
      WRITE(6,30)AVER,SD,VMIN,VMAX$IF(J2)169,169,170
  169 WRITE(6,31)$GO TO 200
  170 NDEN=1
C
C     READ DENSITY VALUES
C
  171 READ(5,32)IR,IC,VDEN(NDEN,2)$IF(EOF(5))175,174
  174 IF(NDEN.EQ.1)WRITE(6,24)
      VDEN(NDEN,1)=ALT(IR,IC)
      WRITE(6,33)IR,IC,VDEN(NDEN,1),VDEN(NDEN,2)
      NDEN=NDEN+1$GO TO 171
  175 NDEN=NDEN-1$IF(NDEN-1)176,176,180
  176 WRITE(6,34)VDEN(NDEN,2)
      DO 177 J=1,NUM
  177 V(J,4)=V(J,4)*VDEN(1,2)
      GO TO 200
  180 WRITE(6,35)NDEN
      DO 181 J=1,NDEN
      X(J)=VDEN(J,1)$Y(J)=VDEN(J,2)
  181 X(J+NDEN)=VDEN(J,2)
      CALL AAS003(X,X,TOT,AVER,SD,VMI,VMA,NDEN,2)
      WRITE(6,36)AVER(2),SD(2),VMI(2),VMA(2)
      WRITE(6,37)AVER(1),SD(1),VMI(1),VMA(1)
```

```
C
C     ASSOCIATE DENSITY WITH ALTITUDE
C
      CALL REG(Y,X,NDEN,COEFF,XINT)$WRITE(6,38)XINT,COEFF
C
C     CALCULATE AND TABULATE WATER EQUIVALENTS
C
      WRITE(6,39)
      DO 182 J=1,NUM
      DENS=XINT+COEFF*CB(J)$CB(J+NUM*3)=CB(J+NUM*3)*DENS
  182 WRITE(6,14)ISS(J),CB(J+NUM*3)
C
C     ASSOCIATE WATER EQUIVALENTS WITH GEOMETRY MEASURES
C
  200 IF(J1-1)210,220,220
  210 IF(NUM-4)220,220,211
  211 CALL ACS001(NUM,4,1,CB,AVER,SD,RX,RR,D,B,T)
      WRITE(6,40)J1,NUM,VA
      DO 215 I=1,4
      DO 214 J=1,4
      IF(I-J)212,213,213
  212 KK=I+(J*J-J)/2
      GO TO 214
  213 KK=J+(I*I-I)/2
  214 T(J)=RR(KK)
  215 WRITE(6,41)VA(I),(T(J),J=1,4)
      CALL ACS002(4,RR,4,3,ISAVE,RX,RY)$CALL GBS002(RX,3,DET,BB,T)
      CALL ACS003(NUM,3,AVER,SD,D,RX,RY,ISAVE,BB,SB,T,ANS)
      DO 216 KK=1,3
  216 PRC(KK)=BB(KK)*(SD(KK)/SD(4))
      WRITE(6,42)(VA(J),J=1,3),ANS(1),(BB(J),J=1,3),(SB(J),J=1,3),
     *(T(J),J=1,3),(PRC(J),J=1,3),ANS(2)
      DO 217 J=1,NUM
  217 CB(J+NUM)=CB(J+NUM*3)
      GO TO 240
  220 IF(NUM-3)250,250,221
  221 DO 222 J=1,NUM
  222 CB(J+NUM)=CB(J+NUM*3)
      CALL ACS001(NUM,2,1,CB,AVER,SD,RX,RR,D,B,T)
      CALL ACS002(2,RR,2,1,ISAVE,RX,RY)$CALL GBS002(RX,1,DET,BB,T)
      CALL ACS003(NUM,1,AVER,SD,D,RX,RY,ISAVE,BB,SB,T,ANS)
      WRITE(6,43)VA(1),ANS(1),BB(1),SB(1),T(1),ANS(2)
  240 WRITE(6,44)(ANS(J),J=3,10)
      GO TO 260
  250 DO 251 J=1,NUM
      CB(J+NUM)=CB(J+NUM*3)
  251 X(J)=CB(J+NUM*3)
      CALL REG(X,CB,NUM,BB(1),ANS(1))$WRITE(6,45)NUM,ANS(1),BB(1)
C
C     LOOP 270 APPLIES REGRESSION EQUATION TO WHOLE GLACIER
C
  260 DO 270 J=1,M
      DO 270 K=1,N
      IF(MR(J,K).NE.0)GO TO 270
      R(J,K)=BB(1)*ALT(J,K)$IF(J1.EQ.1)GO TO 269
      IF(RE(J,K).GT.VMAX(2))R(J,K)=R(J,K)+VMAX(2)*BB(2)
      IF(RE(J,K).LT.VMIN(2))R(J,K)=R(J,K)+VMIN(2)*BB(2)
      IF(RE(J,K).LE.VMAX(2).AND.RE(J,K).GE.VMIN(2))R(J,K)=R(J,K)+RE(J,K)
     **BB(2)
      IF(SL(J,K).GT.VMAX(3))R(J,K)=R(J,K)+VMAX(3)*BB(3)
      IF(SL(J,K).LT.VMIN(3))R(J,K)=R(J,K)+VMIN(3)*BB(3)
      IF(SL(J,K).LE.VMAX(3).AND.SL(J,K).GE.VMIN(3))R(J,K)=R(J,K)+SL(J,K)
     **BB(3)
  269 R(J,K)=R(J,K)+ANS(1)
  270 CONTINUE
```

```
C
C     TABULATE RANGES OF GEOMETRY MEASURES AT SAMPLING LOCATIONS
C
      WRITE(6,47)$CALL RANGE(M,N,MR,ALT,VMAX(1),VMIN(1))
      WRITE(6,48)$CALL RANGE(M,N,MR,RE,VMAX(2),VMIN(2))
      WRITE(6,49)$CALL RANGE(M,N,MR,SL,VMAX(3),VMIN(3))
C
C     TABULATE AND MAP FINAL RESULTS
C
