GLACIER MASS BALANCE MEASUREMENTS

A MANUAL FOR FIELD AND OFFICE WORK

by

G. Østrem and A. Stanley

A GUIDE PREPARED JOINTLY BY

THE CANADIAN DEPARTMENT OF ENERGY, MINES AND RESOURCES

AND

THE NORWEGIAN WATER RESOURCES AND ELECTRICITY BOARD

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G. Østrem and A. Stanley

(Revised edition)

A guide for personnel with limited back-
grounds in glaciology, prepared jointly by

THE CANADIAN DEPARTMENT OF ENERGY, MINES AND RESOURCES

Glaciology Subdivision

and

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Glaciology Section

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PREFACE

Resolution I-14, adopted by the Co-ordinating Council for the International Hydrological Decade (IHD) in 1965, proposes that glaciological research should be undertaken on selected glaciers along chains throughout the world. The resolution encourages all member states whose territory is located in the proposed chains to participate actively in this research.

It is therefore anticipated that during the International Hydrological Decade (1965-1974) glaciological data will be collected at numerous glacier basins in several different countries. To make possible direct comparisons between field data from various glaciers, it is essential that they should be collected in a consistent manner and that the results should be presented in a standard format.

Field procedures followed by the personnel at the Canadian Department of Energy, Mines and Resources and the Norwegian Water Resources and Electricity Board are described in this manual. Originally such field procedures were developed in various countries but - although aiming at the same final objective - they differed slightly from country to country and even within the same country, so that direct comparison of results proved very difficult. Therefore, when projects for mass-balance studies on a large number of glaciers started in Norway 1963 and in Canada 1965, it was necessary to ensure, as far as possible, uniform accuracy and to obtain results that could be directly compared.

This manual for field work in glacier mass-balance studies was first issued in 1966 (see Østrem and Stanley 1966). The present manual is a revised edition of the original book, and it is a result of a co-operation between the Canadian Department of Energy, Mines and Resources and the Norwegian Water Resources and Electricity Board.

The manual describes standard field techniques, outlines practical difficulties and indicates how to overcome them, gives some hints of practical use for the field work, and suggests how the data can be recorded, tabulated and plotted in graphs and on maps. It also gives a suitable form for a summary of the data to be made in the field, makes suggestions for field accommodation, outlines office procedures, means of data processing and the presentation of final results.

The manuscript was read by Dr. Valter Schytt, glaciologist at the University of Stockholm, Sweden, and by Mr. W. Tangborn, research hydrologist at U.S. Geol. Survey in Tacoma, Washington. Their comments were gratefully appreciated.

Oslo and Ottawa, February 1969

Gunnar Østrem, Alan Stanley

SELECTION OF SUITABLE GLACIERS

It is not physically possible to examine all glaciers in a mountain system or within the catchment area of large streams. Therefore, it will be necessary to select one or more glaciers which are considered representative of the whole area under study. However, the results obtained from one or more glaciers can probably be applied to a large glacierized area. It is therefore extremely important that the choice of the representative basin be made very carefully, but practical conditions (mainly accessibility) might influence the choice of glaciers for this kind of study. Thus, it may be necessary to make a compromise in most cases.

A suitable glacier representing each geographical area, climatic zone or catchment area should be selected on the basis of the following considerations:

a) The glacier must have a well-defined catchment area and the degree of glacierization must be as high as possible so that the melt water stream depicts conditions on the glacier rather than conditions on the surrounding terrain.

b) The size of glacier should be comparable with all glaciers in the area of study but small enough to be fully examined by a 2-3 man party. (The upper limit of such an area is probably 10-15 km^2). In special cases, when great economic interests are involved it might be possible to have more people involved in the field measurements and thus a larger glacier area could be examined.

c) The range in altitude between the glacier tongue and the upper firn area should be as large as possible, or at least cover the main part of the range for the glaciers in the area under study.

d) The glacier should be drained by one single melt water stream with local conditions favourable for discharge measurements close to the glacier snout.

e) The glacier should have relatively easy access so that it will be feasible to visit it throughout the year without extensive use of helicopters etc. Easy access should, however, not be overemphasized; an ideal glacier should not be omitted and replaced by another less suitable for reason of accessibility alone. This question, however, must be decided for each particular glacier depending on available resources.

f) The glacier should have few crevasses as they make the work unnecessarily risky for observers and may restrict proper observations to only a small area. However, if a representative glacier within an area has a great number of crevasses the value of this point must also be considered in each particular case.

g) The glacier should be situated in an area for which reliable maps and good air photographs are available or can be readily obtainable shortly after investigations have started. All accumulation and ablation measurements must be plotted on maps, and the scale of 1:10,000 is generally most suitable for this purpose. A contour interval of 10 metres will be appropriate for the glacier surface, 50 m will be sufficient for the surrounding area. The map must cover the entire catchment area above the site of river observations.

BRIEF DESCRIPTION OF THE GLACIOLOGICAL PROGRAM IN WESTERN CANADA

As a part of Canada's contribution to the International Hydrological Decade glaciological studies will be conducted at a number of glaciers. These studies will include measurements of mass balance, meteorological observations on or near the glacier, measurements of discharge and sediment content in outflow streams. In certain cases studies will be made also of the glacier's heat balance. Besides these subjects which are within the scope of the International Hydrological Decade program, studies of the ice movement (i.e. "ice discharge" in a glacierized valley), ice formation in the firn area, ice crystallography and related problems will be carried out. In some cases however the limited sources of trained personnel will restrict studies to the first mentioned subjects.

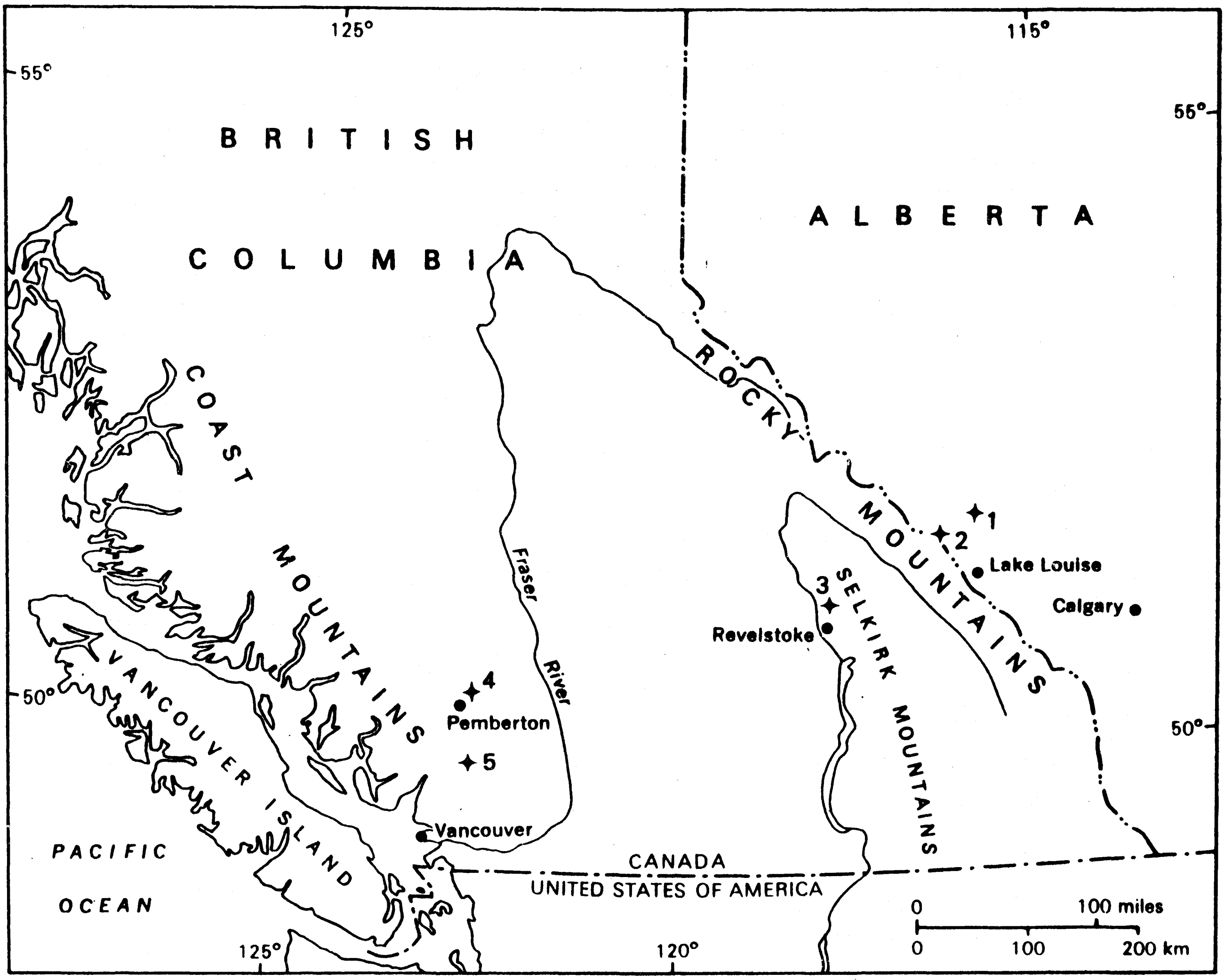
The primary purposes of the glaciological investigations on the selected glaciers will be:

1. To determine the mass balance on the glaciers. The winter accumulation (e.g. "winter balance", see appendix) will be measured as accurately as possible and the total amount of ablation during the summer season will be observed by a network of stakes drilled into the ice. Variations in snow density in the firn area will be observed by pit studies throughout the ablation season.

2. To study the accumulation pattern and, if possible, follow its variation throughout the accumulation season. Furthermore, to make a comparison between the total accumulation on the glacier up to certain dates during the winter and the precipitation records kept by meteorological stations and snow courses in the area.

3. To study the ablation throughout the summer and correlate variations with meteorological parameters obtained at the glacier and/or deduced from observations at distant meteorological stations.

4. To measure the glacier stream discharge continuously throughout the summer in order to check calculations of ablation in selected periods. Discharge observations will be corrected for rainfall in



Location map showing the Canadian glaciers selected for mass balance studies in 1965, along a profile almost east-west across the mountain ranges:

(1) Ram River Glacier, one of the easternmost glaciers in the Rocky Mountains.

(2) Peyto Glacier in Banff National Park.

(3) Woolsey Glacier in Revelstoke National Park.

(4) Place Glacier in the Pemberton area.

(5) Sentinel Glacier in Garibaldi Provincial Park.

the catchment area determined with rain gauges placed at a number of locations.

5. To take water samples from the glacier stream for determination of sediment transport. At the end of the Decade, this will give some information about the effects of glacier erosion and any sedimentation which can be expected in natural or artificial reservoirs. Ideally some supplementary observations should be made downstream, close to these reservoirs.

6. To investigate refreezing of melt water in snow and firn. Refreezing is very pronounced on cold glaciers in the Arctic but the process has not been fully investigated for Alpine glaciers.

In order to compare results obtained from glaciers in different climatic areas, a number of glaciers have been selected across the Canadian Cordillera. The glaciers were selected close to a line running from the Coast Mountains north of Vancouver, B.C., to the eastern flank of the Rocky Mountains north of Banff, Alberta. The selection was made to include humid coastal areas and the dry eastern mountain slopes. Furthermore, a fairly dense network of meteorological stations exists in this part of Canada and there is a good transportation system so that most of the glaciers are fairly accessible. To date, five glaciers have been selected in this profile (a-e below), and two glaciers north of this line; one in B.C., one on Baffin Island:

a) Ram River Glacier at the northeastern border of Banff National Park, Alberta.

b) Peyto Glacier at the provincial boundary close to the Banff-Jasper Highway in Banff National Park, Alberta.

c) Woolsey Glacier, part of the Clachnacudainn Snowfield in Revelstoke National Park, B.C.

d) Place Glacier, 20 km northeast of Pemberton, B.C.

e) Sentinel Glacier in Garibaldi Provincial Park, B.C.

f) Berendon Glacier near Steward, Northern B.C.

g) Decade Glacier in Inugsuin Fjord, East Central Baffin Island, N.W.T.

It is possible that the selection of glaciers will be extended later to include a glacier in an extremely humid area either on Vancouver Island or on the mainland north of Vancouver Island, and a glacier between Woolsey and Peyto.

Measurements will be continued for a period of at least ten years. Accumulation (e.g. "the winter balance") will be measured at the end of the accumulation season (in April or May), but in addition, it will be necessary to make winter visits to glaciers in areas of heavy accumulation to extend the main stakes in the firn areas. Because all accumulation measurements in the spring must be referred to known points on the glacier surface it is vital to keep them visible throughout the winter, and inspection is anticipated in November and February each year. Ablation and river discharge will be measured during the entire melt season by parties of 2-3 men who will also keep records of meteorological conditions. They will make summaries of all their observations so that the processing of data can be performed immediately after their return from the field in September.

A base camp will be established at all glaciers comprising at least an insulated hut for accommodation, a shelter for a snow vehicle and/or storage of supplies, one or more Stevenson screens for meteorological observations, and probably a shelter for an automatic stream gauge.

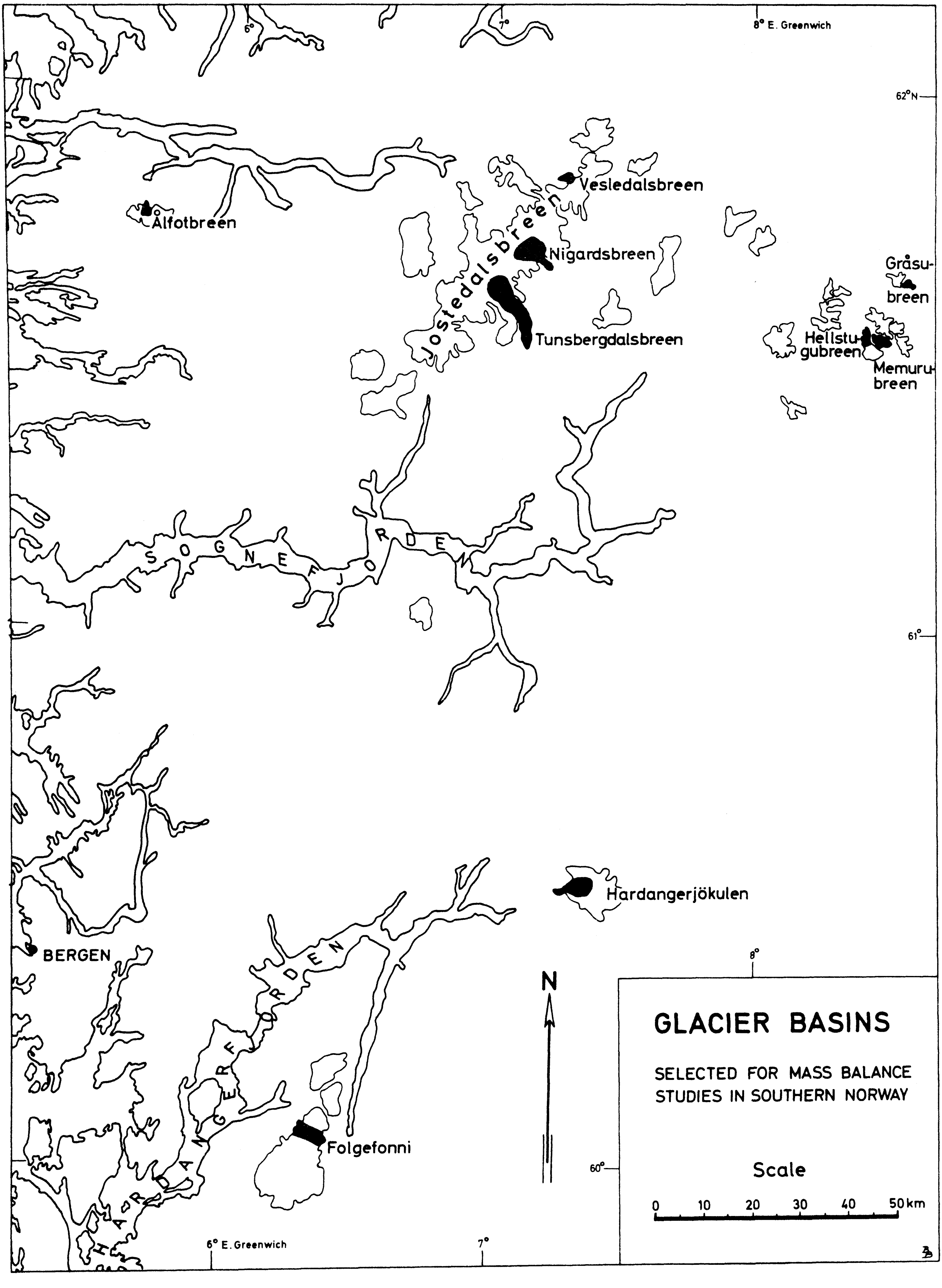
PRESENT GLACIOLOGICAL INVESTIGATIONS IN NORWAY

Most of the mass balance studies in Norway are concerned with hydrological problems for utilization of high mountain rivers for hydroelectric power production. Mass balance studies are therefore undertaken in areas where future power stations are planned. To form a good basis for hydrological calculations it is desirable that the investigations continue for 5 or 10 years. Some of the glacier basins will thus be observed during the entire International Hydrological Decade, whereas other glacier basins will be observed for only part of it.

In addition to short term studies, which are carried out primarily for economic reasons, investigations are being performed at a number of glaciers on a long-term basis. Some of these glaciers are located along an east-west profile across the mountaineous areas in Southwestern Norway. In all, seven glaciers of different sizes were selected, including corrie glaciers, valley glaciers and small ice caps. The profile extends from the humid western coast to the continental dry inland areas. Annual accumulation and ablation figures range from an average of more than 4 m to less than 1 m of water equivalent.

The Norwegian studies include measurements of mass balance, meteorological observations at the glacier, and measurements of discharge and sediment transport in the glacier streams. On most of the glaciers are included studies of ice movement and other glaciological subjects.

The primary purposes of the investigations are generally the same as for the Canadian program and will therefore not be repeated here (see



GLACIER BASINS

SELECTED FOR MASS BALANCE STUDIES IN SOUTHERN NORWAY the previous chapter about the glaciological program in western Canada). In connection with the glaciological studies it is anticipated that glacier maps at a scale of 1:10, 000 will be constructed for all glaciers under study. The location of the glacier basins being investigated at present (1969) are shown on an index map.

A base camp is established at all glaciers under study. The camp includes an insulated hut for accommodation, another hut serving as a shelter for a snow vehicle and/or a storehouse for supplies, at least one meteorological instrument shelter and, for most glaciers, an automatic stream gauge. Observations are carried out continuously during the entire melt season by a crew consisting of 2-3 students. The total snow accumulation which has occurred during the winter is generally observed early in the spring but for practical reasons it is necessary to visit the glaciers 3-4 times during the winter to inspect installations and extend survey stakes.

The results of the Norwegian mass balance investigations are published in annual reports printed and distributed* by the Hydrological Department of the Norwegian Water Resources and Electricity Board (address: P.O. Box 5091, Oslo 3) in a similar format as shown in this manual. These reports are written in Norwegian, but all illustrations have legends entirely in English and captions are also given in English. An extensive English summary is included at the end of each report.

STAKE NETS

As measurements of both accumulation and ablation are referred to stakes placed on the glacier surface,it is advantageous to plan carefully the pattern of the stakes. Ideally, the stakes should be scattered uniformly over the entire surface so that every part of the glacier is covered by an equally dense network of stakes. However, this ideal distribution pattern is not practical and it is suggested that stakes be arranged in one or another geometrical pattern to facilitate the daily work on the glacier. It is impossible to make a rigid recommendation for stake locations which would fit all different-shaped glaciers, but for valley glaciers the most useful is a long line up the centre with transverse lines at regular intervals.

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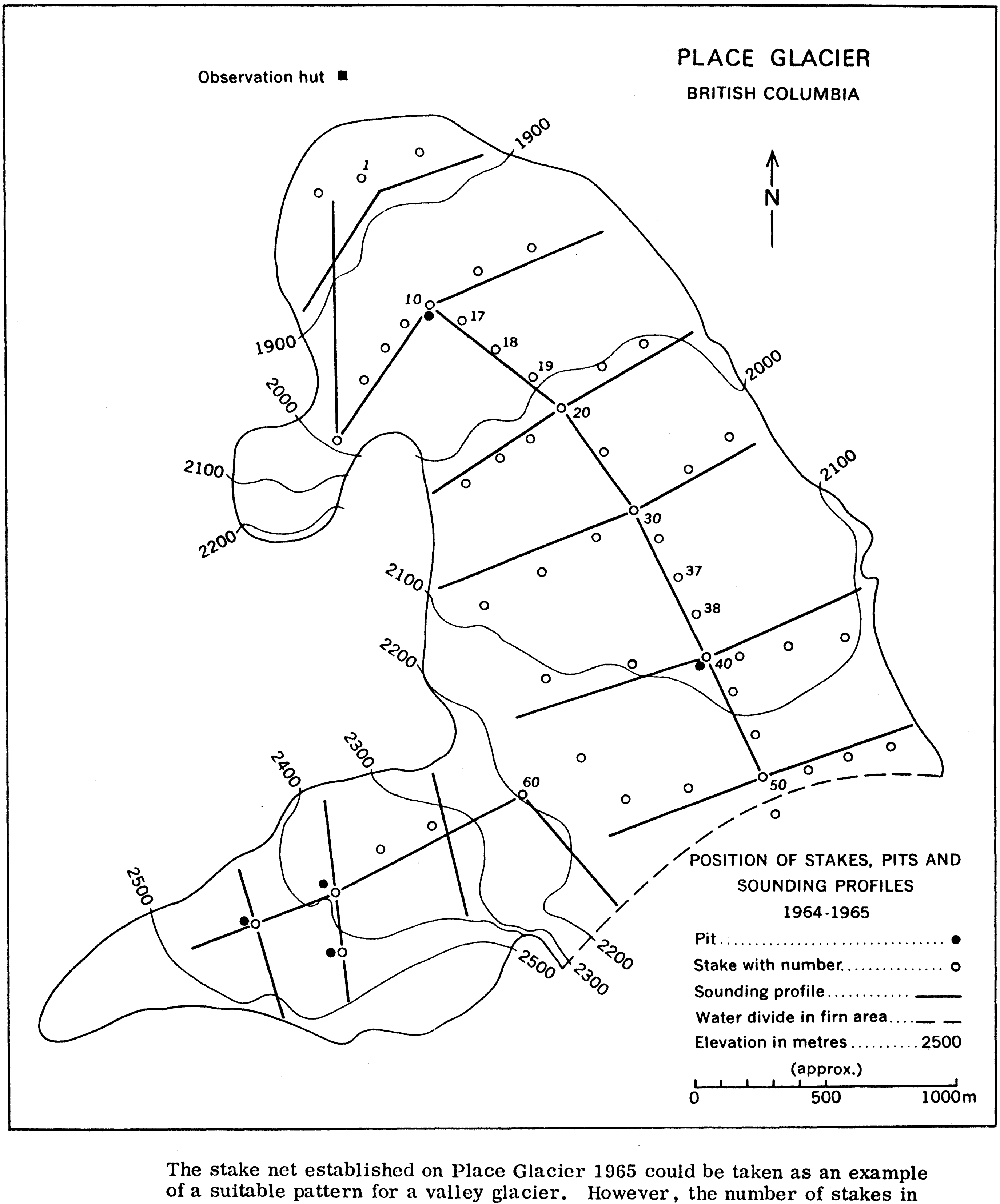
*For one of the glaciers, Storbreen in Jotunheimen, the results are published by Norsk Polarinstitutt in their annual "årbok".



The stake net established on Place Glacier 1965 could be taken as an example of a suitable pattern for a valley glacier. However, the number of stakes in the upper part of this glacier is still too scarce and should ideally be densified.

1. Stake location

One longitudinal profile is approximately along the centre line of the glacier (for numbering of these stakes, see below) and several transverse profiles are located at suitable intervals across the glacier from the snout to the firn area. The transverse profiles should be placed at right angles to the longitudinal profile. Crevassed areas and other "difficult" parts of the glacier must also be considered, although a less dense network might result in such areas, for safety reasons.

2. Numbering system

If stakes disappear or bad weather conditions make navigation difficult on the glacier, a good system makes it easier for the crew to decide their location. In order that each stake can be easily identified, it is necessary to have a logical system of numbering. There are several systems but the following has proved to be very useful for a valley glacier.

The "main" stakes that indicate the centre of transverse profiles in the longitudinal profile are numbered 10, 20, 30, 40, etc. Stakes in the first transverse profile have odd numbers, 11, 13, 15, etc., on the left side of the glacier, and even numbers, 12, 14, 16, etc., on the right side, Stake 10 is in the centre. Similarly, the next transverse profile at stake 20 will carry the numbers 21, 23, 25 on the left side of the glacier; 22, 24, 26, etc. on the right side. If it is necessary to insert more stakes in the longitudinal profile they could be numbered with figures not already used in the transverse profiles, as 18, 19, 28, 29, etc. For most valley glaciers there will be less than 10 stakes in the transverse profiles and sufficient numbers will be available for intermediate stakes in the longitudinal profile. An example is shown among the illustrations.

3. Replacement of missing stakes

If it is necessary to replace a stake which has disappeared, a new stake can be inserted as close as possible to the "original" stake's position. The new stake should carry a number similar to the original but with a prefix which clearly separates it from the previous stake to avoid confusion if the original stake is found later in the season. Example: If stake 24 has disappeared, a new stake numbered 124 should be inserted in the assumed position of stake 24. (If the total number of stakes on the glacier is greater than 100 the prefix should be 2. In this case the new stake would consequently carry the number 224). If also this stake disappears, the replacement should be given the number 324, etc. If the original stake is found later, the replacements should be removed from the glacier, possibly after a period of "parallell" readings during a week or two in the summer.

> Note: In Norway a slightly different system is in use. Replacement stakes are given a suffix, indicating the inserting year. If stake 24 has disappeared, the replacement is given No. 24-69, if it is inserted in 1969.

4. Duplication of stakes

To mark the position of a very short stake so that it can easily be found for triangulation purposes, etc., a duplicate stake should be placed adjacent to the original, but its number should carry a letter as a prefix. Example: If stake 83 is hard to recognize (as it is located in a concave area on the glacier, or because only a small part of it remains above the snow surface) a duplicate must be given the number A83, and inserted close to the original stake. This duplicate stake could then be marked with a big flag to make the position of stake 83 clearly visible at a distance. For very accurate determination of its position the horizontal distance between the two stakes should be measured. In most cases, however, this will not be necessary.

If, for any reason it is necessary to insert another stake at this location (if stake A83 has disappeared or has been bent down), this second duplicate stake should be numbered B83. A letter in front of a stake number would therefore always indicate a duplication of a stake in that particular point. The horizontal distance between a duplicate stake and the original stake should be kept to a minimum (i.e. in most cases less than 1 m). Note the difference between a duplicate stake and the replacement stake mentioned above! The latter will probably be situated at a greater distance from the original stake.

5. Stake extension

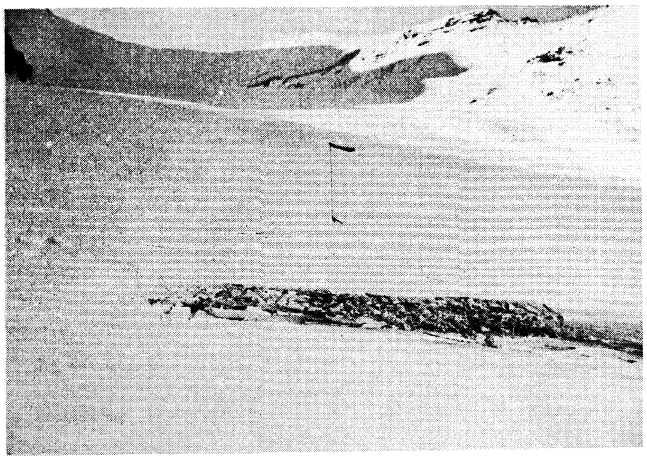
For accumulation measurements made in the spring (see next chapter) it is necessary to know the exact location of all sounding profiles. Therefore, it is important to keep at least the main stakes visible as a system of reference. In the fall it is almost impossible to erect a stake long enough to survive a full winter's snow accumulation, although such arrangements have been made on the South Cascade glacier, Washington (see Tangborn, 1963). The simplest way to keep stakes visible is to extend them by inserting a short steel pipe inside the stake and adding a 2 m long extension tube to the top of the original stake. To number the extension, use the same number as the original stake but with a suffix to show that it is an extension. Example: Stake 70 is extended in November by adding a 2 m aluminum tubing. This

STAKE EXTENSIONS AND SURFACE MARKING

A 2-m aluminum tubing is used to extend the stake. A steel pipe (30 cm long, 1 diameter) has been inserted in the stake and is held in position by friction tape. The aluminum extension is placed on top of the original stake. The steel pipe will hold it in a vertical position.

The stake or the extension should be made visible with a strip of cloth.

To obtain a reference surface for pit studies later in the winter season, an area 10 m from the stake has been marked by powdered dye (Picture taken at Peyto Glacier, November 1965).



extension piece will be numbered 70/1. In February only the upper part of this extension may be above the snow surface (with the number 70/1 visible), so if a second 2 m extension piece is put on top of the first, its number will be 70/2. From the start of the melt season these extensions are successively removed until the original stake is again visible.

Photographs demonstrating details of stake extension work are shown among the illustrations.

6. Technique of inserting stakes

The best material for stakes on a glacier is probably aluminum. Although bamboo is far cheaper it has some pronounced disadvantages. Firstly, its physical strength is not sufficient to withstand heavy storms, especially if hoarfrost becomes attached to the stake, as is normal in humid (maritime)areas. Secondly, the surface becomes bleach and it is difficult to recognize the stake in foggy or overcast weather. In such cases the advantage of a metal stake is obvious. In some extremely humid areas, however, (near the western coast of Norway), even aluminum poles are too weak and must be replaced by steel stakes.

For the Canadian glaciological work the Alcan "65 ST 6" aluminum alloy tubing has been selected ($1\frac{1}{4}$" outer diameter and wall thickness of 0.065"). This is cheaper than, but almost as strong as dur-aluminum. All drilling equipment, extension tubes, inserts, etc. have been standardized so that there will never be any confusion in dimensions. The optimal length of the stakes is 4 to 5 metres, but all stakes should be cut so that their lenght is 4, 5 or 6 m exactly. Usually the tubing is commercially available in standard lengths of 14, 16, or 18 feet etc. but intermediate lengths can be supplied on request.

On Norwegian glaciers two different aluminum alloys are used: 51 SWP (a fairly strong non-corrosion alloy) and AA7075-06 (in Sweden termed SM-6958) which has extremely high mechanical strenght (σ0. 2<49 kg). The first is for general use and the second for use on glaciers where mechanical strength is vital on account of riming, high winds or extensive snowcreep. The outer diameter is 32 mm with a wall thickness of 2 mm. This is very close to the dimensions used in Canada. As a standard lenght, 6 m has been chosen for normal stakes, and 2 m for extensions.

Before any stake is inserted in the glacier, it should be marked all around the circumference by pencil <u>and</u> paint at each metre, to facilitate reading when the stake has been inserted.

The stakes should be placed vertically in the glacier. The technique used for inserting stakes depends upon the kind of surface where the stake is located. In general, there are two different ways of inserting stakes:

(1) In the firn area a stake could be simply pushed into the snow or firn, but recent investigations have shown that such stakes tend to sink into the glacier during the melt season. Therefore, it is necessary to support the stakes at their lower ends to prevent such sinking. Details of the procedure are given below.

(2) In the ablation area the stake should be placed in a narrow hole drilled with an ice drill (hand-operated or motor-operated mechanical drill) or a hot point.

The hole must have a diameter of 1½" and should be so deep that only a small part of the stake remains above the surface. Ten to twenty centimetres are sufficient if the hole is drilled at the beginning of the ablation season, but if it is drilled near the end of the season, 200-250 cm of the stake must be visible above the glacier surface. When less than 100-150 cm of the stake remains in solid ice, the stake is no longer reliable. Experience has shown that stakes remain in a fixed position relative to the surface only as long as the stake is anchored firmly into the hole. When the stake is no longer frozen in, the hole must be redrilled.

Instead of aluminum stakes, it is possible to use wooden stakes (either simple 1" x 1" lumber, bamboo stakes or wooden dowels). However, such wooden stakes do not give reliable results if they float in the melt water in the hole. Even if they are pushed back into position, stake readings will not be reliable as the melt water will tend to melt its way down into the glacier ice during the summer season. Consequently, the stake readings will indicate less than the true glacier ablation. The same conditions appear when a metal stake becomes loose (this will normally happen if less than 1-1,5 m remains in solid ice). Generally, readings are reliable only when the stakes are frozen solidly in the ice.

Redrilling in the same hole may be impossible, due to wet conditions in the ice. Any stake should be relocated as close as possible to the original position. As a rule-of-thumb the stakes should be redrilled 1 m up-stream from their previous location, but if this area is difficult to drill, a new spot must be selected and its position noted. For studies of glacier movement, this measurement is extremely important. If very accurate measurements are applied, special precautions must be taken to ensure accurate calculation of the new position.

A hand operated ice drill consists of a seamless steel tube with 4-6 sharp teeth cut into the lower end. The drilling equipment is shown among the illustrations.* To use a hand operated ice drill is something of an art and requires a distinct knack that cannot be explained in detail without simultaneous practical training. When the drill is rotated ice crumbs will accumulate inside the tube and hinder further drilling. Normally 50 cm can be drilled before the tube has to be cleared. Aluminum extensions with brass couplings can be attached to the drill so that holes 4-5 metres deep can be made easily by two men in 1/2-2 hours depending upon ice conditions, air temperature and the skill of the drillers.**

It is always advisable to drill holes for the stakes when the ice is cold and there is no melt water to percolate down into the hole. However, if the air temperature is above 0°C or there is strong sunshine the drill warms up and might freeze into the hole if the ice is very cold. Under such conditions it might be necessary to drill during the night. To loosen a drill frozen to a hole, alcohol or antifreeze can be poured into the hole immediately. Denaturated alcohol should therefore always be carried by the ice drillers.

To insert a stake in the firn area, a hole should preferably be drilled down to the previous summer's surface. Metal stakes tend to sink in the firn and it is important to support the lower end before a stake is used to measure any variation in the snow or firn surface. In general, the stake should be placed directly on the previous summer crust; this is a relatively hard surface and offers generally better support than any snow or ice layer. However, when melt water percolates through the crust, its mechanical strength decreases and the stake may start to sink. To prevent sinking, one of the following methods is recommended:

(1) Place the stake on a small "platform" made of any cheap material plugged into its lower end. The simplest method is to insert a cork or a wooden plug before the stake is put in position. This cork will form a supporting area that has a cross section approximately corresponding to the stake diameter and it is likely that the stake will be held in correct position for most of the summer.

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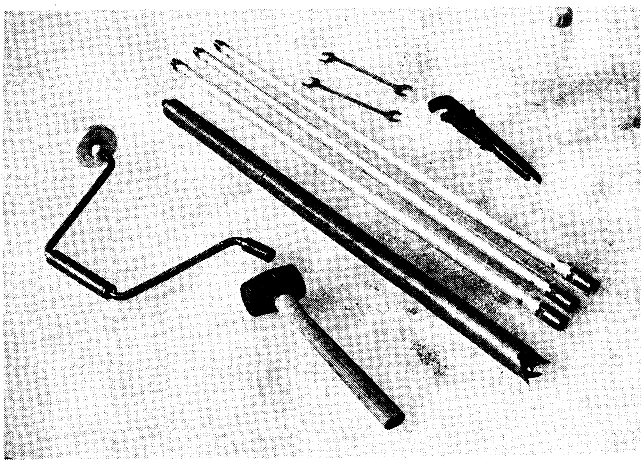
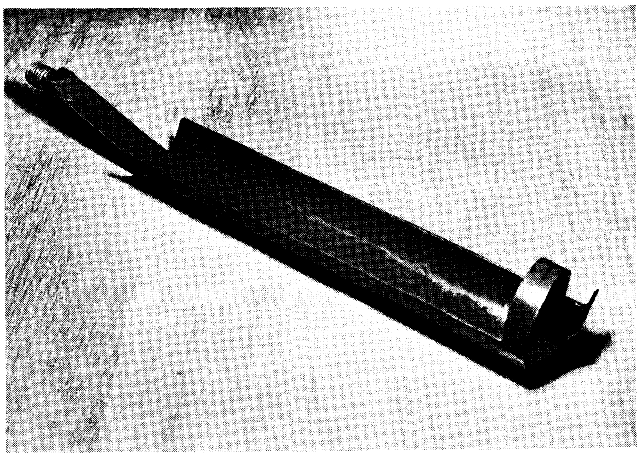
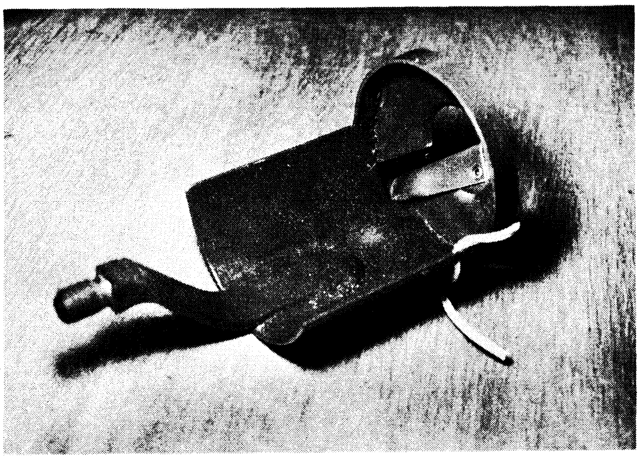
*This equipment was developed in Scandinavia during the last 15 years, and can be obtained from: Institute of Physics (Verksmester R. Holm), University of Oslo, Blindern, Norway. Approximate cost is $ 200 for a complete set.

**Other kinds of drills have been developed, many have a horizontal cutting knife and a long spiral along which fragments are raised. In cases when glacier ice is very wet this type of drill could have some advantages, although raising ice crumbs to the surface might still be difficult.



Upper picture shows a complete set of tools for hand-drilling in glacier ice. 4-metre-deep holes can be obtained with this auger which consists of a seamless 1-1½" steel tube; extensions are made of aluminum with 5/8" threads in the brass or bronze end pieces. The bottle contains alcohol to use if the drill freezes in a hole. The rubber mallet is used when clearing the drill, and the open end wrenches are for disconnecting extensions. The weight of the complete set is approximately 10 kilograms. The lower two pictures show various sizes of a "fisherman's drill" to use in wet ice (middle picture) or in the firn area (bottom picture). The latter will allow stake supports up to 12 cm diameter to be lowered in the hole. Note: in the bottom picture the cutting edge is covered by a leather protection. All drills and extensions have the same standard 5/8" thread.





(2) Place the stake on a plate that is larger than the stake diameter. This can be done by drilling a large-diameter hole (SIPRE-type coring auger or a fisherman's drill; see illustration) and fixing a circular plate to the stake before it is inserted. This method will prove satisfactory under various conditions, provided the plate is strong enough. In practice the simplest method is to use a strong, plastic bottle attached to the stake; the bottom of the bottle forming the supporting "platform". See illustration.

(3) Dig a pit and lay a large plate made of plywood or similar material on the summer surface and place the stake on it before the pit is filled up again with snow. This is a very satisfactory method but it requires much labour. The snow stratification close to the stake will be disturbed, but experience has shown that ablation figures will be reliable.

In remote areas where glaciers will be visited only at long intervals or on glaciers where melt is greater than 4 metres of ice, it is advisable to use a hot point drill to insert a chain of stakes so that no redrilling will be necessary until the ice has melted approximately 20 metres vertically. No description or explanation of the hot point drill is given here as this is beyond the scope of this manual, but assistants who are occasionally working on glaciers where such stake chains have been inserted previously, must be aware of the special technique involved in the observation of glacier melt at these stake chains (or wires frozen vertically into the ice). (See under the description of ablation measurements below).

A complete equipment for hand drilling comprises:

a) a seamless steel tube, 1 metre long with 4-6 teeth cut in the lower end and a 5/8" thread in the upper end.

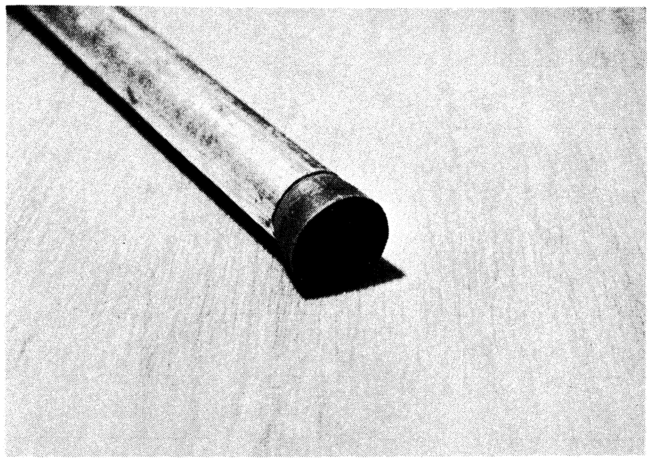
b) aluminum extensions, 1 metre long with brass couplings fitting the above-mentioned thread.

c) handle with an operating radius of approximately 20 cm (this is more than a standard carpenter's brace).

d) rubber mallet to clear ice fragments from within the drill.