      WRITE(6,46)TITLE$CALL ZONE(M,N,ALT,MR,R,Z,VV,VX,D1,D2,KK,0)
      CALL MASMAP(M,N,R,MR,JSCALE,TITLE,BASE,AJUMP,S,VV,VX)
      IF(J3.NE.0)CALL GRAPH(M,N,ALT,R,MR,CB,NUM,BUFF,TITLE,X,ISAVE)
C
C     STORE R FOR CONTOURING IF REQUIRED
C
      IF(J4)60,60,300
  300 DO 310 I=1,M
      DO 310 J=1,N$IF(MR(I,J).NE.0)GO TO 310
      IF(MOD(I,2))305,310
  305 IF(MOD(J,2))306,310
  306 CONTINUE
      ROW=I$COL=J$WRITE(1,50)CNTL,ROW,COL,R(I,J)
  310 CONTINUE$WRITE(1,51)BEND$GO TO 60
 1000 IF(JX.GT.0)CALL PLOT(0.,0.,999)
      STOP$END



      SUBROUTINE REG(X,Y,N,R,Q)
      DIMENSION X(1),Y(1)
C     SIMPLE LINEAR REGRESSION BETWEEN 2 VARIABLES
C     X IS VECTOR OF DEPENDENT VARIABLE
C     Y IS VECTOR OF INDEPENDENT VARIABLE
C     N IS NUMBER OF OBSERVATIONS
C     R IS REGRESSION COEFFICIENT
C     Q IS INTERCEPT
      A=B=XB=YB=0.
      DO 10 J=1,N
      XB=XB+X(J)
   10 YB=YB+Y(J)
      XN=N$XB=XB/XN$YB=YB/XN
      DO 20 J=1,N
      A=A+(X(J)-XB)*(Y(J)-YB)
   20 B=B+(Y(J)-YB)**2
      R=A/B$Q=XB-YB*R
      RETURN$END



      SUBROUTINE RANGE(I,J,M,B,ZHI,ZLO)
C
C     SUBROUTINE TO CALCULATE NO. OF POINTS AND PERCENTAGE OF TOTAL AREA
C     BELOW, WITHIN AND ABOVE GIVEN LIMITING VALUES OF A VARIABLE
C     B    MATRIX OF VARIABLE (I,J)
C     M    MASKING MATRIX     (I,J)
C     ZHI  HIGHER LIMITING VALUE
C     ZLO  LOWER LIMITING VALUE
C
      DIMENSION M(53,48),B(53,48)
    1 FORMAT(1H *TOTAL NO. OF GRID CELLS =*F5.0* ABOVE LIMIT  =*F5.0* (
     **F6.2* PERCENT OF AREA)*/33X*WITHIN LIMITS=*F5.0* (*F6.2* PERCENT
     *OF AREA)*/33X*BELOW LIMIT  =*F5.0* (*F6.2* PERCENT OF AREA)*)
      AR=AHI=AM=ALO=0.
      DO 10 L=1,I
      DO 10 N=1,J
      IF(M(L,N).NE.0)GO TO 10
      AR=AR+1.$IF(B(L,N).LE.ZHI.AND.B(L,N).GE.ZLO)AM=AM+1.
      IF(B(L,N).GT.ZHI)AHI=AHI+1.$IF(B(L,N).LT.ZLO)ALO=ALO+1.
   10 CONTINUE
      A1=AHI*100./AR$A2=AM*100./AR$A3=ALO*100./AR
      WRITE(6,1)AR,AHI,A1,AM,A2,ALO,A3
      RETURN$END
```

```
      SUBROUTINE MASMAP(M,N,R,MR,JSCALE,TITLE,BA,B,S,VMAX,VMIN)
C
C     INPUT NEEDED FOR MAP
C     R(M,N)  MATRIX OF VALUES TO BE MAPPED  VMAX = HIGHEST VALUE
C                                            VMIN = LOWEST VALUE
C     MR(M,N) MASK  ONLY ZERO ELEMENTS MAPPED
C     JSCALE = SCALE OF MAP  DEFAULTS TO 4 IF NOT GIVEN
C     TITLE = TITLE OF MAP UP TO 50 CHARACTERS LONG
C     BA  LOWER LIMIT OF LOWEST CLASS  NEED NOT BE GIVEN
C     B  CLASS INTERVAL  NEED NOT BE GIVEN
C     S = SYMBOLS
C     AL  DIMENSION MUST BE (3,N*10)
      DIMENSION R(53,48),MR(53,48),C(11),AL(3,480),S(3,10),TITLE(5)
    1 FORMAT(1H 135A1)
    3 FORMAT(1H )
    4 FORMAT(1H+135A1)
    5 FORMAT(1H011F7.1)
    6 FORMAT(1H+1X,10(6X,A1))
    7 FORMAT(1H05A10)
   10 FORMAT(1H0*JSCALE CHANGED TO *I3)
      NN=N*10$VMAX=VMAX+.00001$J1=1$JJ=11
C
C     REDUCE SIZE OF MAP IF NECESSARY
      IF(JSCALE.EQ.0)JSCALE=8
      IF(JSCALE.EQ.0)JSCALE=4
   20 IF(NN/JSCALE-133)22,22,21
   21 JSCALE=JSCALE+1$WRITE(6,10)JSCALE$GO TO 20
   22 JCOUNT=0
      IF(B)30,30,50
C
C     CREATE CLASS INTERVAL AND LOWEST LIMIT IF NOT PROVIDED
C
   30 RA=VMAX-VMIN
      B=50.$IF(RA.LE.250.)B=25.$IF(RA.LE.100.)B=10.$IF(RA.LE.10.)B=1.
      IF(VMIN)31,31,34
   31 BA=B
      DO 32 J=1,100
      BA=BA-B$IF(BA.LE.VMIN)GO TO 50
   32 CONTINUE
   34 BA=-B
      DO 35 J=1,100
      BA=BA+B$IF(BA.GT.VMIN-B)GO TO 50
   35 CONTINUE
   50 X=BA-B
C
C     CREATE CLASS LIMITS
C
      DO 55 J=1,11
      X=X+B$C(J)=X$IF(C(J).LE.VMIN)J1=J$IF(C(J).LE.VMAX)JJ=J+1
   55 CONTINUE
      IF(C(1).GT.VMIN)C(1)=VMIN$IF(C(11).LT.VMAX)C(11)=VMAX
      IF(JJ.GT.11)JJ=11$J2=JJ-1
C
C     PRINT TITLE AND CLASSES
C
      WRITE(6,7)TITLE$WRITE(6,5)(C(J),J=J1,JJ)$WRITE(6,3)
      DO 117 J=1,3
  117 WRITE(6,6)(S(J,L),L=J1,J2)$WRITE(6,3)
C
C     CONSIDER EACH ROW IN TURN
C
      DO 200 J=1,M
      JCO=0
      DO 200 L=1,6
C
C     SKIP IF COUNT NOT A MULTIPLE OF JSCALE
C
      JCOUNT=JCOUNT+1$IF(MOD(JCOUNT,JSCALE))200,118,200
  118 JCO=JCO+1
      IF(JCO-1)119,119,165
C
C     BLANK OUT AL
C
  119 DO 120 JK=1,NN
      DO 120 JX=1,3
  120 AL(JX,JK)=1H
      JP=1
```

```
C
C     CONSIDER EACH COLUMN IN TURN
C
      DO 160 K=1,N
C
C     SKIP OUT IF POINT NOT TO BE CONSIDERED
C
      IF(MR(J,K).NE.0)GO TO 160$K1=K*10$K2=K1-9
C
C     LOOP 146  CLASSIFY POINT IN QUESTION
C
      DO 146 J5=1,10
      IF(R(J,K).GE.C(J5).AND.R(J,K).LT.C(J5+1))GO TO 147
  146 CONTINUE
C
C     JJJ INDICATES HOW MANY OVERPRINTS WILL BE NECESSARY
C
  147 JJJ=1$IF(J5.GT.5)JJJ=2$IF(J5.GT.8)JJJ=3
C
C     J9 (FROM K2 TO K1) INDICATES THE 10 ELEMENTS IN AL TO BE FILLED
C     WITH SYMBOLS
C
      DO 150 J9=K2,K1
      DO 150 J7=1,JJJ
  150 AL(J7,J9)=S(J7,J5)
C
C     JP IS THE NUMBER OF ROWS IN AL TO BE PRINTED
C
      IF(JP.LT.JJJ)JP=JJJ
  160 CONTINUE
  165 WRITE(6,3)
      DO 170 J6=1,JP
C
C     AL IS PRINTED IN JUMPS OF JSCALE
C
  170 WRITE(6,4)(AL(J6,J3),J3=1,NN,JSCALE)
  200 CONTINUE$END
```

```
      FUNCTION XMI(A)
      IF(A)10,20,20
   10 XMI=FLOAT(IFIX(A/100.))*100.-100.
      RETURN
   20 XMI=IFIX(A/100.)*100
      END
```

```
      FUNCTION XMA(A)
      IF(A)10,20,20
   10 XMA=IFIX(A/100.)*100
      RETURN
   20 XMA=FLOAT(IFIX(A/100.))*100.+100.
      END
```

```
      SUBROUTINE YAXIS(A,Y,BUFF)
      DIMENSION BUFF(1024)
      CALL PLOT(0.,A,3)$CALL PLOT(0.,0.,2)$YY=Y-100.$L=A+1.
      DO 10 J=1,L
      YY=YY+100.$Z=FLOAT(J)-1.$CALL NUMBER(-.5,Z-.05,.1,YY,0.,-1)
      CALL PLOT(-.05,Z,3)
   10 CALL PLOT(0.,Z,2)
      CALL SYMBOL(-.5,Z+.15,.1,4HALT.,0.,4)$END
```

```
      SUBROUTINE GRAPH(M,N,ALT,R,MR,CB,NUM,BUFF,TITLE,X,ISAVE)
C
C     SUBROUTINE TO PLOT SNOW DEPTH V. ALTITUDE AT STAKE LOCATIONS
C     AND TO GRAPH MEAN SPECIFIC SNOW DEPTH V. ALT. AND VOLUME V. ALT.