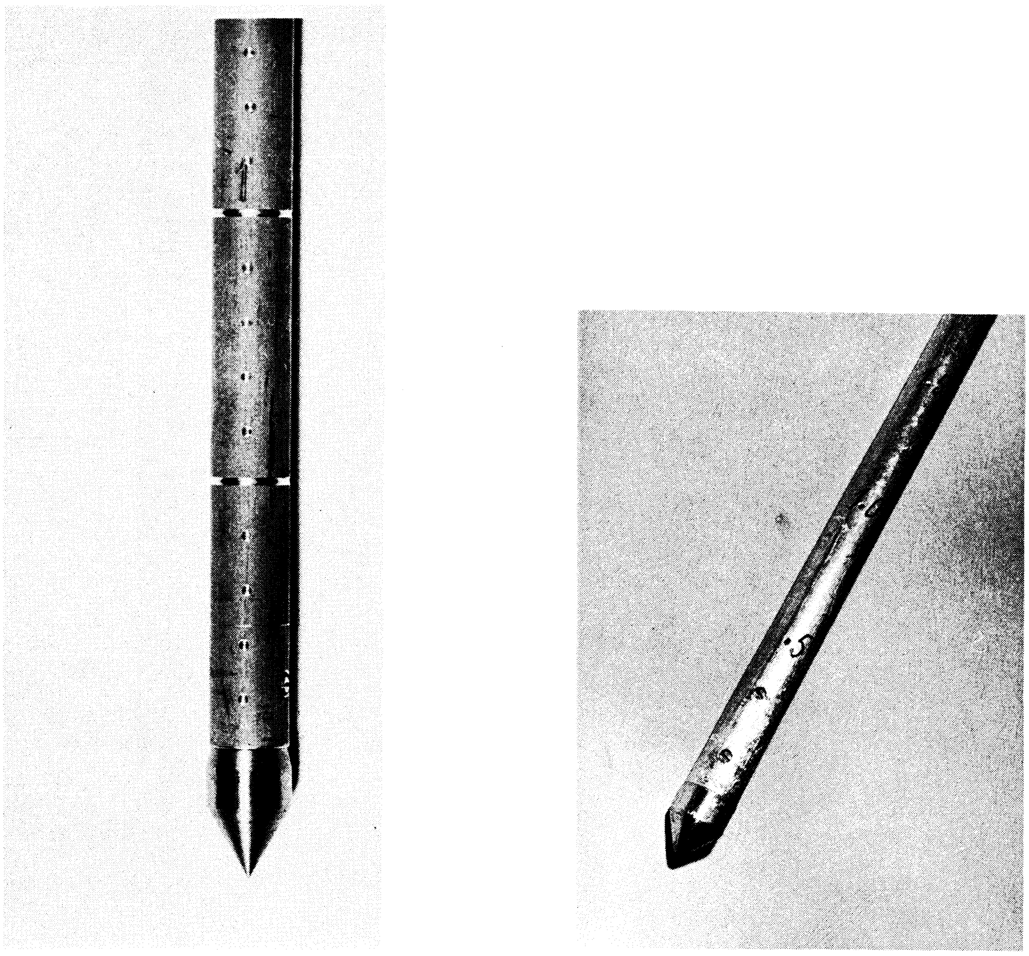
e) 2 open-end wrenches or pipe wrenches to dismantle the drill and extensions.

f) a bottle containing denaturated alcohol to free the drill if it freezes into the ice.



A stake inserted in the firn area must be supported at its lower end. A simple method is to use a cork that may prevent the stake from sinking for at least a part of the summer.

A far better support is a circular plate or - simpler - a plastic bottle fixed to the stake. In this case a wider hole should be drilled down to the summer surface. This, in combination with the large supporting area, will prevent the stake from sinking.



Two slightly different types of snow sounding probes. The swiss probe (left) consists of an aluminum tube, marked with a point for each centimetre and a band for every five. The snow depth can be easily read when the probe is pushed vertically into the snow pack. The steel spear has a diameter slightly larger than the aluminum tube, so that a minimum of friction should occur when the probe is lowered and raised through the hard-packed snow.
The Norwegian type (right) has marks for every five cm and it has a somewhat smaller diameter, the construction is generally the same. Both probes are supplied with 1-m extensions that have similar marks.

ACCUMULATION MEASUREMENTS

1. General

The total thickness of snow that accumulates over the entire glacier surface must be measured at the end of the accumulation season. (For most glaciers in southern Canada this will be during the month of April or May). Snow will then start to disappear from the glacier surface due to strong radiation although ambient air temperatures remain below zero. Additional accumulation may occur during May and June and increase the winter balance as measured in April/May.

Due to practical difficulties in visiting all glaciers at the right time it will be necessary, at least for some glaciers, to perform a snow survey prior to the actual end of the accumulation season. For such glaciers additional accumulation after the snow survey must be recognized and recorded.

To study the rate of accumulation during the winter it will be necessary to make several visits to each glacier and to make a complete accumulation measurement at each visit. However, the method will be similar to those used at the end of the accumulation season and they are described in this chapter. See also a following section about the "snow pillow".

As the accumulation is expressed in water equivalent it is necessary to measure snow depth and use a snow density factor to calculate the water equivalent in each measuring point. However, as snow density seems to be relatively uniform over large areas whereas snow depth normally shows large variations even in short distances, it will be necessary to make a great number of snow depth soundings and relate them to a comparatively small number of density observations. Snow depths are measured directly with a "sounding stick" or probe* which is pushed vertically through the snow pack to previous summer's crust (or the ice surface). The snow density is measured by weighing a known volume of snow obtained from the snow pack between the existing snow surface and previous summer's crust (or the glacier ice surface).

Results of water equivalent determinations at numerous places are plotted on a map and lines of equal accumulation drawn. From this accumulation map the total accumulation, expressed in millions of m^3 of water equivalent can be calculated.

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*The Swiss snow probe is made by Dr. P. Kasser, Abt. für Glaziologie, Voltastr. 24, Zürich 7/44, Switzerland.

2. Snow depth soundings

Snow depth can be highly variable as deposition is greatly affected by topography and wind action. Prevailing winds will probably produce a deposition pattern of the winter snow cover which is similar from year to year for any particular glacier. However, great variations might occur even in two consecutive years and before the snow accumulation pattern can be anticipated it will be necessary to measure the snow depth at a large number of points. A density of 100 points per km^2 will probably be desirable for a valley glacier whereas a less dense network might be sufficient for a large ice cap.

Ideally, the measuring points should be uniform over the entire glacier surface. However, as this is not practical soundings along profiles are recommended.

Sounding profiles (i. e. straight lines along which soundings are performed at equal intervals - normally 50 metres) should be laid in a pattern which will cover the entire glacier. If snow conditions are more or less known from previous experience, a skeleton network could be placed in areas of even snow distribution and a denser network in areas where large local variations are expected. Even distribution generally occurs on the tongue or on the intermediate part of the glacier, whereas wide variations are commonly expected in the upper firn areas, that also tend to have greater thicknesses of snow.

The easiest method is to locate sounding profiles between the "main" stakes down the length of the glacier and extend other lines at right angles to this center profile. At 50-metre intervals along all profiles, snow depth should be sounded to the nearest cm.

It is advisable to plot all field measurements the day they are obtained. In this preliminary plotting all figures will express snow depth only and not water equivalent, but they will show any irregularity in distribution and determine the position of additional sounding profiles.

It is advantageous to first sound the snow depth on the glacier tongue for two good reasons:

1. The previous summer surface is represented by glacier ice and there will be no doubt about the location of the lower boundary of the winter's snow.
2. The snow cover will be thinner than on the upper parts of the glacier and untrained personnel will rapidly gain experience in using a snow sounding rod.

As snow sounding profiles are extended into the accumulation area at higher altitudes, it may become difficult to locate the lower boundary of the winter snow pack. During a warm summer a rigid "summer crust" will be developed and its location can be detected with a probe. However, during a cold summer, no real "summer crust" develops, and summer snow falls may give a number of poor developed crusts. It becomes difficult to decide which of them should be defined as the previous summer's surface.*

Generally the greatest variations in snow depth can be expected in the upper part of the glacier which also has the heaviest accumulation. It is important to spend more time in this area and have more sounding profiles than on the tongue. Generally travel becomes difficult and each sounding takes more time, so work may take 2-3 times longer than on an equal area on the glacier tongue.

Before the soundings are completed on the glacier, make sure that all data are plotted on a map and contours are drawn to show areas of equal accumulation. Additional soundings might then be necessary in areas where it seems difficult or impossible to interpolate the data to obtain a reasonable pattern.

All snow depth soundings must be converted into figures of water equivalent using density determinations obtained from snow pit studies.

3. Pit studies

The density of the winter's snow pack will generally show little variation in areas of approximately equal altitude. The number of pits necessary to obtain accurate accumulation measurements will depend on the range of altitude for each glacier. If time is very short it would be advisable to dig at least 3 pits, one on the tongue, another in the middle part, and one high up in the firn area. Intervening pits should be dug according to the time available.

Before digging a pit, first make a number of snow depth soundings to determine the depth which will be necessary for the pit and to ensure that no crevasses are present. The initial hole must be large enough that the final pit will be at least 1 x 1 m at the bottom. Digging should continue approx. 50 cm in the old snow (firn) below the previous summer's crust. Normally the pit will have a square or a rectangular cross section and before starting one must decide which of the four sides should remain untouched. Otherwise it will be impossible to determine the original upper surface of

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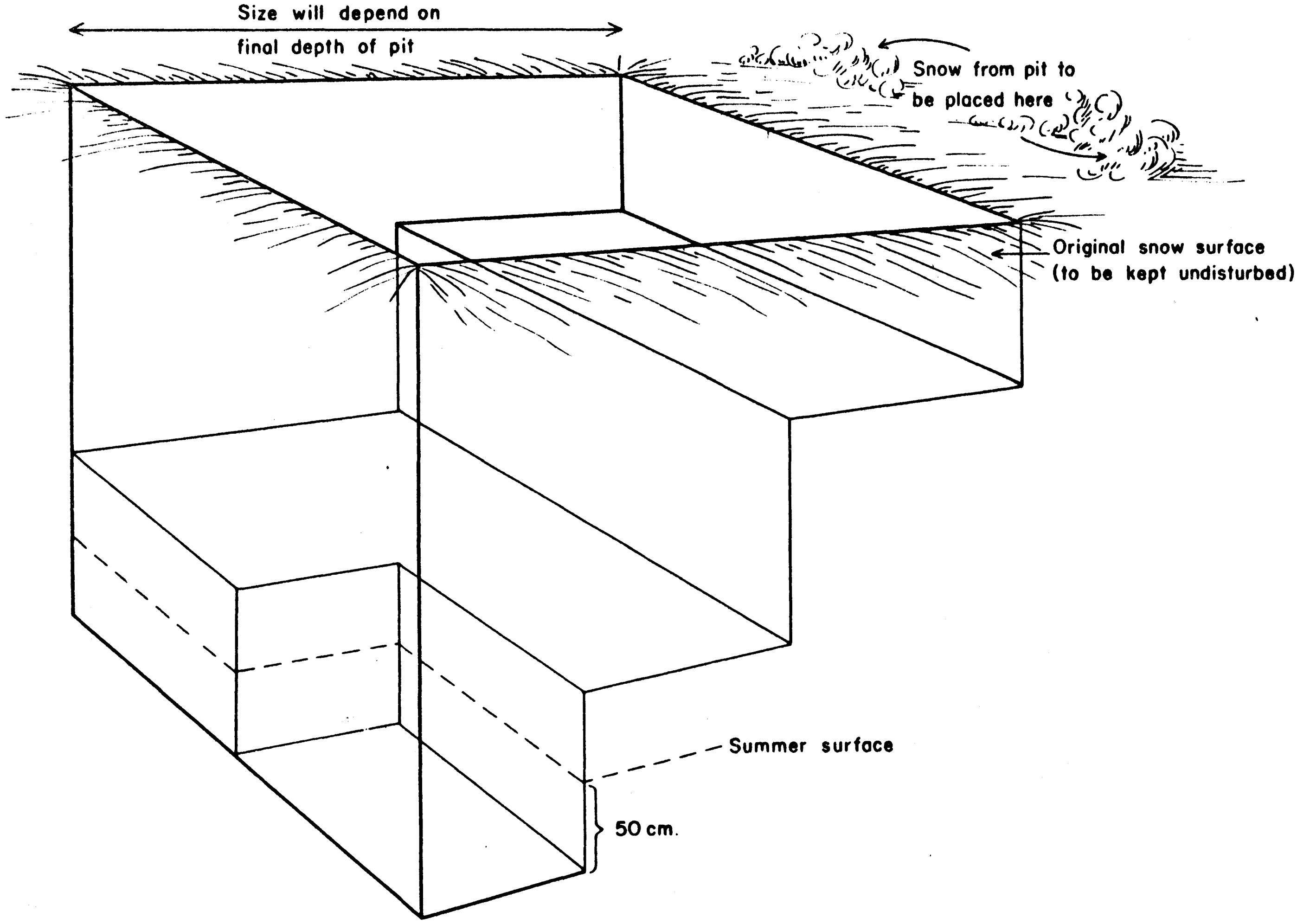
*If such conditions are observed during the ablation season in a particular year, special measures should be taken by the crew to mark a surface which could be defined as that summer's crust (see later).



Sketch of a snow pit

Time and labour can be saved if the pits are planned properly. At least one wall should be vertical (preferably on the southern side of the pit), extending from the undisturbed original snow surface down to 50 cm below the previous summer's crust. Snow dug from the pit should be placed near the edge to facilitate refilling the pit. For deep pits, it is advisable to use a large bucket and a rope to rise the snow from the deeper parts of the pit.

the snow pack. To avoid changes in snow conditions due to direct sunlight, it is advisable to select the southern pit wall for sampling.

If a pit is dug near an existing stake, it should as a rule be dug at a standard distance downstream from the stake. A distance of 5 or 10 m is recommended. The same distance should be maintained for all pits dug on the same glacier. If there is no stake at the pit location it is advisable to place a stake there, because if repeated pit studies are necessary, the exact location can be easily recognized at each visit.

Snow samples are taken vertically in the pit wall from the untouched snow surface downwards to approx. 50 cm below the previous summer surface. The samples must be taken continuously but the length of each sample is arbitrary, its length being normally determined by the physical condition of the snow, presence of ice layers, etc.

To obtain the sample: push a steel plate horizontally into the undisturbed pit wall about 20 to 40 cm below the surface, then push a stainless steel snow sampling tube vertically downwards onto the steel plate and measure the vertical distance between the surface and plate to the nearest 0.5 cm. This is the length of the sample and although snow may settle inside the tube it will not effect the density measurement.

Remove some of the snow from the pit wall to release the sample tube and transfer the content of the tube to a suitable bag. Weigh the bag and contents with a 1,000 gram spring balance[*] to the nearest 5 gram. Subtract the weight of the empty bag to obtain the net weight of the snow sample.

The length and weight of the sample must be noted carefully (for completion of appropriate forms, see below). From these figures the snow density and water equivalent can be easily calculated and a diagram of their variations with depth constructed.

If sampling is performed in warm weather or during a day with strong radiation, the sampling tube might become warm and snow may stick to it. Then it will be difficult to transfer the snow sample from the steel tube to the plastic bag in which it is weighed. It might be necessary to push out the snow with a piston or work during the nights when temperatures are low. A thin layer of wax on the inside of the snow sampler might also help.

A series of temperature observations should be carried out at regular intervals in the snow pack to determine if melting has occurred. If freezing temperatures are present in the lower part of the snow pack no

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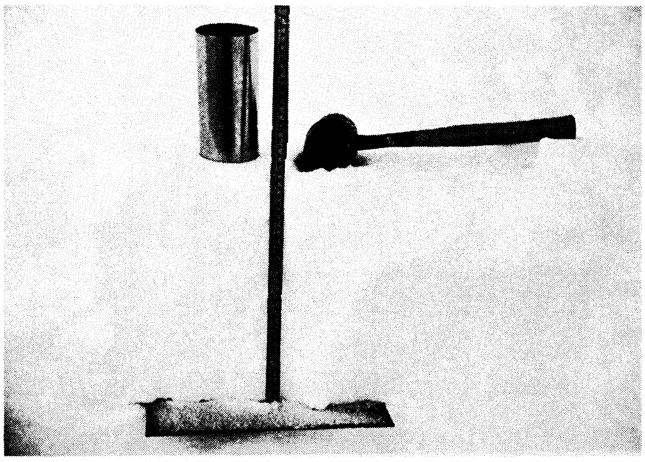
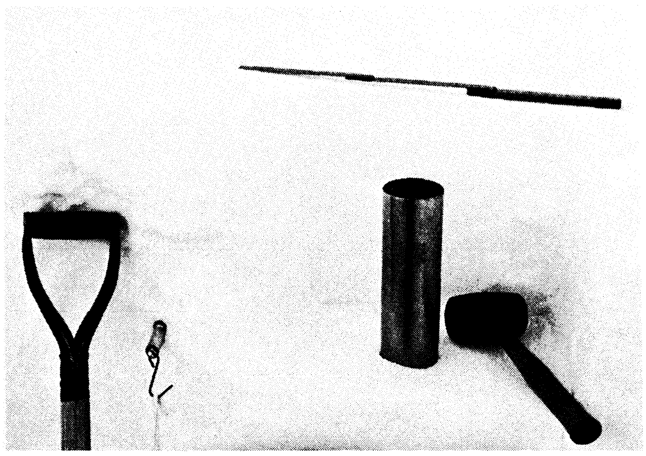
[*] A suitable balance can be obtained from Thorolf Gregersen, Tollbugt. 24, Oslo, Norway, for approx. $ 10.-.





SNOW SAMPLING TECHNIQUE

A steel plate is pushed horizontally into one of the vertical walls in the snow pit (in this case approx. 30 cm from the original and untouched snow surface). The sampling tube is then pressed vertically down to obtain a sample of the upper first section of the snow pack (upper picture).

When the area of the first sample has been cleared, the steel plate is moved another step downwards and the steel cylinder pressed into its second sampling position (middle picture). The ruler is indicating the original snow surface, the rubber mallet is resting on the surface introduced by the steel plate.

Instead of a sampling cylinder, rectangular blocks can be cut out of the pit wall by a carpenter's saw. The blocks must be carefully measured to obtain the volume before they are weighed. A small spring balance, capacity 0-1000 grams, is used to obtain the weight of each sample. The "block method" is probably most accurate but very time-consuming.

substantial amount of melt water has disappeared and the water equivalent observations would be reliable except for surface evaporation. The amount of evaporated snow is difficult to determine but for most purposes it may be neglected.

After completing all measurements, mark the previous summer surface with a layer of saw dust, powdered dye or with a plywood or masonite sheet. First, the bottom of the pit must be filled with clean snow to the level of the previous summer crust. The datum of powdered dye will make it easier to recognize the actual summer surface later in the season because percolating melt water will form ice layers in the snow pack and, eventually, loosen the summer crust. The boundary between last winter's snow and firn from previous years will gradually be obscured. Pits that are dug later in the summer should be located so that the above-mentioned datum appears in a corner of the new pit.

Even if continuous study of snow density and water content variations is not made, it will be necessary to dig pits at the end of the ablation season to measure the remaining part of last winter's accumulation. For further details, see chapter on ablation measurements.

4. Density determinations performed from the snow surface

Many attempts have been made to avoid time-consuming pit digging to obtain snow density values, but one of the main difficulties in all these methods is to recognize the previous summer's surface, i. e. to what depth the sampling should continue. Another problem is the accuracy of these methods. (See Williams, 1964 or Work et. al. 1965). Many samplers used in wooded areas will be difficult or impossible to use on most glaciers due to great snow-depths or hard, wind-packed layers.

a) The coring drill

With a SIPRE type coring drill it is possible to obtain snow samples similar to those taken with a cylindrical snow sampler. However, due to variations in physical conditions (degree of packing, crystal size, density), almost each time the auger is raised the snow core breaks and a part of the sample core is lost before a density measurement can be made. Special precautions must be taken to ensure that measured densities are valid for the whole snow pack. Example: The coring auger has been lowered 50 cm in the hole and a 50 cm cylindrical snow sample should have been obtained. When the auger is raised the length of the sample is only 45 cm. The water equivalent of this sample will therefore be approx. 10 per cent less than expected and a correction must be made accordingly. To make the correction a special form has been developed for field use, and it is described in a following section. It is advisable to check at least some of the results obtained by the coring auger with pit studies at the same location. In loose snow such check is vital, as the coring auger has shown a tendency to overregister the density of light snow.

b) Radioactive methods

A method based upon radioactive penetration is described by Danfors et al. (1962), Leighty, (1966), and others. A specially designed probe is lowered into a hole and the average water equivalent is determined for snow within a radius of 12-40 cm from the probe. With this device it is essential that the hole has parallel walls because air between the probe and the snow will give erroneous figures for the water equivalent. There are also some problems with calibration. The total weight of necessary equipment is higher than the weight of a complete SIPRE coring auger, and is not yet practical for field use.