C     CURVES FOR WHOLE GLACIER
C
      DIMENSION ALT(53,48),R(53,48),MR(53,48),CB(1340),X(124),BUFF(1024)
     $,TITLE(5),B(2),AV(2),SD(2),ISAVE(4),RX(4),RR(3),D(2),T(2),RY(2),
     *ANS(10),SB(2),BB(3),SIZE(100),AVER(100)
      IF(NUM-3)50,50,60
   50 CALL REG(X,CB,NUM,BB(1),ANS(1))
      GO TO 70
   60 CALL ACS001(NUM,2,1,CB,AV,SD,RX,RR,D,B,T)
      CALL ACS002(2,RR,2,1,ISAVE,RX,RY)$CALL GBS002(RX,1,DET,BB,T)
      CALL ACS003(NUM,1,AV,SD,D,RX,RY,ISAVE,BB,SB,T,ANS)
   70 CALL ZONE(M,N,ALT,MR,ALT,100.,VV,VX,SIZE,AVER,K,1)
      CALL ZONE(M,N,ALT,MR,R,100.,V1,V2,SIZE,AVER,K,1)
      CALL PLOT(0.,-30.,-3)$CALL FACTOR(.394)$CALL PLOT(2.,2.,-3)
      AK=K$YMIN=IFIX(VX/100.)*100$YMAX=YMIN+AK*100.
      A1=ANS(1)+BB(1)*YMIN$A2=ANS(1)+BB(1)*YMAX
C
C     IF REGRESSION COEFF. LE.0  REGRESSION LINE WILL NOT BE DRAWN
C
      IF(BB(1))90,90,80
   80 XMIN=XMI(A1)$XMAX=XMA(A2)$IF(XMAX-XMIN-1000.)100,100,90
   90 DO 91 J=1,NUM
   91 X(J)=CB(J+NUM)
      CALL AAS003(X,CB,T1,T2,T3,A1,A2,NUM,1)
      XMIN=XMI(A1)$XMAX=XMA(A2)$IF(XMAX-XMIN-1000.)110,110,200
C
C     PLOT REGRESSION LINE
C
  100 CALL PLOT((A1-XMIN)/100.,0.,3)
      CALL PLOT((A2-XMIN)/100.,(YMAX-YMIN)/100.,2)
C
C     ANNOTATE GRAPH
C
  110 CALL YAXIS(AK,YMIN,BUFF)
      CALL SYMBOL(0.,-.4,.1,8HCM(W.E.),0.,8)
      CALL SYMBOL(0.,-.6,.1,TITLE,0.,50)
      CALL SYMBOL(0.,-.8,.1,25HW.E.=        +        *ALT.,0.,25)
      CALL NUMBER(.5,-.8,.1,ANS(1),0.,1)
      CALL NUMBER(1.3,-.8,.1,BB(1),0.,4)
      CALL SYMBOL(0.,-1.4,.12,21HSNOW DEPTH / ALTITUDE,0.,21)
      CALL SYMBOL(0.,-1.64,.12,16H     RELATIONSHIP,0.,16)
      IF(NUM.LE.3)GO TO 115
      CALL SYMBOL(0.,-1.,.1,25HCORRELATION COEFFICIENT =,0.,25)
      CALL NUMBER(2.6,-1.,.1,ANS(2),0.,3)
  115 XM=(XMAX-XMIN)/100.
      CALL PLOT(XM,0.,3)$CALL PLOT(0.,0.,2)$L=XM+1.$XX=XMIN-100.
      DO 120 J=1,L
      XX=XX+100.$X1=FLOAT(J)-1.$CALL PLOT(X1,0.,3)$CALL PLOT(X1,-.05,2)
      IF(XX)116,119,116
  116 CALL NUMBER(X1-.15,-.2,.1,XX,0.,-1)
      GO TO 120
  119 CALL NUMBER(X1-.05,-.2,.1,XX,0.,-1)
  120 CONTINUE
C
C     PLOT STAKE VALUES
C
      DO 130 J=1,NUM
  130 CALL SYMBOL((CB(J+NUM)-XMIN)/100.,(CB(J)-YMIN)/100.,.05,0,0.,-1)
      CALL PLOT(XM+2.,0.,-3)
```

```
C
C     START SECOND GRAPH     ANNOTATE GRAPH
C
  200 CALL YAXIS(AK,YMIN,BUFF)
      CALL SYMBOL(0.,-.4,.1,TITLE,0.,50)
      CALL SYMBOL(0.,-.75,.05,2,0.,-1)
      CALL SYMBOL(.3,-.75,.05,2,0.,-2)
      CALL SYMBOL(.4,-.8,.1,16HSPECIFIC W.E.(M),0.,16)
      CALL IBS016(0.,-.95,.3,-.95,1)
      CALL SYMBOL(.4,-1.,.1,12H10  M  WATER,0.,12)
      CALL SYMBOL(.6,-.9,.1,4H6  3,0.,4)
      CALL AAS003(AVER,SIZE,T1,T2,T3,A1,A2,K,1)
      XMIN=XMI(A1)/100.$IF(XMIN.GT.0.)XMIN=0.
      XMAX=XMA(A2)/100.$RA=XMAX-XMIN
      CALL PLOT(RA,0.,3)$CALL PLOT(0.,0.,2)
      XL=XMIN-1.$X1=-1.$L1=RA+1.
      DO 210 J=1,L1
      X1=X1+1.$XL=XL+1.$CALL PLOT(X1,0.,3)$CALL PLOT(X1,-.05,2)
  210 CALL NUMBER(X1-.05,-.2,.1,XL,0.,-1)
      IF(XMIN)211,215,215
  211 CALL PLOT(-XMIN,0.,-3)
      CALL PLOT(0.,AK,3)$CALL PLOT(0.,0.,2)
C
C     DRAW AREA / ALTITUDE CURVE
C
  215 CALL PLOT(0.,0.,3)
      DO 220 J=1,K
      AJ=FLOAT(J)$SI=SIZE(J)/100.$CALL PLOT(SI,AJ-1.,2)
  220 CALL PLOT(SI,AJ,2)$CALL PLOT(0.,AJ,2)
C
C     DRAW MEAN SPECIFIC SNOW DEPTH / ALTITUDE CURVE
C
      CALL SYMBOL(AVER(1)/100.,.5,.05,2,0.,-1)
      DO 230 J=2,K
  230 CALL SYMBOL(AVER(J)/100.,FLOAT(J)-.5,.05,2,0.,-2)
C
C     DRAW VOLUME / ALTITUDE CURVE
C
      DO 240 J=2,K
  240 CALL IBS016(SIZE(J-1)*AVER(J-1)/10000.,FLOAT(J-1)-.5,
     *SIZE(J)*AVER(J)/10000.,FLOAT(J)-.5,1)
      CALL PLOT(XMAX+3.,0.,-3)
      END
```

```
      SUBROUTINE ZONE(I,J,A,M,B,Z,VV,VX,SIZE,AVER,K,JJ)
C
C     INPUT -- A    MATRIX OF ALTITUDES (I,J)
C              M    MASKING MATRIX      (I,J)
C              B    MATRIX OF VARIABLE  (I,J)
C              Z    ZONE SIZE  DEFAULTS TO 100M
C              JJ   IF  JJ.EQ.0  PRINTOUT GIVEN
C     OUTPUT - VV    MAXIMUM VALUE IN B
C              VX    MINIMUM VALUE IN B
C              SIZE  VECTOR CONTAINING NO. OF GRID CELLS IN EACH ALT.ZONE
C              AVER  VECTOR CONTAINING MEAN VALUE OF B IN EACH ALT. ZONE
C              K     NUMBER OF ZONES
C
      DIMENSION M(53,48),B(53,48),A(53,48),C(1340),D(1340)
      DIMENSION SIZE(100),AVER(100)
    1 FORMAT(1H018X*MEAN        STD        MAX        MIN      RANGE     NO.
     10F GRID CELLS*//2X*WHOLE AREA  *5F10.2,I10//6X*ZONE*/)
    2 FORMAT(1H F5.0* - *F5.0,5F10.2,I10)
    3 FORMAT(1H )
      K=0
      DO 10 L=1,I
      DO 10 N=1,J
      IF(M(L,N).NE.0)GO TO 10
      K=K+1$C(K)=B(L,N)$D(K)=A(L,N)
   10 CONTINUE
      CALL AAS003(C,D,T,AV,SD,VX,VV,K,1)
      IF(JJ.NE.0)GO TO 20
      RA=VV-VX$WRITE(6,1)AV,SD,VV,VX,RA,K
   20 CALL AAS003(D,D,T,AV,SD,VMIN,VMAX,K,1)
      IF(Z.EQ.0.)Z=100.$Z2=-Z
      K=0
      DO 100 L1=1,1000
      Z2=Z2+Z$IF(Z2.LE.VMIN)GO TO 100
      Z1=Z2-Z$IF(Z1.GT.VMAX)RETURN
      K=K+1$JX=0
      DO 50 L=1,I
      DO 50 N=1,J
      IF(M(L,N).NE.0)GO TO 50
      IF(A(L,N).LT.Z1.OR.A(L,N).GE.Z2)GO TO 50
      JX=JX+1$C(JX)=B(L,N)
   50 CONTINUE
      IF(JX)55,55,60
   55 WRITE(6,3)
      GO TO 100
   60 CALL AAS003(C,D,T,AV,SD,VMI,VMA,JX,1)
      SIZE(K)=JX$AVER(K)=AV
      IF(JJ.NE.0)GO TO 100
      RA=VMA-VMI$WRITE(6,2)Z1,Z2,AV,SD,VMA,VMI,RA,JX
  100 CONTINUE
      RETURN$END
```

Appendix B
Program Output

APPENDIX B. Program Output.