5. Additional Accumulation

Snow that falls after spring accumulation measurements have been made, must be accounted for before the total accumulation is computed. This correction for "additional accumulation" can be made either by using precipitation observations from a meteorological station or by direct measurements on the glacier surface. In the first case the amount of precipitation between the snow survey and the end of the accumulation season can be used in connection with a correlation coefficient and calculations of prevailing temperatures on the glacier, see below. In the latter case a simple measurement is made of the actual snow cover which has developed between the snow survey and the beginning of the ablation season. This method is the most reliable and should be used whenever possible. It can be facilitated by marking the existing snow surface at the time of the snow survey with masonite sheets anchored to the stakes or scattering sawdust or powdered dye near the stakes. Also a piece of chicken net can be used, as this has little influence on the snow melt at the stakes.

During a short period in the spring some additional accumulation can result from rain falling on snow that remains well below 0°C. The rain water will freeze within the snow pack and form layers that increase the total amount of accumulation. This kind of additional accumulation, however, will be negligible in temperate areas. To check the amount of additional accumulation, pits should be dug at the beginning of the ablation season (especially in the firn area) and the total water equivalent measured in the snow pack. A comparison with figures obtained by the snow survey in April/May will indicate if a correction is necessary.

A meteorological method using precipitation data from a meteorological station is very complicated for it is necessary to decide if precipitation is falling as snow or rain at the glacier on each occasion and, furthermore, to decide if rain water will freeze within the snow pack or not. If it does not freeze it is assumed that the rain water drains completely off the glacier, and does not increase the amount of accumulation.* Even in cases when it is assumed that the air temperature at the glacier is above 0°C, this does not necessarily mean that the precipitation is falling as rain. Snow may accumulate at air temperatures of +1°C. Thus, a calculation of the additional accumulation could be very ambiguous.

A direct measurement of additional accumulation should be made immediately after arrival at the glaciers in May/June.

6. Snow pillow

During recent years a new instrument has been developed for direct observation of snow accumulation. It is generally well known that a conventional precipitation gauge does not give reliable values for snow precipitation. Snow may blow into or out of the gauge during a snow storm and false values are frequently obtained. Therefore, direct observations of the snow accumulated on a representative area on the ground would probably give far better results.

The construction of the snow pillow is an attempt to solve the problem of a continuous study of snow accumulation throughout the winter. The pillow consists of a flat circular rubber or plastic container filled with anti-freeze liquid. Snow that falls on this "pillow" will increase the pressure of the anti-freeze within the container and this pressure can be either directly measured in a stilling well (by a normal recording gauge) or by a transducer, an electronic pressure-sensing device. The data from a snow pillow will give the time and amount of each snowfall during the winter with a detail that cannot be obtained by any conventional snow survey. Even decreases in the

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*This statement is based on the assumption that the temperature of the firn is at melting point. Such conditions are generally assumed to be valid for glaciers in temperate areas. (The conditions of additional accumulation are, however, completely different for a "cold" glacier in the Arctic.)

Table for Snow Density Calculations

Valid for cylindrical snow sampler, diam. = 7.27 cm.
(Cross-sectional area 41.5 cm^2). Length of sample = 10 cm.

Weight	Density	Weight	Density	Weight	Density
100	0.241	400	0.963	700	1.687
110	0.265	410	0.988	710	1.712
120	0.289	420	1.012	720	1.735
130	0.314	430	1.036	730	1.759
140	0.338	440	1.060	740	1.783
150	0.361	450	1.084	750	1.807
160	0.386	460	1.108	760	1.832
170	0.410	470	1.132	770	1.856
180	0.434	480	1.156	780	1.879
190	0.458	490	1.181	790	1.903
200	0.482	500	1.204	800	1.928
210	0.506	510	1.229	810	1.952
220	0.530	520	1.252	820	1.976
230	0.554	530	1.277	830	2.000
240	0.578	540	1.301	840	2.023
250	0.602	550	1.325	850	2.048
260	0.627	560	1.349	860	2.072
270	0.651	570	1.373	870	2.097
280	0.674	580	1.397	880	2.121
290	0.699	590	1.422	890	2.143
300	0.723	600	1.446	900	2.169
310	0.747	610	1.471	910	2.191
320	0.771	620	1.494	920	2.215
330	0.796	630	1.518	930	2.241
340	0.819	640	1.542	940	2.264
350	0.843	650	1.567	950	2.290
360	0.867	660	1.591	960	2.313
370	0.892	670	1.614	970	2.338
380	0.916	680	1.639	980	2.362
390	0.940	690	1.663	990	2.385
				1000	2.410

If snow sample is not 10 cm, multiply by the following factor

length cm	factor
2	5.000
3	3.333
4	2.500
5	2.000
6	1.667
7	1.428
8	1.250
9	1.120
11	0.908
12	0.833
13	0.769
14	0.714
15	0.667
16	0.625
17	0.588
18	0.566
19	0.527
20	0.500
21	0.476
22	0.454
23	0.435
24	0.417
25	0.400
26	0.385
27	0.371
28	0.367
29	0.345
30	0.333
31	0.323
32	0.313
33	0.303
34	0.294
35	0.286
36	0.278
37	0.271
38	0.263
39	0.256
40	0.250

snow pack during the winter (caused by evaporation or snow drift) will be recorded; such information will not normally be obtained by other methods. For further details on snow-pillow installation, necessary corrections for temperature variations and other sources of error, see Beaumont (1965^a and 1966^b) and Penton and Robertson (1967). See also p. 106.

7. Recording data and completion of forms

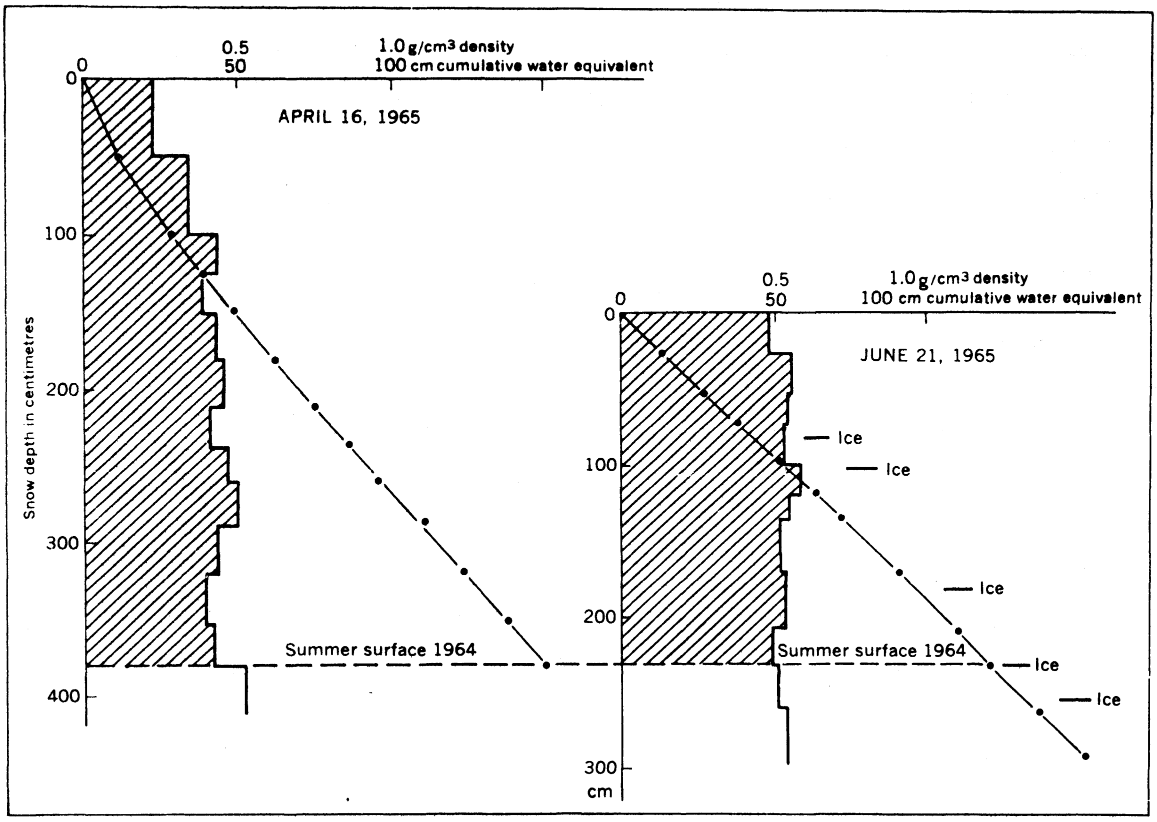
In this section data forms for snow pit work and core drilling will be described together with a table for snow density calculations.
It is essential that the forms are completed in the prescribed manner.

a) The snow pit form

On this form, the first three columns should be completed at the pit. The next three columns are for calculations and the last column is for remarks. The following should be observed when the form is used:

1. Fill in the name of the glacier, the date etc., in appropriate space on the top of the form.
2. Column No. 1 should show the depth as measured from the original snow surface to the lower end of the snow sampler (i.e. to the horizontal steel plate mentioned above). Note that this column will show the total depth measured. If possible, use a hanging tape fixed at the original snow surface.
3. Column 2 shows the actual length of the snow sample or, more correctly, the vertical distance between the positions of the horizontal steel plate. It is important that the distance be measured before any snow is removed to release the snow sampler. Note that the actual length of the snow sample obtained in the steel cylinder might be somewhat less, as snow may compact during the sampling procedure. The cumulative value of figures in column 2 should agree with the figures shown in column 1.
4. In column 3 record the net weight of the sample (deduct the weight of any bag which is used in the weighing procedure).
5. Calculations necessary to complete column 4-6 can be simplified using a table that shows the density for a sample 10 cm long. If a snow sample is not 10 cm the obtained density must be multiplied by a factor. As such tables give only the density to be placed in column 6, further calculation must be made to obtain the figures necessary for columns 4 and 5. The inner diameter of snow samplers is seldom exactly the same, so various tables should be constructed for each.

   Note that the water equivalent for each sample is placed in column 4 and that column 5 shows only the cumulative value of the figures in column 4. - A sample form is included in the appendix.



Place Glacier, Birken, British Columbia. Density diagrams (shaded) obtained in pits dug at the same location (elevation 2,440 m) in spring and in mid-summer. The dots show the cumulative water equivalent versus depth. During the first part of the summer the density of the snow had increased, partly by settling and partly by refreezing of melt water in the snow pack. The total water equivalent, however, decreased in the same time interval from approximately 150 cm to approximately 125 cm of water.

A diagram showing the variations in density with depth must be constructed as well as a diagram for the cumulative water equivalent versus depth. Both diagrams should be plotted on the same graph paper and an example of a combined diagram is shown among the illustrations.

b) The coring drill form

This form is a little more complicated than the snow pit form but follows the same format with the following exceptions:

1. Column 1 shows the depth as measured from the original snow surface to the lower end of the auger. This can be measured along the drill extensions or on a probe carefully lowered into the hole.

2. Column 2 shows the distance of the drill between each sample, and is calculated as the difference between the depth of each sample.

3. Column 3 shows the actual length of the sample measured when it is removed from the auger. This length will normally be slightly less than the distance between sample depths. It can also happen that the sample has to be trimmed at the ends to make a proper cylinder.

4. Column 4 gives the net weight of the snow sample.

5. Column 5 shows the volume of sample. This figure can be obtained by multiplication of the cross sectional area with length of sample. There is no standard size coring auger and consequently no standard table has been constructed to calculate the sample volume.

6. Column 6 shows the density of the snow sample. Note that this is an actual density, calculated from the weight and volume of the snow sample (which is generally shorter than the drill penetration). This figure should be used when plotting the depth/density diagram (the depths taken from column 1).

7. Because the figure in column 7 is a subjective judgment made in the field, it is extremely necessary that the column is properly completed. Parts of a sample can be lost and thus no actual density measurements obtained for parts of the snow pack. The missing part might have the same density as the previous snow sample, or the same density as the next sample, or it might originate from a layer of very loose and light snow which cannot be sampled.

   Any decision is difficult to make, but when using a drill the operator may feel when he is drilling in heavier snow and when he is penetrating loose snow. The decision must therefore mostly be based upon the working conditions when the snow sample is taken.

   The cumulative value of figures in column 7 must agree with the figure in column 1.

8. Column 8 expresses the water equivalent assumed to be present in the area indicated in column 7. Note that this figure is the adjusted water equivalent and not the actually measured value for the individual snow sample.
9. Figures in column 9 are the cumulative values of figures in column 8, and can be directly plotted in the diagram.

8. Winter survey

Some glaciers in maritime areas will receive such a large amount of snow during the winter that the stakes may be completely buried during the accumulation period. As the stakes are often used as reference points for navigation on the glacier, it is desirable to keep them visible throughout the winter. Furthermore, in areas of very large snow accumulation it may be difficult to measure the total thickness of the snow pack at the end of the accumulation season. Therefore, one can divide the total accumulation measurements into smaller units, i. e. measure the accumulated snow at selected time intervals during the winter and simply add the results at the end of the accumulation season. This demands some visits to the glaciers during the winter.

It is not possible to apply this theory to all the snow-depth soundings. However, the method can be considered for the density measurements, performed in pits as described previously in this chapter. This is most time-consuming and laborious work and it is recommended that pit studies should be included when glaciers are visited in the winter for stake extensions.

At the end of the melt season a crust will generally develop on all snow surfaces in the upper part of the glacier. Last winter's snow will have partly recrystallized during the summer, rock particles and plant fragments may have blown onto the surface, so that it has become more or less grey in colour. The snow has been transformed into firn (defined as snow that has survived one melt season) and this firn has got a "summer surface" (defined as the border or division between the firn and the succeeding winter's snow fall. The summer surface will normally form a relatively stable crust that can be easily detected with a probe, even through a heavy snow pack. All accumulation measurements are aimed at the determination of the water equivalent of the snow resting on top of the summer surface. The summer surface is therefore an extremely important reference plane for all mass balance investigations. If this crust is poorly developed due to unfavourable weather conditions in the summer, it may be necessary to mark its position by artificial means.

A thin layer of powdered dye or sawdust or chicken wire have been used with success on various glaciers. This marked surface must be made large enough to be easily found later in the accumulation season, but it should be placed so that it does not influence the stake readings the following summer. An area measuring 3 x 3 m should be placed 10 m from the stake in a down-stream direction from it. If this standard distance is always used, the winter crew can easily dig down to the surface and find it, even though a small error should be made in the distance and direction determination.

At the first winter visit, preferably when approximately 2-3 m of snow have fallen, a pit should be dug down to the summer surface (either the natural "dirty" summer crust or the artificially marked surface). Snow-density measurements in the pit will give the total water equivalent for this snow pack. If the snow surface is then marked by sawdust or similar material, it will facilitate the work at the next visit to the glacier, as the second pit may be dug only down to this surface. Information about the lower part of the snow pack has already been obtained at the first visit.

It is obvious that extending the stake is very important, as regards the stake that identifies such a pit location. If the stake is completely buried, the above-mentioned surfaces are lost and it will be necessary to dig all the way down to the previous summer surface. For glaciers in maritime areas they may be buried 5-10 m by the end of the winter. Even snow-density measurements with the coring auger (see section 4 above) may be difficult to perform in areas with such heavy snow accumulation. It is therefore important to follow the meteorological conditions throughout the winter, so that the winter visits can be made at times suitable for stake extensions.

ABLATION MEASUREMENTS

1. General

Glacier ablation comprises all material which is removed from the glacier by melting, calving, evaporation or wind action (Ahlmann; 1948, p. 26). The most important factor on mountain glaciers is melt, most of which occurs on the surface. Wind action is negligible and evaporation is dominant only for short time periods during the spring. The amount of material lost by evaporation is commonly only a fraction of the material which is removed from the glacier by melting. Investigations of the relationship between the many factors, the influence of meteorological parametres (air temperature, wind speed, humidity, radiation etc.) is extensively described in the literature and is not dealt with in this manual. (See, par example, Wallén, 1948; or Hubley, 1957).

The total amount of material lost from the glacier during the summer is called total ablation and it can best be obtained from observing the relative lowering of a large number of points on the glacier surface. (Ablation within or under the glacier ice is negligible compared with the melt on its surface). Changes of surface elevation can be measured by photogrammetric means and this method is still used to measure the volume change at a large number of glaciers in Europe and in North America.*

The annual variation in a glacier's mass results from both accumulation and ablation and is defined as the glacier's mass balance. (A negative balance means that the glacier volume has decreased; a positive balance that it has increased).

> Note: The terms used in this kind of investigation have been defined in a discussion of glaciological mass balance terms by Meier (1962) and later revised by him. According to decisions made at the Berne Meeting of the International Commission of Snow and Ice in 1967, these revised terms should be used in all future glacier mass balance studies. A list of the terms and their definitions is being printed by UNESCO, see Meier (1969) and the short description given in the appendix. The revised terms have been generally adopted for use in this manual.

Information on ablation can be obtained from the position of the snow-line (the lower border of last winter's snow cover) at the end of the ablation season. However, under equal melting conditions it will be situated higher in a year of less accumulation, and it is difficult to base calculations of total ablation on this concept. But a series of photographs showing the position of the transient snow-line throughout the summer will be extremely valuable support in the construction of ablation maps. Such photographs should therefore be taken by the field crew at 7-10 day intervals from suitable fixed points.

2. Stake readings

Lowering of the ice surface can be measured directly by comparing the

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* For a number of Canadian glaciers, terrestrial photogrammetry has been used by the Water Survey of Canada to determine volume changes of the tongue. However, as this method only covers the lower part of the glacier, a figure for the total balance is not obtained. The mass balance for the glacier over a period of several years may be obtained by photogrammetric means only if the entire glacier is photographed at the beginning and at the end of the period. The annual variations, however, are more difficult to determine by this method, as the accuracy is not sufficient to give results within the error limits normally accepted in mass balance studies.

visible length of a stake in a given time period. Example: A stake inserted in the ice has only 20 cm visible, but one month later it extends 120 cm above the ice surface. This means that 100 cm of ice has disappeared and this represents an ablation of approximately 90 cm of water equivalent.

To obtain valid comparisons, all stake readings must be made in the same manner and some "rules of thumb" must be followed:

a) For stakes drilled into ice:

A measurement is taken from the top of the stake down to the glacier surface and recorded to the nearest cm. The top of a stake is always easy to locate, whereas the glacier surface might be very uneven and difficult to determine accurately. To avoid large variations due to uneven topography, the ice surface should be defined by an ice axe placed on the ice touching the stake and resting in a direction perpendicular to the ice flow. If an ice axe is not available any straight rod or plank approximately 1 m in length can be used.

b) For stakes drilled in ice which is still covered by snow:

A measurement must include the visible length of stake (i. e. from the top to the snow surface defined similar to the ice surface above) and the snow depth. The snow depth is measured with a snow probe as outlined in the previous chapter. The probe is pushed down vertically in at least three places within 1-2 m of the stake. The arithmetic mean of these soundings is used for the snow depth figure at this location* and is noted on the stake form. (See further below, under office procedures).

At the beginning of the ablation season the glacier ice is relatively cold and percolating melt water will refreeze at the ice surface to form superimposed ice (Schytt, 1949). Superimposed ice will disappear later in the summer, at least on lower parts of the glacier. It must, however, be taken into account when short-term studies are made of ablation variations. The amount of superimposed ice can be calculated from stake observations and must be shown on the stake forms.

c) For stakes in the firn area:

Stakes in the firn area are not normally supported in a solid mass similar to stakes drilled into glacier ice, some artificial support must be

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*As snow depth alone does not give information of the water equivalent it will be necessary to determine the snow density from time to time. See previous section about pit studies.

used so that the stake does not sink into snow or firn. See previous section describing techniques of inserting stakes! If a stake is not supported it must be expected that it will suddenly start to sink at any time during the summer and all subsequent readings will be false.