PEYTO GLACIER -- BASIC STATISTICS

ALTITUDE INFORMATION

	MEAN	STD	MAX	MIN	RANGE	NO. OF GRID CELLS
WHOLE AREA	2634.99	188.03	3185.00	2125.00	1060.00	1340
ZONE						
2100. - 2200.	2168.14	24.94	2197.00	2125.00	72.00	7
2200. - 2300.	2270.57	23.70	2299.00	2205.00	94.00	65
2300. - 2400.	2333.12	26.07	2398.00	2300.00	98.00	86
2400. - 2500.	2458.55	27.47	2498.00	2400.00	98.00	125
2500. - 2600.	2545.14	30.13	2599.00	2500.00	99.00	280
2600. - 2700.	2645.75	28.59	2699.00	2600.00	99.00	262
2700. - 2800.	2745.18	28.39	2798.00	2700.00	98.00	233
2800. - 2900.	2846.82	27.37	2898.00	2800.00	98.00	177
2900. - 3000.	2940.58	31.37	2997.00	2900.00	97.00	86
3000. - 3100.	3033.94	25.50	3090.00	3000.00	90.00	17
3100. - 3200.	3175.00	14.14	3185.00	3165.00	20.00	2

LOCAL RELIEF INFORMATION WITHIN ALTITUDE ZONES

	MEAN	STD	MAX	MIN	RANGE	NO. OF GRID CELLS
WHOLE AREA	-.65	6.16	42.20	-55.60	97.80	1340
ZONE						
2100. - 2200.	-3.86	3.67	.80	-9.60	10.40	7
2200. - 2300.	-.25	1.82	2.00	-7.60	9.60	65
2300. - 2400.	-.64	2.87	5.80	-13.80	19.60	86
2400. - 2500.	-.41	2.84	15.00	-9.60	24.60	125
2500. - 2600.	-1.12	4.16	12.20	-50.80	63.00	280
2600. - 2700.	-1.92	5.67	8.40	-55.60	64.00	262
2700. - 2800.	-.92	4.97	17.40	-36.40	53.80	233
2800. - 2900.	-.01	7.37	30.80	-35.80	66.60	177
2900. - 3000.	.68	11.54	42.20	-30.00	72.20	86
3000. - 3100.	11.38	14.54	35.60	-18.00	53.60	17
3100. - 3200.	32.00	14.14	42.00	22.00	20.00	2

SLOPE ANGLE INFORMATION WITHIN ALTITUDE ZONES

	MEAN	STD	MAX	MIN	RANGE	NO. OF GRID CELLS
WHOLE AREA	12.93	8.45	53.26	.57	52.69	1340
ZONE						
2100. - 2200.	12.95	2.70	18.32	10.53	7.79	7
2200. - 2300.	5.79	2.31	13.10	2.55	10.54	65
2300. - 2400.	6.39	4.71	23.38	1.15	22.23	86
2400. - 2500.	8.47	5.13	34.82	3.54	31.28	125
2500. - 2600.	9.51	5.35	53.08	2.00	51.08	280
2600. - 2700.	14.23	7.58	53.26	2.55	50.70	262
2700. - 2800.	14.24	8.92	50.35	1.62	48.73	233
2800. - 2900.	16.67	7.42	46.82	5.71	41.11	177
2900. - 3000.	25.09	8.29	46.65	2.70	43.95	86
3000. - 3100.	22.98	12.14	42.48	.57	41.90	17
3100. - 3200.	23.58	.44	23.89	23.27	.62	2

PEYTO 1968-69 WINTER ACCUMULATION

-0 -0 1 -0 -0 -0.0000 -0.0000 -0.0000 -0.0000 -0.0000

STAKE	ALT.	REL.	SLO.	SNOW
10	2148.0	-1.8	14.7	66.0
20	2183.0	.8	11.3	66.0
21	2245.0	1.4	7.6	66.0
22	2238.0	1.8	10.3	87.0
30	2249.0	.6	7.9	71.0
31	2261.0	.8	6.5	76.0
32	2252.0	1.0	7.8	65.0
40	2277.0	1.6	5.8	81.0
41	2275.0	.2	4.4	69.0
42	2287.0	2.0	5.3	59.0
50	2310.0	1.2	3.4	66.0
51	2300.0	-.6	3.7	89.0
52	2312.0	.4	2.7	80.0
60	2331.0	1.4	4.3	80.0
61	2310.0	-2.0	3.8	66.0
62	2326.0	0.0	3.8	62.0
70	2343.0	0.0	3.7	82.0
80	2365.0	-.2	7.9	73.0
90	2458.0	-.6	4.0	123.0
99	2452.0	-2.0	4.1	115.0
110	2469.0	-1.2	7.8	118.0
111	2437.0	-.6	6.7	101.0
119	2506.0	2.0	11.0	138.0
120	2517.0	1.6	7.0	87.0
122	2571.0	-.6	9.9	132.0
129	2509.0	-3.2	4.9	103.0
130	2581.0	2.0	9.2	137.0
131	2597.0	-5.2	10.4	137.0
140	2635.0	2.8	2.6	143.0
160	2502.0	.2	3.8	122.0
162	2498.0	1.0	5.1	113.0
170	2581.0	4.6	11.0	90.0
171	2609.0	0.0	5.6	113.0
172	2516.0	0.0	2.2	120.0
174	2528.0	0.0	6.6	110.0
180	2614.0	-.4	3.7	132.0
182	2687.0	-.4	9.1	180.0
190	2729.0	.2	4.3	143.0

TOTAL NUMBER OF STAKES CONSIDERED = 38

MEANS	2421.3	.2	6.4	99.0
STD	153.1	1.7	3.0	30.3
MINS	2148.0	-5.2	2.2	59.0
MAXS	2729.0	4.6	14.7	180.0

NO DENSITIES GIVEN

SELECTION =-0 OBSERVATIONS = 38 3 INDEPENDENT VARIABLES

CORRELATION MATRIX

	ALT.	REL.	SLO.	SNOW
ALT.	1.000	-.071	-.113	.878
REL.	-.071	1.000	.028	-.165
SLO.	-.113	.028	1.000	.013
SNOW	.878	-.165	.013	1.000

	INTERCEPT	ALT.	REL.	SLO.
AMOUNT =	-331.580	.175	-1.873	1.168
STANDARD DEVIATIONS OF REGRESSION COEFFS.		.015	1.378	.790
T-VALUES		11.288	-1.359	1.477
STANDARD PARTIAL REGRESSION COEFFS.		.884	-.106	.115

MULTIPLE CORRELATION COEFFICIENT	.892
STANDARD ERROR OF ESTIMATE	14.306
SUM OF SQUARES ATTRIBUTABLE TO REGRESSION	27020.098
DEGREES OF FREEDOM ASSOCIATED WITH SSAR	3.000
MEAN SQUARE OF SSAR	9006.699
SUM OF SQUARES OF DEVIATIONS FROM REGRESSION	6958.875
DEGREES OF FREEDOM ASSOCIATED WITH SSDR	34.000
MEAN SQUARE OF SSDR	204.673
F-VALUE	44.005

RANGE IN ALTITUDES OF STAKES
TOTAL NO. OF GRID CELLS =1340. ABOVE LIMIT = 436. (32.54 PERCENT OF AREA)
WITHIN LIMITS= 903. (67.39 PERCENT OF AREA)
BELOW LIMIT = 1. (.07 PERCENT OF AREA)

RANGE IN LOCAL RELIEF OF STAKES
TOTAL NO. OF GRID CELLS =1340. ABOVE LIMIT = 82. (6.12 PERCENT OF AREA)
WITHIN LIMITS=1096. (81.79 PERCENT OF AREA)
BELOW LIMIT = 162. (12.09 PERCENT OF AREA)

RANGE IN SLOPE ANGLES OF STAKES
TOTAL NO. OF GRID CELLS =1340. ABOVE LIMIT = 411. (30.67 PERCENT OF AREA)
WITHIN LIMITS= 923. (68.88 PERCENT OF AREA)
BELOW LIMIT = 6. (.45 PERCENT OF AREA)

SUMMARY OF DEPTH VALUES FOR WHOLE GLACIER PEYTO 1968-69 WINTER ACCUMULATION

	MEAN	STD	MAX	MIN	RANGE	NO. OF GRID CELLS
WHOLE AREA	142.56	36.05	234.01	61.95	172.06	1340
ZONE						
2100. - 2200.	67.55	4.16	73.14	61.95	11.20	7
2200. - 2300.	72.67	3.36	86.88	67.31	19.57	65
2300. - 2400.	84.35	9.57	109.32	72.99	36.33	86
2400. - 2500.	108.35	6.53	128.73	91.64	37.09	125
2500. - 2600.	125.65	9.90	148.99	103.05	45.94	280
2600. - 2700.	146.69	9.22	166.31	125.20	41.11	262
2700. - 2800.	162.39	9.31	184.67	136.53	48.14	233
2800. - 2900.	182.47	7.90	201.64	163.68	37.96	177
2900. - 3000.	200.54	9.60	219.48	171.05	48.42	86
3000. - 3100.	210.20	11.13	232.37	188.82	43.56	17
3100. - 3200.	232.26	2.47	234.01	230.51	3.50	2

PEYTO 1968-69 WINTER ACCUMULATION

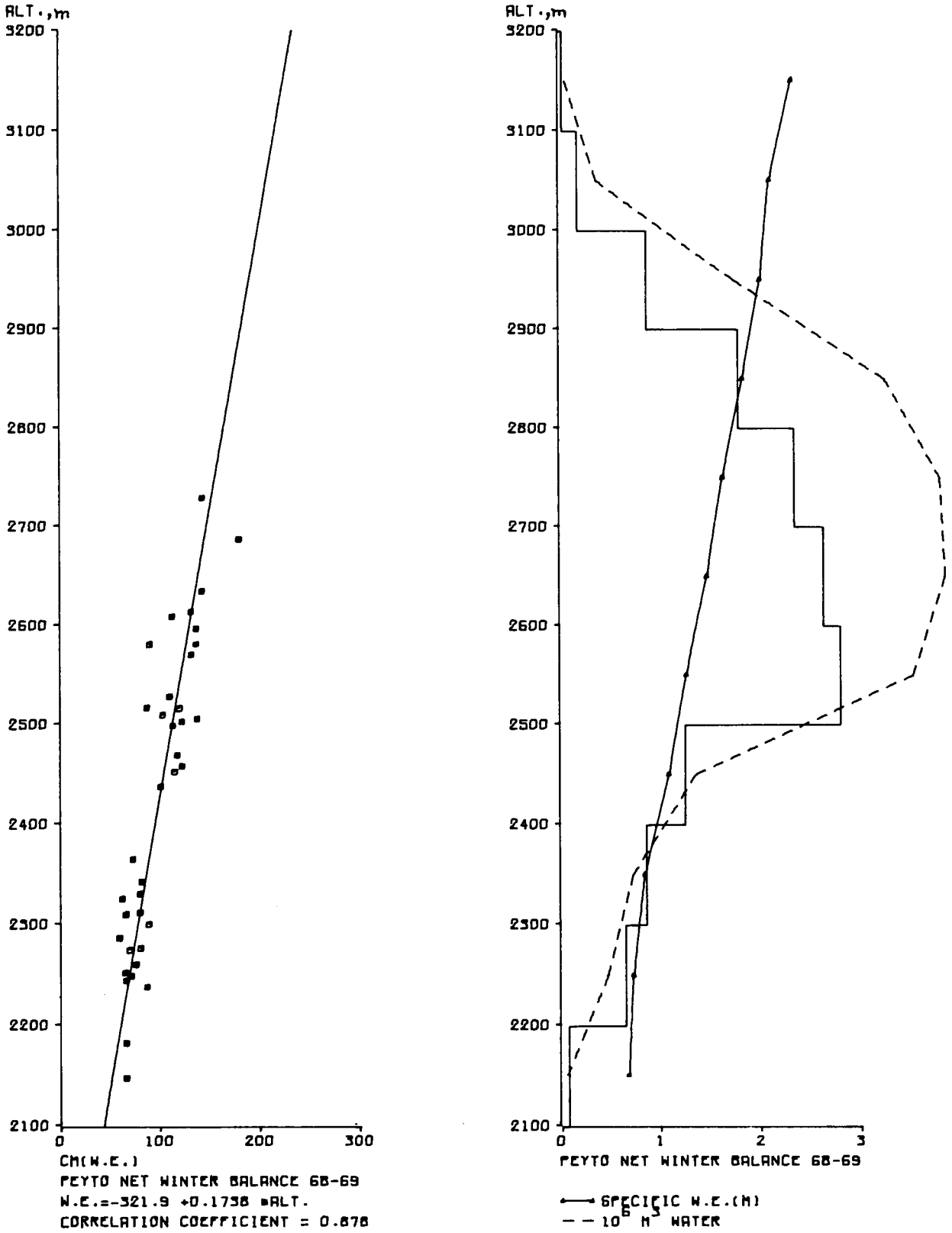

Figure B-1. Peyto Glacier – Snow depth *vs* altitude.