If a stake has an efficient support at its base the following measurements should be made at each reading:

1. Length from stake top to snow surface in cm.
2. Snow depth from the present surface to the previous summer's crust. This measurement is performed by a snow sounding stick and the summer crust identified by feeling a hard layer at or near the expected depth, based upon previously made observations. (Compare accumulation measurements in the area). However, formation of numerous ice layers within the snow pack might confuse measurements of snow depth. An ice layer can easily be taken for the previous summer's crust and the measurement would be worthless. To overcome this difficulty it is generally possible to make a snow depth measurement to a plate previously placed on the summer surface. The stake form (see chapter about office procedures) will give information whether a plate is present or not.

Variations in snow density already mentioned in section b above will also apply to the snow cover in the firn area and consequently the snow density must be determined several times during the summer so that the water equivalent of the snow pack can be calculated.

d) Special stake chains or wires inserted in a hot point drill hole:

As mentioned previously, in areas of great ablation stakes may be replaced by a stake chain (or a wire) frozen vertically in the ice in a very deep hole made by a hot point drill. These stake chains or wires will not be visible until the snow has disappeared and readings will give information of ice ablation only. Reading a stake chain or a wire is basically identical to reading a normal stake. The length of the stake chain or wire from its free end to the ice surface corresponds to the normal distance from the top of the stake to the ice surface. The only difference is that a considerably higher number may appear in the stake form if the stake chain or wire is several metres long.

To locate a stake chain or a wire on the glacier surface, it is advisable to insert a normal stake and mark it with a flag, or to tie the upper end of the wire to a small wooden construction (a tetrahedron) that can be seen from a distance.

3. Completing the stake diagram

All stake readings should be recorded so that the data can easily be processed in the office. This can be done by transferring the data from the field note-book to special stake forms, on which all observations concerning one and the same stake for the whole summer season are collected. The completion of the stake form will be described in a following chapter about office procedures. To avoid making simple mistakes in the handling of the data, it is strongly recommended that the field crew should construct a stake diagram that will give them a continuous picture of the conditions at all stakes on the glacier under observation.

In the stake diagram (see illustration) time is plotted along the X-axis and stake elevations along the Y-axis. Furthermore, the variations in the glacier surface, as measured from the top of the stake, are plotted so that surface lowering or ablation is shown as a descending line and accumulation as an ascending line. A horizontal line indicates that the balance between observations has been zero, or that accumulation and ablation have been equal at the stake. In normal cases a surface lowering will occur during warm periods in the summer. As ablation is greater in the lower part of the glacier than in the upper part, this will be shown in the stake diagram as different slopes of the lines. On the contrary, if a snow storm causes material to accumulate on the glacier, it is likely that more snow is falling in the upper part of the glacier than on the tongue. There, it may happen also that the precipitation is falling as rain which, in such cases does not produce any accumulation at the stake. Stakes in the same elevation interval will normally show similar trend in the surface variations and the curves for these stakes will be more or less parallel. Therefore, if stake readings have been made erroneously, or data has been interchanged, this can be detected immediately by inspection of the stake diagram.

On the stake diagram shown, it is obvious that an interchange of readings was made for stakes 27 and 30 on July 22nd, or some incorrect figures were obtained on July 17th, when also stake 25 showed anomalous conditions. In the latter case all other readings indicate definitely that ablation has taken place since the last reading but in the case of stake 25 the stake diagram indicates an accumulation. This is most unlikely, and a check of the figures in the note-book should be made and, if possible, the stake should be re-read.

The stake diagram should be plotted by the field crew immediately after each reading at the stakes, so that anomalous conditions can be checked at once. The stake diagram has proved to be a most valuable guide for the field crew in their continuous observations of the ablation during the summer. If the stake diagram shows "normal" conditions throughout the summer for all stakes, it is most probable that the readings have been made correctly and that the results are reliable. However, the stake diagram cannot be used directly to calculate the actual ablation at various stakes, as the surface lowering may have been caused, to some extent, by snow densification and settling. The amount of ablation expressed in centimetres of water equivalent, can only be calculated when the stake readings proper are compared with variations in the snow depth and the snow density at the stake location. This is dealt with in a following chapter on office procedures.

4. Pit studies at the end of ablation season

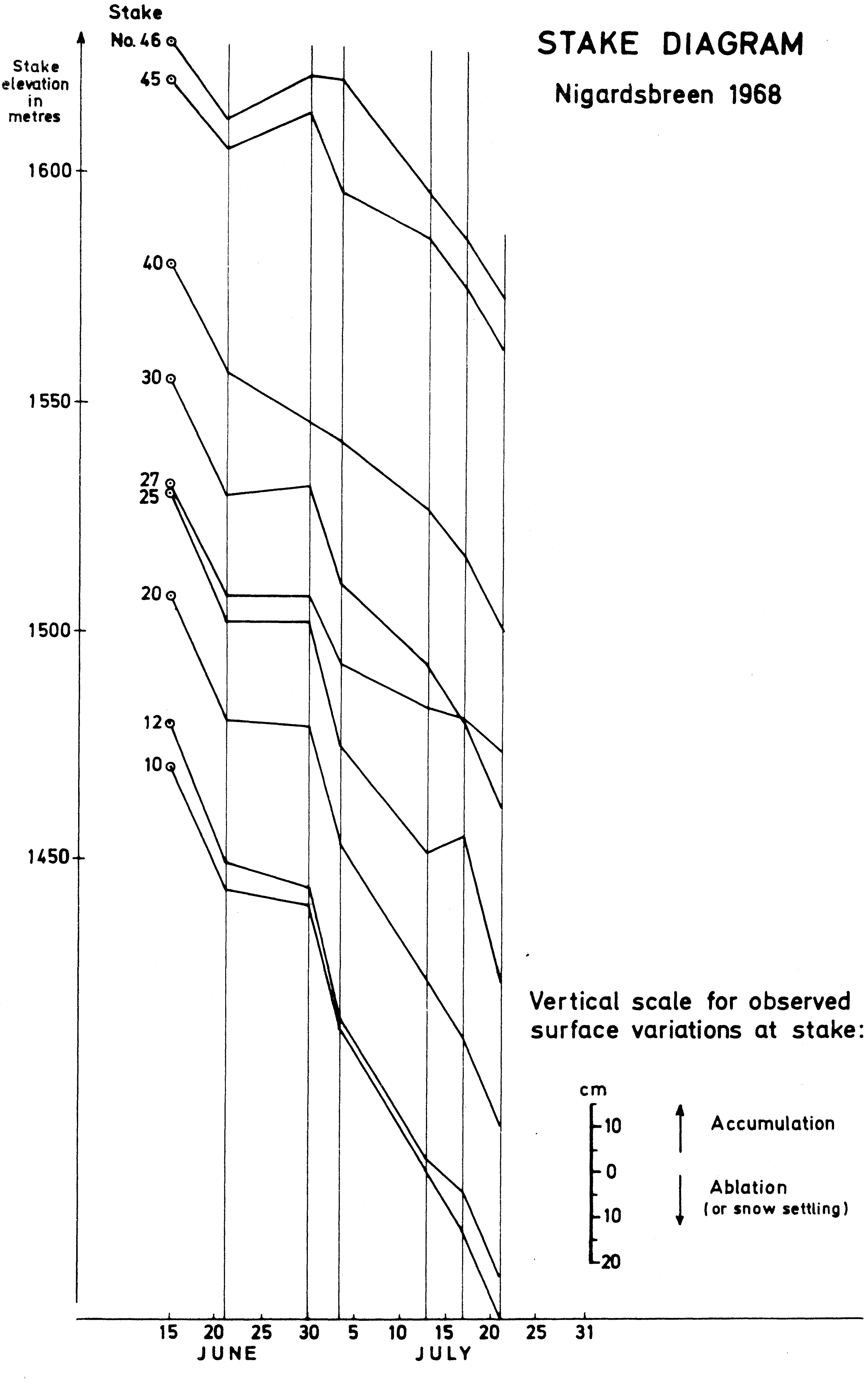
The total ablation must be determined at the end of the ablation season. On the glacier tongue this is easily determined from stakes where the entire winter accumulation has disappeared and glacier ice exposed. In the upper part of a glacier, normally, only a part of the winter's snow will disappear and it will be necessary to determine the water equivalent of the remaining snow. Depth soundings may be difficult if the boundary between the winter's snow cover and previous year's firn has been obliterated or obscured during the summer. However, recognition of the summer surface can probably be made in pits, and this work will be greatly facilitated if layers of sawdust, dye or other materials were placed at the bottom of a pit in the spring. If stakes in the firn area are inserted so that the lower end rests on the previous year's summer surface, the thickness of the remaining snow can be readily observed, even when snow depth soundings are impossible to obtain. The density of the remaining snow cover, however, must be observed in pits redug at locations where the summer surface has been marked. The technique of measuring snow density has been described in the chapter on accumulation measurements.

5. Transient snow-line observations

At the beginning of the melt season the total glacier surface is normally covered by snow that has accumulated during the previous winter. Bare ice may be visible only on small, convex parts of the glacier or in crevassed areas. When melting starts, the snow will normally first disappear on the glacier tongue. The lower border of last winter's snow is called the transient snow-line. This border will continuously move to higher elevations during the summer and reach its highest position at the end of the melt season. This highest position of the transient snow-line will normally (or, more correctly, in years when the glacier's balance is 0, i.e. when it is in a "steady state" condition) be located very close to

STAKE DIAGRAM

Nigardsbreen 1968



Vertical scale for observed surface variations at stake:

the equilibrium line. At the equilibrium line proper the ablation is exactly equal to the accumulation.[*]

The position of the transient snow-line throughout the summer depends on both the rate of melt and the original amount of snow deposited on various parts of the glacier. Information about the location of the transient snow-line during the summer will therefore be a valuable guide in the compilation of an accumulation map. A record of the snow-line migration can be obtained by different methods:

(1) Sketch the transient snow-line in the field on a glacier map throughout the summer season.

(2) Note the position of the transient snow-line with reference to stakes at each reading, e.g. "snow-line is 50 m upglacier from Stake 32".

(3) Take black-and-white photographs from selected points, so that the location of the transient snow-line can be plotted on a glacier map for each week or 10-day period throughout the summer. These photographs can then be used together with the sounding data (obtained in the spring), when the accumulation map is constructed.

The photographic stations should be selected in such a way that large parts of the glacier can be seen, as well as suitable reference points. Photographs must be taken from the same stations and accurate records must be kept, giving all details of the photographs (date, station number, direction, etc.).

PLOTTING AND CONTOURING

Most of the data from glaciological mass balance studies are processed graphically and some of the basic methods should be mentioned briefly in this manual. It is desirable that most of the preliminary data processing is done in the field, in order to obtain the final results as quickly as possible, so they can be readily published.

1. General

All accumulation and ablation measurements as well as some meteo-

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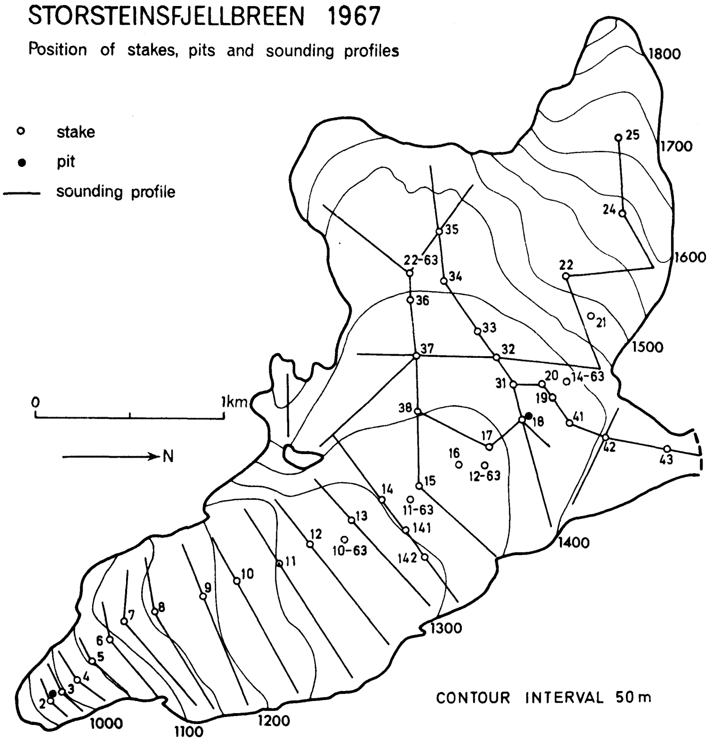
[*] As superimposed ice is a part of the glacier's accumulation there may be a small vertical difference between the equilibrium line and the highest position of the transient snow-line in a balanced year on certain glaciers. For most "temperate" glaciers, however, this difference is only an academic question, unless the glacier surface is very flat in the equilibrium zone.



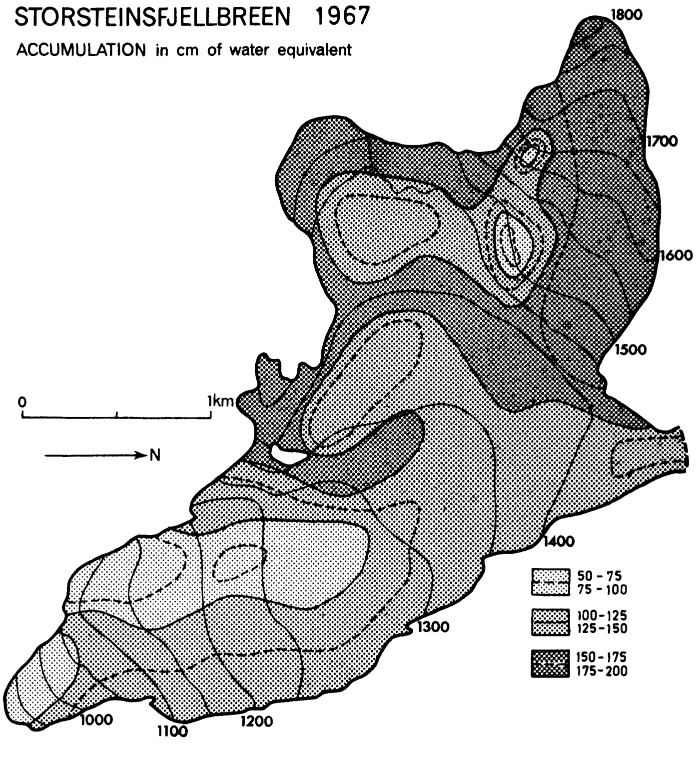
STORSTEINSFJELLBREEN 1967

Position of stakes, pits and sounding profiles

EXAMPLE OF THE CONSTRUCTION OF A WINTER BALANCE MAP

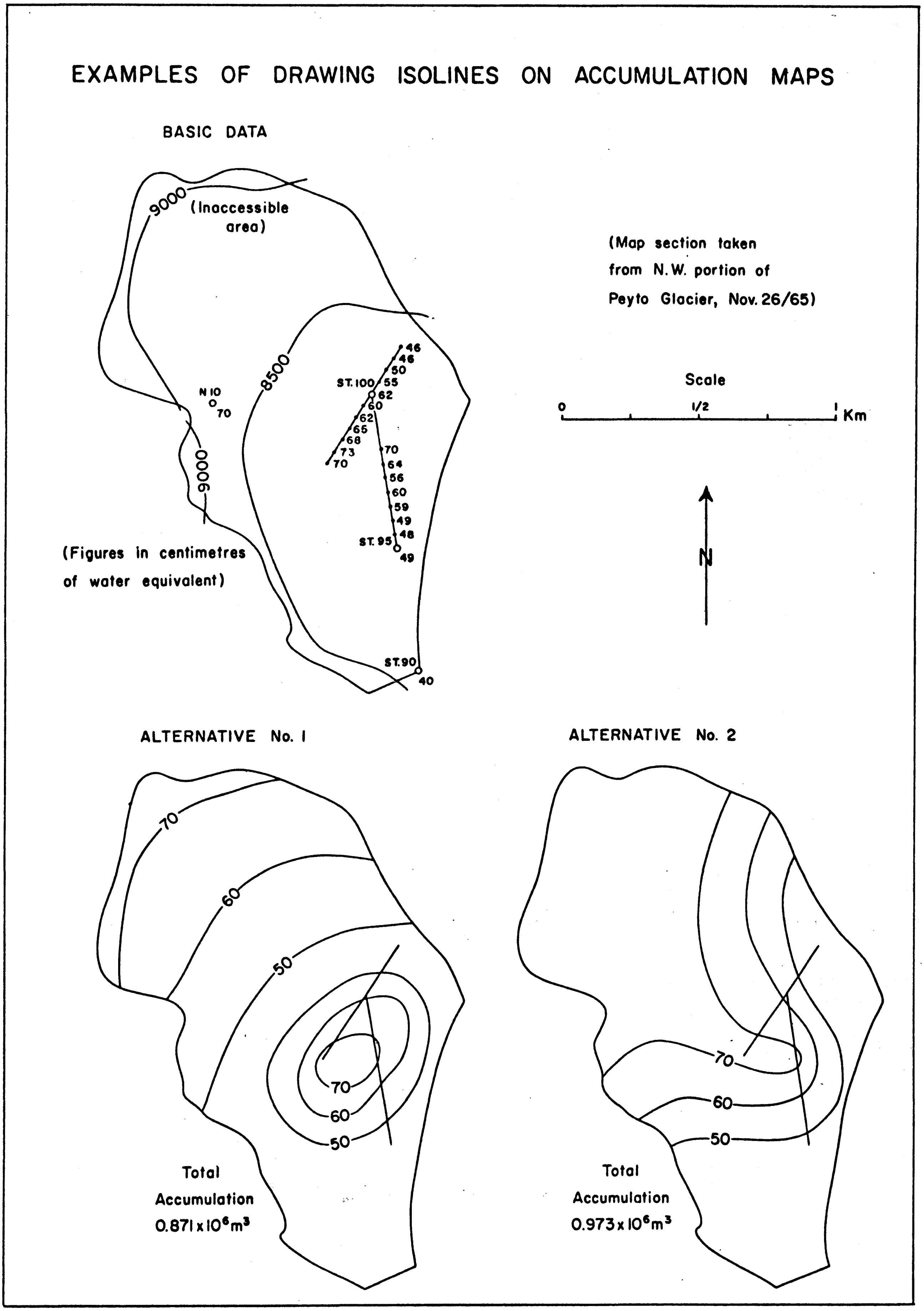
Snow depth soundings were performed with 50-m intervals along profiles shown on the upper map. In all, 190 depth figures were obtained, and their water equivalents calculated from density measurements in pits.

Iso-lines were drawn for selected water equivalent intervals (75, 100, 125, 150, etc., cm of water) and, after shadowing, the map of winter balance (earlier termed accumulation map) is ready for publication.



STORSTEINSFJELLBREEN 1967

ACCUMULATION in cm of water equivalent



EXAMPLES OF DRAWING ISOLINES ON ACCUMULATION MAPS rological results (see below) should be plotted on a large scale map of the glacier. A scale of 1:10,000 with 10 metre contour intervals has been recommended. Such maps will normally be required for field use and a sufficient number of copies must therefore be supplied before the field work starts.

For the accumulation map the positions of the main stakes should be marked together with all sounding profiles showing the location of all snow depth soundings, which are given in actual snow depths and their water equivalents. Isolines should then be sketched to divide the glacier into areas of selected accumulation intervals. Example: Isolines could be drawn between areas that have accumulations of 100 cm, 150 cm, 200 cm etc. of water equivalent. The interval between the isolines must be selected for each particular glacier, as it might be necessary to decrease or increase the intervals if the accumulation is unusually small or large. An example of a completed accumulation map is shown among the illustrations.

Similarly an ablation map should be constructed. The ablation is more closely related to elevation and isolines will in many places almost follow contour lines on the map, although exceptions might result from shadow effects of mountains etc.

2. Ambiguities

When isolines are constructed it may be necessary to decide between two or more different possibilities, and the resulting map will for most alternatives give almost the same result for total accumulation or ablation. But for some choices the difference can be considerable and an example is shown among the illustrations. (Compare also an interesting paper by Dodd et al., 1965). If an ambiguous situation is discovered before the crew leaves the glacier a sufficient number of additional readings must be taken in the doubtful area. For this reason it is absolutely necessary to plot results immediately in the field.

A contoured map can be used to calculate the total accumulation or total ablation, respectively, using a planimeter in the manner described in recent reports on mass balance studies (Østrem, 1966). This work will normally be done in the office after field season. See also a following chapter about office procedures.

3. Use of colours on manuscript maps

Contour lines will normally be drawn on base maps to show areas of equal accumulation, ablation, etc. Practice has shown, however, that such maps are improved considerably by use of colours. Coloured maps will serve as a base for further calculations (such as area measurements by planimeter) and for drafting purposes. They will generally not be directly reproduced, but are considered as manuscript maps.

A standardized and consistent use of colours will facilitate future work on the manuscript maps, and therefore the following system should be used whenever possible:

0 - 50 cm water equivalent : yellow
51 - 100 " " " : light red or pink
101 - 150 " " " : light green
151 - 200 " " " : light blue
201 - 250 " " " : orange
251 - 300 " " " : grey or brown
301 - 350 " " " : dark red
351 - 400 " " " : dark green
401 - 450 " " " : dark blue

METEOROLOGICAL OBSERVATIONS

1. General

In order to correlate ablation and run-off with meteorological conditions, field crews will take daily weather observations. The observations consist of a few relatively simple readings which should be made at all glaciers. In addition, some more advanced observations might be added when detailed studies are desired. Only the basic observation program is dealt with in this manual.

The time of observation has been chosen so that it will not hinder glaciological and hydrological field work, i.e. observations should be made early in the morning and in the evening. However, to obtain data that are comparable with data collected at permanent meteorological stations, it is desirable that the observation time is simultaneous and the field crew should take the observations at the same time as the main weather stations in the area.

The basic observations are those of air temperature, humidity, precipitation, cloud cover, wind direction and wind speed. At some stations even incoming and outgoing radiation or hours of sunshine may be observed. The glacier ablation is greatly dependent upon variations in meteorological parameters; in some areas more energy is transferred to the glacier surface by warm and moist air masses than by incoming radiation. In other areas radiation may be the most important factor.

As many of the meteorological parameters are inter-related, one cannot postulate that any one of them is more important than the others. However, experience has shown that air temperature (which in most cases is dependent upon incoming radiation) is closely correlated with the ablation, so that temperature observations should be considered important in cases in which only a limited observation program can be carried out. It is therefore proposed to give the temperature observations a high priority. In maritime areas wind speed measurements should also be given a high priority.

Precipitation is normally measured in a standard precipitation gauge, but measurements at a single point will normally not be representative of the whole catchment area or the whole glacier. Therefore, it is necessary to instal more than one precipitation gauge; a cheap solution to this problem is described below.

To obtain reliable figures for daily mean temperature, a recording instrument (preferably a thermohygrograph) should be installed in a Stevenson screen near the base camp. A second screen should, if possible, be placed near the equilibrium line on the glacier or in the firn area.

The daily mean wind speed can be obtained by a counting anemometer. This instrument gives the total wind distance (in miles or kilometres) so that the daily mean wind speed can be easily calculated. This figure is more useful than spot measurements of wind velocity made by a hand-held instrument or similar device.

2. Air temperature measurements

The thermohygrograph should be placed in the Stevenson screen immediately after the crew's arrival at the base camp. Charts are normally changed each Monday morning when the clock is wound and the pen filled with recording ink. The thermohygrograph registration is checked every morning and evening by simultaneous observation of the pen and the standard mercury thermometer placed in the screen. These two figures are noted on a form. Furthermore, a check of the clock is made by making a "time mark" every morning. Discrepancies between the time mark and the correct time are used when the chart is processed (see below). The calibration screw on the instrument could be used to adjust the instrument to as correct a temperature as possible at the beginning of the season but the adjusting screw should then not be touched during the season.

3. Cloud cover

To estimate the amount of incoming and outgoing radiation it is valuable to know the total amount of cloud cover (expressed in tenths). The daily mean cloud cover should be estimated for each day and if the cloud cover changes considerably during the day this should be mentioned on the form, and also whether the clouds are low, medium or high altitude. It is, however, not expected that the observer should have a complete knowledge of different kinds of clouds, but in case he has such knowledge, a sufficient space is available for notation on the meteorological forms.

4. Precipitation

Precipitation is measured at the base station by a conventional precipitation gauge. In addition to this instrument, which is permanently installed, it is necessary to make a number of observations at various points within the basin to obtain reliable data for a calculation of the total amount of water originating from precipitation. This can be arranged by placing small rain gauges of the Pluvius type [*] on the glacier and on adjacent ground. This little rain gauge is fairly accurate for observations of liquid precipitation and probably for wet snow as well. Snow must be melted before the measurements are made. Precipitation occurring as dry snow will often be blown past the gauge by wind and readings will not be reliable. During the summer, however, most of the precipitation will be in the form of rain, so it is anticipated that the observed "Pluvius-values" will be reliable.

Daily precipitation observations will normally be made only at the camp or in its vicinity, whereas precipitation for several days may be collected in more distant gauges.[**]

It is advisable, however, to visit all rain gauges as regularly as possible, to facilitate calculations connected with comparison between runoff, ablation and precipitation. Ideally, all rain gauges (and all stakes on the glacier) should be read after every major rainstorm, or at least every 5 days.

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[*] Manufactured by Nyströms Bläckkärls-fabrik, Torshälla, Sweden, for less than $ 2.00 each.

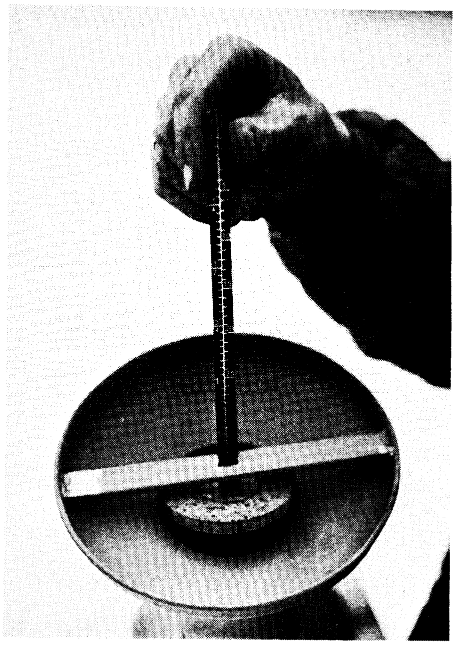
[**] During cold periods it is necessary to use glycerin or anti-freeze liquid to prevent collected rainwater freezing in the gauge. A known amount (corresponding to a few mm of rain) should be placed in the gauge, and corrections in readings made accordingly.

THE "PLUVIUS" RAIN GAUGE

The "Pluvius" rain gauge has a collecting area that is five times the storing cylinder. Thus, each millimetre of rain precipitation will be "enlarged" five times on the scale.

A circular cork float, with a diameter almost equal to the inner diameter of the storing cylinder, hinders the water from evaporation. The vertical scale, fixed to the float, will show the amount of collected water as millimetres of rain. Note: The scale on the lower picture has also a division giving the precipitation in inches.

The "Pluvius" registers normally up to 35 mm of rain.



If heavy precipitation has occurred, the rain gauge may overflow and intermediate readings are therefore necessary.

The total amount of rain water must be calculated for the whole catchment area by plotting all single gauge observations on the map. Assuming each gauge represents a separate area, the total amount of water can be found graphically. Precipitation maps can be made for the whole summer or for each rain period, and the total amount of rain water can be found by methods similar to those used for accumulation maps. Examples of precipitation maps are shown among the illustrations.

5. Wind direction and speed

Observation of wind direction should be made every morning and evening; they are most easily made in connection with the temperature readings in the screen. The direction from which the wind travels is noted as well as the number (showing miles or kilometres) shown in a little window in the anemometer. The difference between the present figure and the figure that was noted the day before (if given in miles, this must be converted into kilometres*) must be multiplied by 1000 and then divided by the number of seconds between the two observations. Thus, the mean wind speed will be obtained in m/sec.

If no anemometer is available, the wind speed must be estimated. To facilitate this estimation, a feather or a small piece of paper may be allowed to travel a known distance in the wind and its speed calculated roughly. Such an estimation should preferably be made several times a day to obtain the daily mean wind speed.

6. Field processing of meteorological data

Meteorological observations must be summarized for each week, and the field crew will process all temperature charts and calculate daily mean temperatures as well as number of positive degree days. It is also desirable that the total amount of rain water is calculated as indicated in previous section, but the temperature summaries are the most important and must have priority.

As soon as a chart is completed and taken off the thermohygrograph the air temperature for each hour is read from the chart (corrected for errors in the clock mechanism and for temperature discrepancies, as found by the two daily comparisons with the mercury thermometer). A special form has been developed for this work. When the form is completed the daily

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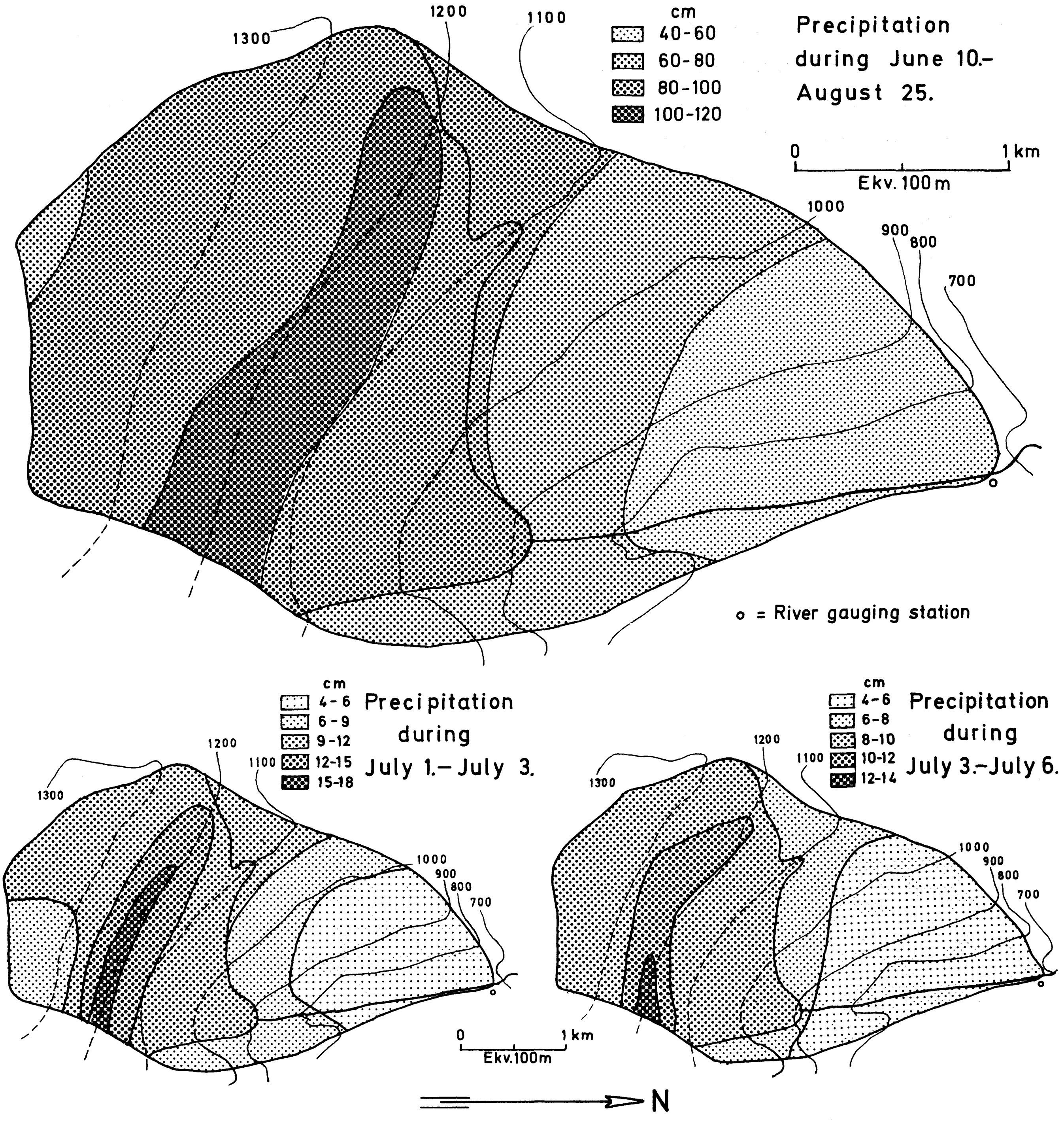
*One mile equals 1.60934 km.

Part of ÅLFOTBREEN 1966



EXAMPLES OF PRECIPITATION MAPS

The lower two maps demonstrate the amount of rain falling in the glacier basin at Ålfotbreen, W. Norway. All "Pluvius" gauges - numbering more than 20 on a total of 8.6 km^2 drainage area - were observed after two main rainstorms in 1966, and iso-lines drawn for selected values in each case.

On the upper map the total precipitation is shown for most of the summer season. Note that all maps show a similar precipitation distribution pattern - most rain was defintely falling at about 1200 m a.s.l. that season.

The total volume of rain water can be found by measuring the various areas on the map. This calculation is desired to check the discharge past the gauging station. The discharge should approximately equal the sum of ablation and precipitation in the basin.

mean temperatures should be calculated and the chart attached to the form and filed. At the end of the season both the form and the chart must be returned to the Head Office for further processing.

The number of positive degree days is calculated as follows: All the figures for positive temperatures is noted for each hour and totalled (negative temperatures omitted); the sum divided by 24 to give the number of "positive degree days" for that day. Such calculations must be made for each day throughout the summer. The resulting figure will coincide with the daily mean temperature if the air temperatures are above $0^{o}C$.

WATER DISCHARGE MEASUREMENTS

1. General

The water draining froma glacierized basin originates from mainly three different sources:

(1) glacier melt
(2) rain falling on the glacier
(3) rain falling on the glacier-free parts of the basin

Apart from some water loss to the atmosphere through evaporation, (or, in humid areas, water gain by condensation) the sum of the measured ablation on the glacier and the total volume of rain water (found by calculations described in a previous chapter) will be discharged in the glacier stream. To check short-term ablation measurements, it is necessary to measure the water discharge as accurately as possible.

The glacier stream also transports most of the material originating from the glacier's erosion. A continuous observation of the sediment content in the river can therefore be used to study the amount of material eroded beneath the glacier under different conditions. See also the next chapter.

Discharge calculations are generally based upon water-level readings on a vertical gauge or on data from an automatic water-level recorder. The relation between the water level at a given site and the actual discharge (expressed in m^3/sec) must be determined by a large number of direct measurements of the river flow for different gauge readings to obtain a graph of levels vs. discharge, the rating curve, for each measuring site.

It is anticipated that the river discharge conditions will not be disturbed by changes in the river bed. The cross-sectional area should ideally be controlled by bed-rock and the vertical gauge placed in a little pool above this bed-rock control. If the channel is changed, the rating curve is no longer valid and a new curve must be constructed, i. e. a new series of direct discharge measurements must be made.

Direct measurements of water discharge can be obtained in many ways. For streams with "laminar flow" a standard current meter can be used to measure water velocity, but this method is difficult to use in glacier streams because they are highly turbulent. Turbulent streams can be measured using colourimetric methods but this is not recommended if the sediment content is high. It is preferable to use a method which is independent of the sediment content in the water, such as the "salt method". In this method (or in a similar method using soluble radioactive compounds), an agent is poured in the river in one point and, at another point downstream, the dilution will be a measure of the water discharge.

All direct discharge measurements are difficult to perform without training and specialized equipment. Therefore the methods will not be described in detail in this manual. For a closer description, see Østrem(1964).

As soon as a rating curve has been established all future gauge readings can be easily transformed to discharge figures. However, if the river cross section changes or the gauge is moved relatively to the river bed, it is obvious that a previously obtained rating curve will no longer be valid and a new series of direct discharge measurements will be necessary to establish a new rating curve. It is therefore important that the crew observe conditions in the river and check the position of the gauge several times during the summer. This must be done by a levelling instrument, see next section.

2. Stream gauges

A gauge is a vertical rod marked in metres and centimetres and placed so that the height of the water level can be measured on it. The gauge should be placed at a location in the river where the water is as tranquil as possible. A pool in bed-rock may be the best site to erect a gauge and the gauge must be located so that both a small discharge and a very large discharge can be measured directly. In some streams, however, it may be necessary to use one gauge for very high levels and another gauge for the lower water levels, but is must be ensured that one and the same water level in the pool is always reported as a reading on the lower gauge. The zero point (the lower end of the gauge) should be levelled relative to three fixed points in bed-rock, installed to give identical readings. The reason for using three fixed points in bed-rock is a security measure if any of the points should be destroyed or become inaccessible.

In the fall or when the water discharge is very low it is necessary to determine a reading on the gauge that corresponds to zero water discharge (i.e. generally the height of the threshold in the pool). This reading gives important information for construction of the rating curve.

3. Number of readings

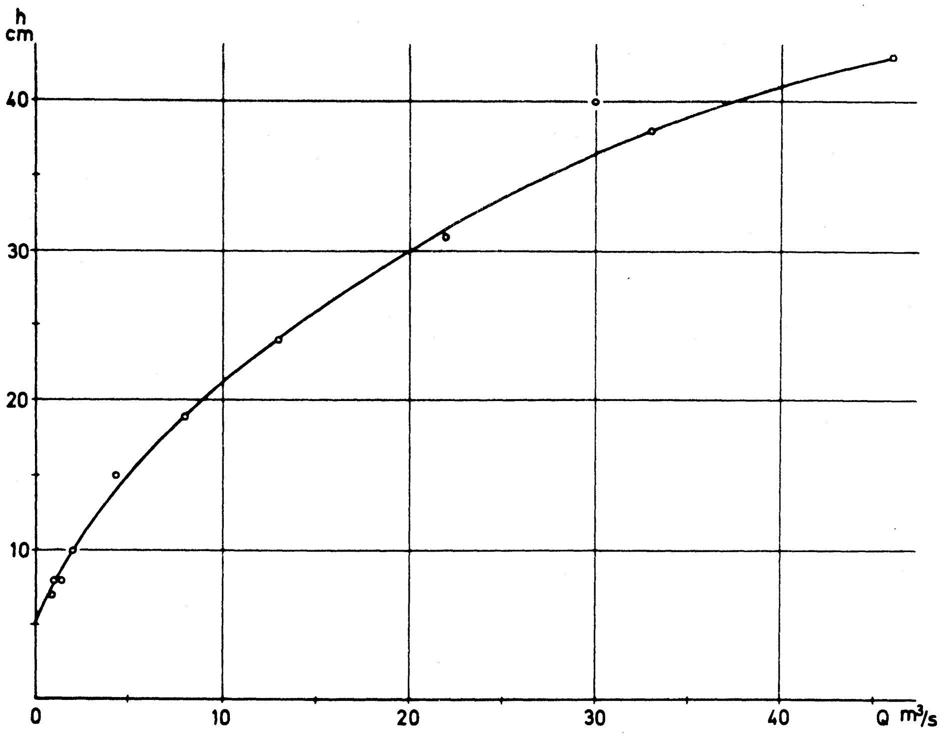
Water discharge in glacier streams is normally subject to great daily variation, so to obtain accurate information about the total discharge numerous readings must be taken throughout the day and night. However, for streams without an automatic gauge the crew may not have sufficient time to make the necessary measurements at all times. This difficulty can be partly overcome if frequent gauge observations are taken for a number of days and the variations in discharge during these days are considered representative for other days when few readings can be made. From experience obtained during the summer it will probably be possible to draw curves showing water level variations in the river based upon readings taken only three or four times a day. Two readings must be made in the morning (one as early as possible, another before departure for field work) and two readings in the afternoon or evening (one immediately after return from field work and another as late as possible). If the crew is not out for a full day's field work or weather prevents outside activities, additional readings should be made during the day.

Shortly after heavy rainfalls or during periods of very high temperatures a river will not follow the normal pattern so frequent observations become essential. Under special circumstances when extremely high discharge is expected the gauge must be observed every half hour.

4. The automatic gauge

To overcome the difficulties described in the previous section, an automatic gauge can be installed. This installation, however, is relatively complicated and is not dealt with in this manual. In principle, the automatic gauge consists of a float, a counter-weight and a recording device. Variations in water level move the float and the counter-weight and the movement is transferred to a pen that registers the movement on paper wrapped on a drum. The drum is rotated by a clock and one rotation may be completed in 24 hours, one week or a month. For glaciological use, especially during the summer, when great variations occur, the one-week type will probably be the most suitable. Maintenance of the instrument is very similar to that of a thermograph. The chart should be changed when necessary as in the case

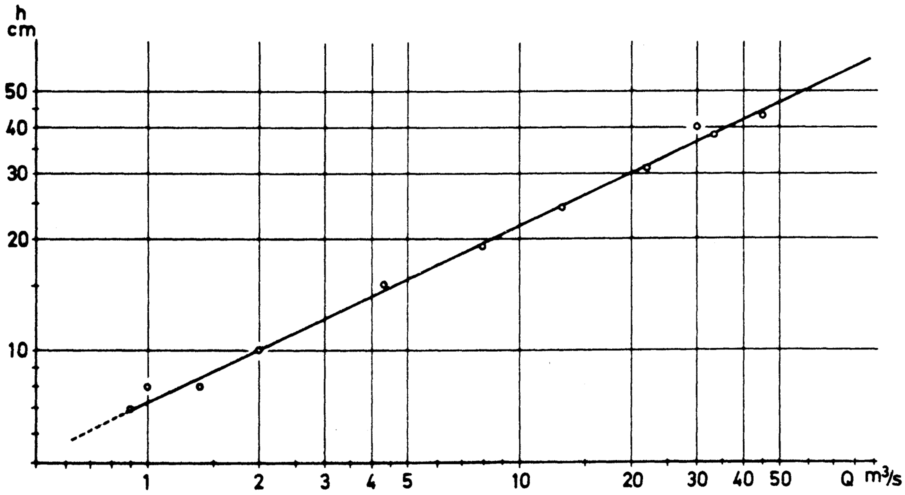
RATING CURVES



Linear plot

Observations

Water level h (cm)	Dis-charge Q (m³/s)
7	0,9
8	1,0
8	1,4
10	2,0
15	4,3
19	8,0
24	13,0
31	22,0
40	30,0
38	33,0
43	45,0



Logarithmic plot

of the thermograph. Every time the chart is changed and, if possible, once or twice in between, the water level, as read on the vertical gauge, should be written directly on the chart together with information about date and time. This check is important when the chart is used for calculations of total water discharge.