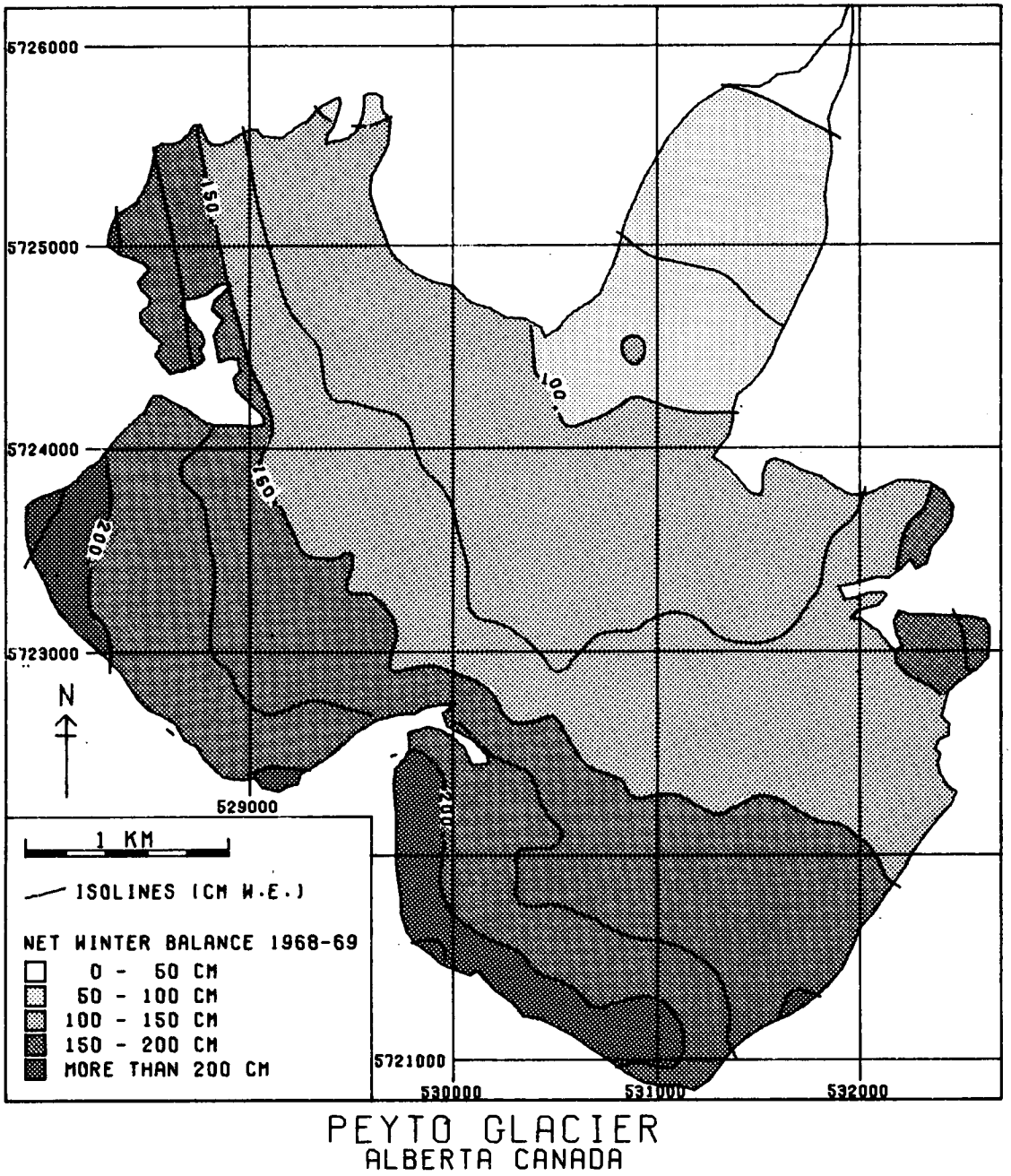

Figure B-2. An example of final mapped output.