As the charts from an automatic gauge give information about water level (cm) it is necessary to convert the data into discharge figures (m^3/sec) before further calculations are made. For such conversions, see the discussion about the rating curve in a previous section.

5. Calculation of discharged water volume

Calculations of water volume discharged in a given time interval can only be calculated if a rating curve has been established. From the readings on the gauge (the vertical scale) or from the automatic gauge chart, it will be possible to calculate the water discharge for any given time. If the water level shows rapid variations within short time intervals (compare the chart from a thermograph), it may be necessary to calculate the amount of discharged water for each hour or for even shorter intervals. When the water level shows small variations, i. e. when the river discharge is fairly constant, periods of several hours can be used for the calculation. Experience has shown that a 6 hour period will generally be sufficient.

For each selected period, a mean water level should be determined, The corresponding water discharge is found from the rating curve (or from a table giving figures for corresponding water levels and discharges). It is anticipated that this discharge will be representative of the period and the total volume of water will be found by a simple multiplication.

Where necessary, the volume of water discharge should preferably be calculated for the following 6-hour periods: 0000-0600, 0600-1200, 1200-1800 and 1800-2400 (midnight). The greatest discharge will probably occur in the last two periods and special attention should be given to possible variations within them (see above concerning discharge calculations during shorter periods). The results of these calculations should be recorded on summary forms (see sample form included in the appendix). The sum of the discharged water volumes in the above-mentioned 6-hour periods is called the daily discharge. Variations in daily discharge may later be compared with meteorological parameters, such as daily mean temperature, daily precipitation, etc. by computer techniques. See a following chapter about office procedures.

MEASUREMENTS OF SUSPENDED MATERIAL

1. General

Glacier streams transport a great load of sediment (silt, sand, gravel, rocks and boulders) that results from glacier erosion. Part of the material is carried in suspension, and some of it is moved along the bottom. The sizes of the particles that can be moved by the stream at various water velocities are not dealt with in this manual. See further Hjulstrøm (1935), Sundborg (1956) and others.

The bed load is only a relatively small part of the total material transport in the stream, and good information about the rate of glacier erosion can therefore be obtained by taking samples of the river water, analysing it for its content of suspended material and calculating the sediment transport. The bottom transport of fragments, including boulders, is difficult to observe and, until methods for its determination have been developed, it will be necessary to estimate the size of this transport. The amount of suspended material moved by the stream is easier to determine, as it can be calculated from known water discharge and laboratory analysis of water samples.

Results of sediment studies will not only give valuable information about glacier erosion under various conditions but also indicate the possible rates of sedimentation that can be expected in reservoirs and lakes along rivers from glacierized areas. Natural or artificial lakes are greatly affected by sedimentation and - in the case of water utilization - the capacity of storage dams will gradually be reduced. The smaller fractions which pass through the lakes and reservoirs will - in the case of water-power stations - drastically increase the wear on turbines etc. Studies of sediment transport in glacier streams have direct practical importance.

2. Location of sampling site

Water samples should be taken as close to the glacier as possible but below any confluence of melt water channels that originate from the glacier. Sampling site should be selected anywhere the flow is turbulent so that the sample can be regarded representative of the total discharge past the site at the time of sampling. This means generally that the sample should be taken just below a small waterfall or in a section of extremely turbulent water.

Where the flow is not turbulent the sediment concentration in the water will be a function of the depth and generally the highest concentration is found close to the bottom. Under these conditions it is necessary to take several samples at various depths or to use a depth-integrating sampler. In the latter case water samples from various depths are continuously collected in one and the same bottle to give a representative sample. This sampling technique is not easy and it is strongly recommended that sampling should be made where the river water is highly turbulent.

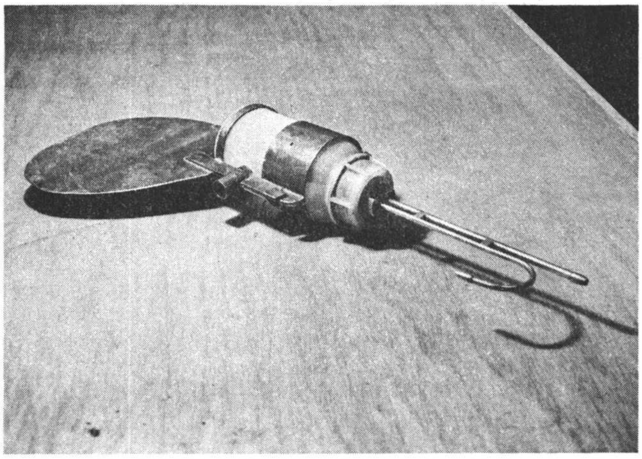
3. Sampling method

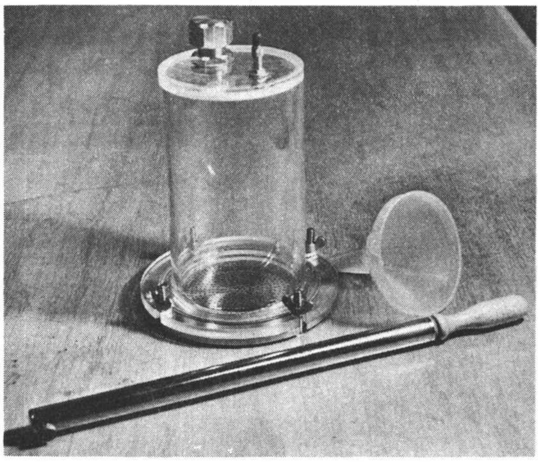
Numerous water samplers have been designed but most of them are developed for use in streams of laminar flow and are not suitable for highly turbulent streams. Experience has shown that a simple method - a bottle is lowered into the turbulent water and raised immediately after filling - is probably as good as using any complicated water-sampler. It is important that the bottle should be raised immediately after it has been filled with the river water, otherwise additional sediment will enter the bottle (Hjulström, 1935, p. 386). The size of each sample should be 1 litre, but most bottles readily available are not calibrated to this volume, so it is necessary to measure the exact volume of the sample. The volume of the water sample must be noted on the form, where all sediment sampling data are collected.

4. Filtering

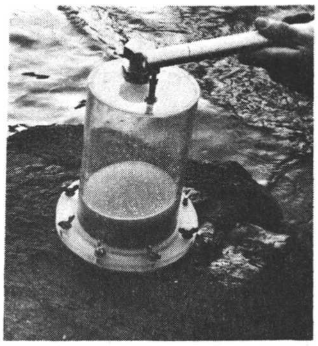
The water sample must be filtered in the field, so that only one filter paper with sediment particles originates from each sampling. This filter paper will be further processed in the laboratory, (see below). The filtering procedure should be carried out in a suitable place where no additional material can blow into the sample or filtering equipment. A tent without a floor may be used for this purpose. The filtering can be done either by pouring the water into a funnel through a filter paper, allowing the water to soak through the paper, or by pressing it through the filter paper. In the latter case, the filtering procedure takes only a few minutes for a 1-litre sample. When using funnels, it may be practical to construct a simple stand by drilling holes in a wooden plank. All water from each sample should be poured into one funnel and passed through one filter paper. Great care should be taken so that samples are not interchanged.

Bottles generally contain more water than can be placed directly in the funnel. It is therefore necessary to pour water in the funnel in small amounts and the complete process may take almost 1 hour for one sample. For samples with high sediment concentration it may take even longer due to sealing effects on the paper surface. The filtered water (leaving the funnels after passing the filter paper) should be completely clear. If it is not, it must



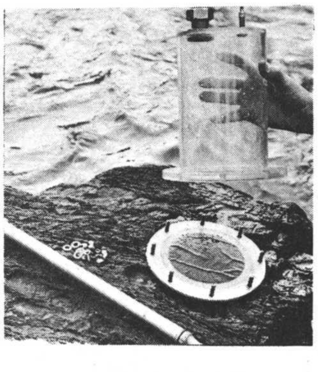


DEPTH-INTEGRATING SAMPLER
and
FILTERING EQUIPMENT



In laminar streams, a representative water sample can be obtained by a depth-integrating sampler, (upper picture).

The pressure-filtering equipment consists of a plastic cylinder with a perforated metal bottom. A water sample is poured into the container after that a filter paper is placed on its bottom. The pressure is raised with a bicycle pump so that the water is pressed through the filter. A 1-litre sample can be processed in a few minutes.



be re-filtered through a denser filter paper.

For most normal water samples any quick filter paper may be used and a Swedish paper (Munktell No. 00) has proved to be adequate. If very fine fractions are present, a denser paper must be used (Munktell No. 0A or similar) but, as such paper is slower in filtering, it should be used only when it is deemed necessary.

In pressure filtering devices the whole sample is poured into a plastic container and the water is pressed through the filter paper by raising the air pressure above the water. This is easily done with a bicycle pump. The pressure should not be increased too far as the filter paper may tear or the container be damaged. Normally a 1-litre sample can be filtered within a few minutes.

After filtering, one should check that all sediment which may have settled in the bottle is included in the sample. To rinse the bottle, only sediment-free water—ideally distilled water—should be used. The filter paper is left to dry in the air and is then wrapped and placed in an envelope marked with the sample number and other pertinent data. Only one filter paper must be placed in each envelope, but several envelopes from one day's sampling may be collected and transferred to a larger plastic bag.

Information about all samples should immediately be transferred to a standard form on which the sample number and other data should be noted. See specimen form included in the appendix. The form should be completed in duplicate, one copy inserted in a separate binder, the other packed together with the samples. All samples noted on one form should be packed together with it in the same plastic bag. This particular detail is necessary for a proper handling of the samples in the laboratory.

At the end of the season all sediment samples should be packed together (including the above-mentioned forms) and brought to the head office for laboratory analysis. Samples must not be sent by mail or freight but brought personally by a member of the field party as hand luggage.

5. Numbering of samples

A special numbering system has been developed for sediment samples. Each number consists of eight digits, the first four indicate the date, the last four the time of the day when the sample was taken. Example: 13071145 means that the sample was taken on July 13 at 11.45. In this system the day is divided into 24 hours so that number 03082000 indicates a sample taken on August 3 at 20.00 hrs in the evening.

On the form all samples should be noted in consecutive order together with information about the sample volume, water discharge and significant information of conditions at the time of sampling. Such information may be of interest especially under unusual weather conditions (heavy rain, thunderstorm, etc.). As soon as one form has been completed, it should be packed together with the samples, so that no confusion occurs.

6. Laboratory procedures

This section describes an ashing procedure that was originally tried out in the Institutes of Geography at the Universities of Uppsala and Stockholm, Sweden. For several years many thousands of sediment samples from glacier streams have been processed uniformily, so it is strongly recommended that the same procedure should be followed to allow comparisons of the results.

In addition to the traditional ashing procedure, experiments have also been made with methods that do not include ashing. Filtering, drying and weighing the paper (with corrections for the weight of the filter paper) and the use of membrane filters and suction pumps have been tried. The results showed fairly good agreement with data obtained by the ashing procedure except in cases of very low sediment concentration, when the moisture in the filter paper caused unexpected large errors.

When they arrive at the laboratory; all samples should be checked, as regards sampling place, so that no confusion may arise between samples from different areas. The samples from one and the same location should generally be handled consecutively and the results transferred to a laboratory form or a diary. The laboratory work is briefly described in the following numbered paragraphs:

(1) A number of empty porcelain crucibles with lids should be weighed. The crucibles should then be placed in an ashing oven and kept at a temperature of 700°C for two hours. After cooling off, they should be weighed again to ensure that no weight differences appear. For new and unused crucibles, the weight will normally change slightly during this first procedure.

(2) One filter paper is placed in each crucible.

(3) One crucible at a time should be carefully heated by a Bunsen burner so that the paper starts burning. To enable the smoke to escape, the lid should be placed so that is covers only part of the crucible.

(4) After this procedure, i.e. when the smoking has almost ceased, the crucibles should be placed in the ashing oven, with the lids covering them completely. The temperature should be raised to 600-650°C.

(5) After two hours at this temperature, the crucibles should be transferred to a drying oven and kept at 105°C until they can be processed further.

(6) An appropriate number of crucibles, still containing the ash, should then be transferred to a desiccator and from this they should be moved one by one onto an analytic scale. The crucibles are weighed as quickly as possible, as the moisture in the air will immediately tend to change the weight of the dry ash. As a test for possible errors originating from humidity, some crucibles should be moved back to the drying oven and the procedure should start again at stage (5). No error larger than 0.2 mg can be accepted.

(7) The ash is removed from each crucible by a suitable brush or similar device, and the empty crucibles are then weighed again. To check that they have not changed their original weights (see paragraph (1), it is important that each empty crucible should be weighed each time it is used. The weight varies almost continuously, due to humidity changes.

(8) The gross and net weight of the crucibles as well as the weight of the ash should be plotted on a form or in a suitable table in the laboratory diary. From the information about the original volume of the water sample, the sediment concentration (expressed in mg/l) should be calculated. From the information about the river discharge at the time of sampling, the sediment transport (expressed in g/sec) should be calculated. Both the sediment concentration and the sediment transport should be given in the final report from the laboratory.

Note: If the oven temperature rises above the above-mentioned temperature, carbonates will easily start to decompose and a too small sediment content may be obtained by this analysis. On the other hand, if the temperature is too low some organic components will not be completely removed from the samples. However, when samples are taken close to a glacier there should be no risk of having too much organic material in the river water.

SURVEYING - HINTS FOR FIELD CREW

1. General

Glacier maps are being constructed for all the investigated areas as a base for plotting results, indicating stake locations and other data. For initial studies the provisional maps were enlargements of existing small scale topographic maps, but it is planned to replace them with more accurate maps constructed from air photographs. Where air photographs have not been taken it will be necessary to survey the glacier by conventional methods, but this will not be a task of a field party based at the glacier. However, it is desirable for crew members to become familiar with the area to help in surveys carried out by a visiting party. Vantage points overlooking large parts of a glacier should be marked in a manner so that they can be identified on vertical photographs. Furthermore, if photography is expected during the same summer, an additional number of key positions on the glacier should be marked (see below).

2. Selecting fixed points

Points on bed-rock or on stable ground overlooking large parts of a glacier and a number of other points should be selected. Access to these fixed points should not be too difficult but in special cases it will be necessary to locate a fixed point on a mountain peak. If crewmembers visit such a point they should build a cairn on the first possible occasion and mark it with a flag mounted on a vertical pole (aluminum poles for this purpose will be available at the camp). If the mountain peak is very steep and undoubtedly the highest point within an area of several hundred metres' radius, it is not necessary to mark this point further with cairn or flag. For all other points, however, it is necessary to mark them so that they will be clearly visible on air photographs (see below) and can be easily identified and used for ground triangulation.

3. Marking fixed points

Pieces of white cloth one yard in width and at least 5 yards in length should be placed in an L with the inner corner of the L at the selected point. White paint is better than cloth, and it could be applied in a similar pattern on the ground. If bed-rock is not exposed it is acceptable to move boulders into some suitable pattern. Note however, that when the painted area is seen from above it should form a continuous white surface. Approximately 2 quarts of white paint are required to make one such mark.* In places where space does not allow an L to be marked on the ground another pattern might be used such as a triangle or a square. Note however, that in the air photographs a painted mark can easily be mistaken for a natural spot so any shape selected should not be natural. (The L shaped mark described above is probably the least natural shape).

4. Marking points on the glacier

It would be of great value if the main stakes or at least the most important are marked so that their position can be directly recognized and plotted from air photographs. Prior to air photograph the following procedures should make stakes visible on the photographs:

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*When the ground is painted for aerial photography it is advisable also to paint the top of the cairn so that it can be more easily recognized.

a) On the glacier ice:

Stakes on the glacier ice will normally not be visible on the air photographs unless taken from a low altitude. Large flags however, might be visible on photographs and therefore it is recommended that large pieces of cloth be attached to each main stake. If the glacier is very dirty a white flag should be used; if the glacier ice is comparatively clean a dark colour should be used. Either the flag itself or its shadow (or both) might then be recognized on the phtographs.

To facilitate recognition of stakes their locations might be indicated by two rows of boulders placed at the glacier ice radiating in straight lines out from the stake. The directions should be chosen so that they do not coincide with the natural ice pattern (cracks, crevasses, bluebands, surface streams, etc.).

Due to surface melt it will be difficult to keep all the rocks in the right position for a long time and adjustments must be made frequently. It is therefore advisable not to try and mark too many stakes in the ablation area. It is better to mark one or two and keep the markings in good shape throughout the summer.

b) In the accumulation area:

Locations of stakes in the firn area are marked by powdered dye or lampblack distributed on the snow surface in a circle around the stake. A circle is established by means of a 10-metre rope attached to the stake. The dye powder is sprinkled in the circle making a very thin layer approximately 1 m broad. Two or three pounds of lampblack or about 5 pounds of powdered dye will be sufficient to make a complete ring. If time is short or only limited amounts of dye are avaiable a half circle may be sufficient.

During the summer dye will increase the snow melt but it will still be clearly visible from above except when it is covered by new snow. The rings must therefore be inspected and reinforced during the summer and kept visible until it is certain that air photographs have been taken. No dye should be sprinkled near the stake as this will disturb the normal rate of ablation at the stake.

5. Supplementary ground control

As a horizontal check for the scale in the map construction at least two distances between outstanding points should be measured with a tape. The distance can be measured between two stakes that are marked with dye in the firn area, or between two points near the glacier tongue. (Large, single rocks on the glacier, a hut or similar outstanding features on the ground might be used). The horizontal distance, at least 200 m, should be measured as accurately as possible and all information about the selected points and the results of the measured distance should be recorded.

ACCOMMODATION

1. General

At glaciers where long-term observations are planned, it may be practical to erect small semi-permanent buildings, instead of using tents for the accommodation of the field crew. This chapter deals with two types of simple and easily erected buildings:

1) houses for accommodation and
2) garages or buildings for storage etc.

Both types have the same original design - a wooden framework (2" x 4"), nailed together as triangles with almost equal sides and covered with lumber and roofing paper on the outside; in the case of the house it is insulated and also covered with lumber on the inside. The design has been made as simple as possible, to make it easy for unskilled personnel to erect the buildings. The original design is by Mr. Wibjörn Karlén, a Swedish glaciologist. The uninsulated type is suitable for storage buildings and may serve as a garage for snow vehicles. The triangular construction with no side walls (only two triangular end walls) has proved to be very stable and will withstand extremely high wind velocities, provided that it is tied to the ground by strong guy wires. The building may be erected in the field by the crew and some hints may help in the construction. The following sections will give some details about this work.

2. Building site and foundation

When the location for the huts is being selected, it will be valuable to know something about the snow conditions at the site in wintertime. The huts should preferably be placed on bed-rock that is exposed throughout the winter or sited at a place where only small amounts of snow collect. This is to avoid an unnecessary load from snow accumulation on the construction and to allow easy access to the huts all the year round. On the other hand, if the snow vehicle is to be used in summertime (which is normal practice on most glaciers), it is an advantage that a garage should be placed close to an area where snow remains all summer. Then the vehicle can be driven easily to and from the garage.

The bed-rock surface should be as level as possible to support the foundation, which is made of 4" x 4" lumber. At least two 4" x 4" beams should be used, but three or four are recommended, as they will give better support to the floor joists, especially if a heavy load is expected. The foundation beams should be placed parallel to each other and levelled. The floor joists joined to the roof rafters (thus forming a wooden triangle; see sketch) should then be raised vertically, resting on the foundation at right angles.

3. The framework

The 2" x 4" framework is joined together as follows. One floor joist is placed horizontally on the ground. Two roof rafters are also placed horizontally so that they form a triangle together with the floor joist. The corners of the rafters are cut so that they can easily be nailed to the floor joists at their lower ends and nailed together at their other (upper) ends. The lengths of the rafters should be equal to the lengths of the floor joists, thus forming a triangle with 60° angles. If a lower house is desired on account on unusual wind conditions, the rafters must be shorter. It is not recommended to build a higher house, unless in a very sheltered position.

When the first triangle has been completed, the rest of the framework is made by placing pieces of lumber for the next set on top of the first constructed triangle and cutting the pieces to the same size. Five complete triangles should be made for an A-frame hut of normal size. However, if wood is scarce, only three triangles could suffice, but the floor will be extremely weak and two extra floor joists will be necessary.

Two of the completed triangles are selected to carry the end walls. Vertical supports for window and door should then be nailed in their proper places in these triangles before they are erected. Pieces of 2" x 4" lumber can be used for these supports. The space between them and between the horizontal supports for the window will be determined from the size of the window and the door, respectively.

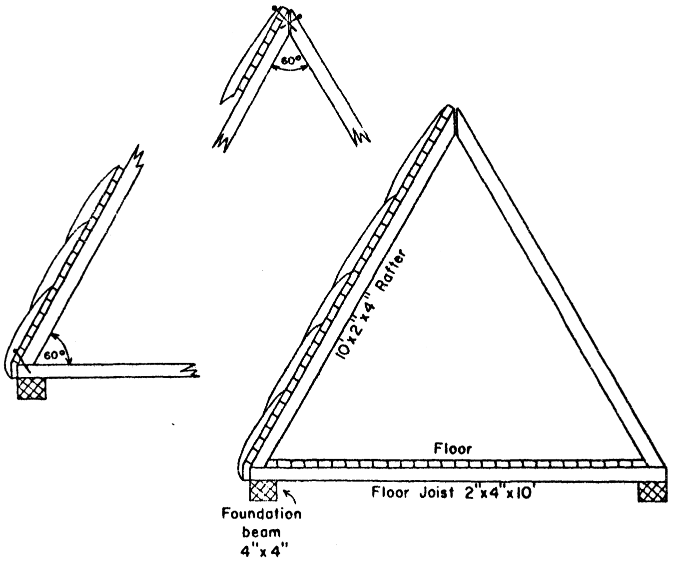
4. Roof and end walls

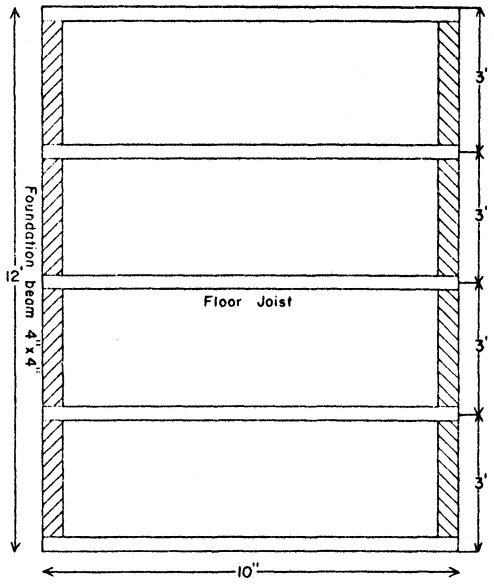
The roof consists of planks of rough lumber, preferably pre-cut to the same length as the distance between the end walls or 1'-2' longer. In the latter case the house will have a better appearance and the vertical end walls will be better protected. When the woodwork is completed, the whole roof is covered with heavy roofing paper.

The side walls are made in a similar manner to the roof, but each

A-FRAME HUT

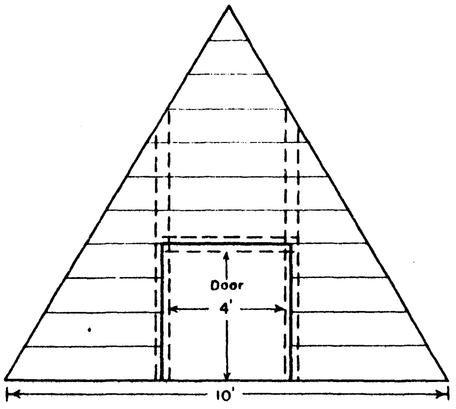
FRAMEWORK

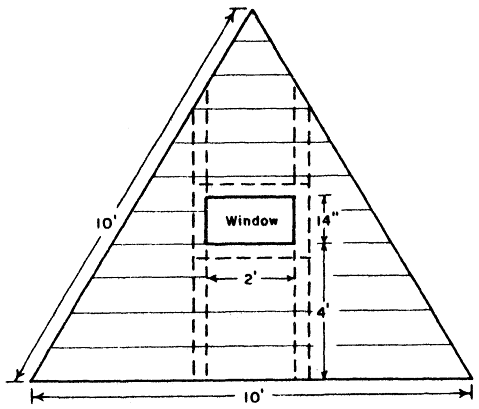




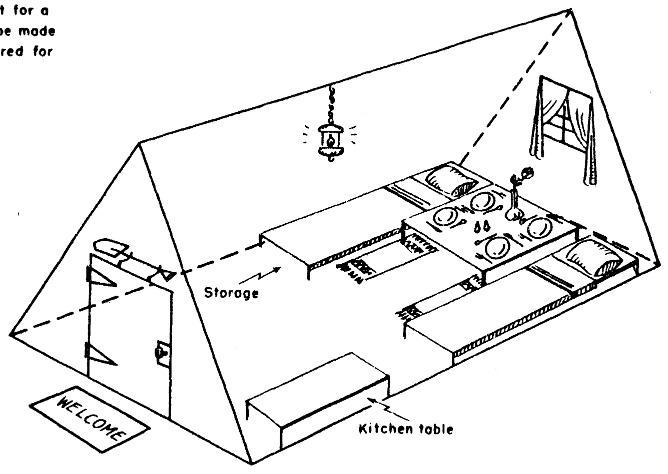
A-FRAME HUT

END WALLS AND PERSPECTIVIC SKETCH





NOTE: Size of door is sufficient for a ski-doo, but it might be made higher if hut is considered for accommodation.



plank must be cut at 60° angle to make a good join with the roof. Sufficient space must be provided for door and window. It is recommended that the end walls also should be covered with heavy roofing paper, and the walls can therefore be made of fairly rough lumber. It is advisable to pre-cut planks for the end walls to save transportation costs and time when the house is erected. Note, however, that every piece must then be numbered properly.

5. The floor

The best floor is made from 1" to 1½" planks with tongue and groove, to ensure a draft-free surface and to allow the planks to support each other when a heavy load is applied. These planks also may be pre-cut to equal lengths, but, owing to the framework construction, it will be necessary to adjust the lengths of some of them so that they fit properly inside the house.

For an insulated house, a support for the floor insulation and the insulation itself must be placed in position before the floor is laid.

6. Door and window

As the storage building is built to form a shelter for supplies or as a garage for a snow scooter it is not necessary that it is made completely air-tight so it is not necessary to make a complicated door. A sheet of heavy plywood or a number of planks nailed together will form a simple door. The door should fit the opening made in the vertical front wall or it may be made a few inches larger, so that it overlaps the opening. To ensure a sturdy construction, it should be mounted on three hinges. Two ordinary hooks can be used to close the door, one on each side. For the house, a conventional door is preferred to avoid drafts and to keep the inside free of drifting snow.

The window can be any kind of wooden frame window which can be squeezed into the opening provided in the end wall. To obtain tight joints between the window-frame and the wall, use a caulking compound or sheets of aluminum cut into suitable strips.

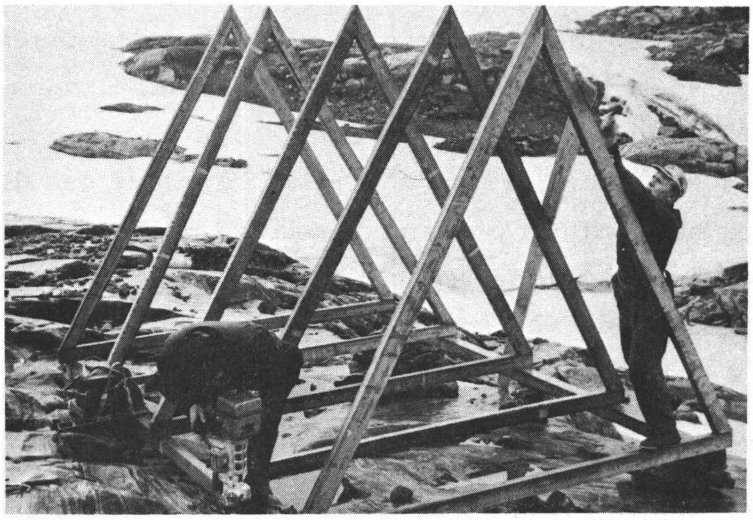
7. Outside cover, insulation, paint, etc.

To waterproof a hut, both roof and end walls should be covered with roofing paper of the best quality. The manufacturers' instruction for application should be followed, but, to prevent the roofing paper being torn off by high winds, each strip should be glued and nailed and a plank should be fixed along the edge of the roof after the paper has been laid and trimmed.

ERECTION OF AN A-FRAME SHELTER

The three pictures show various steps in the building of the A-frame shelter at the front of Vesledalsbreen, Norway.

(1) After that the foundation is laid and levelled, the roof rafters are cut and nailed together in the correct angle.



(2) The roof rafters are raised, nailed to the floor joists and provisionally held in position by a plank, diagonally fixed to the rafters. Holes for bolts are drilled into bedrock by a motor-drill. These bolts are used for the guy wires.

(3) Pre-cut roof and floor materials are nailed into position. This shelter is not insulated, and it was erected by two men in less than two days.

To strengthen the edge along the top of the roof and to protect the roofing paper from damage caused by the guy wires, it is advisable to fit a strip of aluminum or galvanized steel along the edge. At the outside corners, between the end walls and the roof, it is recommended that 1'' x 1'' (either square or quarter-round) flashing material should be applied to make the joints as tight as possible.

Insulation is placed between the outer roof (and the end walls) and the inner panel. Rockwool, foamed plastic sheets or similar materials are well suited for insulation. The thickness of the sheets should be 4'' at the maximum, as this will be the width between the roof and the inner panel corresponding to the size of the roof rafters. As panelling, 3/4'' planed boards can be used; plywood can also serve for this purpose, but lumber will normally have a better appearance and needs no painting.

8. Guy wires

The house must be anchored to the ground with wire cables or guy lines. Ideally, the cables should be fastened to steel bolts drilled into bed-rock near the corners of the house. However, if it is impossible to drill holes, or the ground consists of moraine material with no exposed bed-rock, dig a hole, attach a wire to a boulder and drop it into the hole. Fill up the hole with gravel and pile large rocks on top. The wire attached to the buried boulder should be long enough to form a loop 20-50 cm above the ground. The guy wires are then attached to this loop and tightened with turnbuckles.

One heavy guy wire across each end of the roof will normally be sufficient. But if strong winds are expected to confront the end walls, additional guy wires could be fixed at the top of the end walls. To tie these wires to the roof rafters, a small hole must be made in the wall.

9. Materials necessary for one complete hut

The size of the hut depends on its purpose. As a shelter for a skidoo, a 10' x 12' floor surface will be sufficient, and this size has been selected for some A-frame huts constructed at glaciers in western Canada. This size will also be ample for occasional use as accomodation for two people. The total cost of materials depends upon quality of lumber and location where the materials are purchased. The estimated cost in 1969 for the necessary material is $ 200-250 for a garage and some $ 150 more for an insulated house.

The materials necessary for a complete garage are given in the list below, but paint and materials for shelves, tables, beds, etc. have not been included. For a house, the inner panel, a conventional door and insulation must be added. The length of the guys will depend on local conditions, but 150 feet will probably be sufficient for most huts.

For roof: 1" planks, rough wood (grade 2 or 3)	300 sq. ft.
For front and end walls: 1" planks rough wood (grade 2 or 3)	150 sq. ft. = total 450 sq. ft.
For floor: 1" or 1½" tongue and groove (grade 2 or 3),	140 sq. ft.
Floor joists	5 lengths, 2" x 4" x 10'
Rafters	10 lengths, 2" x 4" x 10'
Door and window supports	4 lengths, 2" x 4" x 8'
Door, plain 3/4" plywood (for garage only)	4' x 4'
Finishing rod 1/4 round	140 linear ft.
Roofing paper	5 rolls (90 lbs. a roll)
Roofing nails 7/8" galvanized	8 Lbs. box
Nails (1000) 2" (gum nails, box coated)	5 Lbs.
Nails (300) 2½" (gum nails, box coated)	3 Lbs.
Hinges for door	3 pieces + screws
Door hooks and eyes	2 sets
Foundation	2 lengths, 4" x 4" x 12'
and, if possible, further	2 lenghts, 4" x 4" x 12'
Guy wire, turnbuckles, cable clamps:	quantity to be decided in each case, according to local conditions.

Experience has shown that this simple A-frame hut can be erected by two men in less than 2 days. The total weight of all necessary materials amounts to approximately 2,500 lbs.

FIELD ORGANIZATION

1. General

Many different glaciers will be investigated in the coming years and it is obvious that a large volume of data will be accumulated in these investigations. Much of the data must be processed in the field, so that results of mass balance measurements, meteorological data, etc. can be published without delay.

The office staff will handle many lists of data and, to avoid confusion, it is essential that all sheets of paper are marked with the name of the glacier and the year. In addition, each individual sheet must have some sort of title and the work initialled in the bottom right-hand corner. The senior crew member will be held responsible for marking sheets with the full title.

Example: Place Glacier 1969
Snow Pit Measurements

At the end of the field season the senior crew member will:

(a) Check that all data are adequately tabulated and summary forms completed.

(b) Ensure that all records reach the Head Office safely (not sent by mail or included with equipment that is sent as luggage).

(c) Leave at the glacier (in the hut) a copy of a map showing all stake locations, together with a list of the last readings (as made before leaving the glacier).

For most of the field observations and for the results of the data-processing done in the field, special forms have been developed and these standard forms must be used.

As a guide for future operations, it is vital to make a complete inventory of the equipment etc. that is left in the hut at the end of the field season. Special standard inventory lists have been developed for this purpose and the responsible senior crew member must ensure that these forms are carefully and correctly completed.

To maintain an atmosphere conducible efficient work the field crew should pay special attention to keeping all equipment inside and outside the houses in good order. Damaged materials should be repaired or, if irreparable, they should be discarded. In the latter case, a report of discards should be sent to the Head Office. All garbage should be burnt so that it will not attract animals (mice, squirrels, bears). The best method of garbage disposal is to build an incinerator of rocks or out of an old gasoline drum. The ash, unburned tins, etc. should then be buried in the ground. The toilet may consist of a pit dug in the ground. A small amount of chlorinated water or similar fluid should be sprinkled in the pit after use. It is strictly forbidden to throw garbage on the glacier, even in the firn area!

At the end of the field season there are several duties connected with the closing of the station. Full details are given in a following section.

2. Data, summaries and forms

All observed field data must be listed on standard forms. However, if it is more practical to make the field notations in a pocket-size note-book these notations should be transferred to the standard forms immediately after return to the camp. If the note-book is lost, only one day's observations will be missing. Under no condition should several days' notations be kept in the note-book.

To facilitate office procedures and to make possible a quick publication of the mass balance results, summaries of certain data should be made in the field. Summaries may be plotted as graphs but generally presented in tables. The stake diagram may serve as an example of a "graphical" summary (although this graph is mainly made to check the stake readings). Summaries made in the form of tables are: daily values of precipitation, mean temperature (corrected thermograph readings), maximum and minimum temperatures, relative humidity, hours of sunshine, run of wind, mean cloud cover, and water discharge. Although most of these data are already plotted in other forms such as the temperature correction chart, the daily meteorological observation form, etc., it is extremely helpful to have each kind of data listed in a special table, i. e. the summary forms. From these summaries meteorological and other results can be directly plotted in diagrams for reproduction. (See a following chapter about office procedures). A collection of sample forms is included in the appendix.

It is expected that the following records and summaries should be handed in as soon as possible after return from the field:

1. Brief diary showing date and work accomplished.

   Example:

June 6	Arrive Lake Louse.
June 7	Arrive glacier, ferry supplies, helicopter 2 hours. (Flight report to be enclosed).
June 8	Read all stakes on lower part of glacier, sorted supplies.

2. Summaries of daily meteorological observations including:

   a) Daily mean Temp. (centigrade)
   b) Positive degree days (centigrade)
   c) Rainfall (in mm's)
   d) Mean cloudiness (in 10ths)
   e) Hours of sunshine
   f) Run of wind
   g) Other data according to given instructions

   Note: Standard forms should be used and the columns between those with headings should be left blank for they will be used in later calculations of sub-totals for selected periods, etc.

3. A table to show dates when each stake has been read throughout the whole season. (Use standard form).

4. Stake diagram completed in all respects. See example among the illustrations.

5. Table of river discharge - to show daily discharge and, where requested, sub-totals for periods from 0000 to 0600 hrs; 0600 to 1200, 1200 to 1800, and 1800 to 2400 hrs.

6. Snow pit measurements - completed standard forms - and, for each pit, graphs showing density and water equivalent vs. depth. See example among the illustrations.

7. A list of all equipment and supplies remaining at the hut (standard list).

8. A list of all equipment and supplies returned to the Head Office (standard list).

9. When applicable: Report of losses or disposal of equipment (Departmental form).

10. Any remaining statement of disbursements (on printed forms) together with all receipts arranged chronologically, neatly glued or stapled on 8½" x 11" (or standard A4) sheets of blank paper.

Deviations from the above-mentioned list of records and summaries may be stated in special cases. The leader of the project must ensure that the summer assistants are given complete instructions on this point, so that the completion of the appropriate forms can be carried out continuously during the field season. The senior crew member must check, before leaving the Head Office, that sufficient forms are sent to the field.

3. Closing the station

The base camp must be left tidy and in good order. All personal belongings that are not brought back must be burned or buried with all other garbage. The remaining food supplies should be checked for items that may deteriorate during the fall and winter, and such items must be removed.

A list of supplies and a sketch showing the location of gasoline drums etc. must be left in the hut. Stakes, stake extensions (2-m pieces), extension tubes and masonite plates must be placed so that they will be readily accessible during the winter.

The station may be visited several times during the winter, and as an emergency measure a stove and limited supplies of fuel and food must be left in the garage. The garage will normally not be locked.

All batteries that have been used (or partly used) must be thrown away. Only unused batteries should be left, and must be placed in a plastic bag - never left in radios, flashlights or other equipment! Such batteries should be marked with the year when they were brought to the station. Example: "New 1969 - unused".

A shovel must be placed on the outside wall above the doors of all houses, and fuel for lighting, cooking and the snow scooter must be left in handy containers inside.

To facilitate any winter surveys, it is essential to leave in the hut a map of the stake positions and a list of the last stake readings. The reason for this is that, when the stakes are being buried in the snow, the winter crew could concentrate on finding the longest stakes first. On comparing their present lengths with the last stake readings, the crew will then deduce which stakes may be completely buried and not worth searching for.

4. Inventory of essential equipment

In general there is a standard set of equipment that is absolutely necessary on each station. Shovels, ice drills, snow samplers, balances, etc. must be present to enable the work to be done. In most cases it is also necessary to have a reasonable supply of spare parts. Some stations may need a larger number of certain items than others, or the number of spare parts must be larger for logistic reasons. It is obvious that a detailed record must be kept of the equipment situation for each station. For this purpose a special inventory form, consisting of several pages, has been developed. This form should be completed at least by the end of the field season so that replacements can be arranged in good time before the next season. In some cases a complete inventory should also be made in the middle of the summer, to make possible the efficient use of a helicopter when the crew is taken down at the end of the season. Replacements and supplies such as gas may then be brought up to the glacier when personnel, damaged equipment, etc. are brought down.

All equipment should be stored in suitable boxes under beds or on the shelves, in such an order that they can be easily found. Office equipment may be collected in one place, hand tools in another, and so on. A sketch showing the location of various boxes should be made in duplicate; one copy should be left in the hut (fixed to the wall) and another copy included among the data sheets brought back to the Head Office at the end of the field season.

5. Some statistical considerations

(by W.J. Campbell, U.S. Geological Survey, Tacoma, Washington)

The observations of accumulation and ablation are some of the most fundamental in glaciology, yet considerable disagreement concerning the accuracy of these measurements exists in the literature. Some investigators feel that a certain number of stakes per given area must be fixed, as a kind of statistical constant, in order to obtain measurements of sufficient accuracy, but such a concept fails to allow for the vast topographic variations that occur on glaciers. For example, one stake in central Greenland might be representative for hundreds of square kilometers, whereas a stake on a valley glacier might be representative for a few square meters. Other investigators feel that the individual glacier under consideration must determine the number and array of stakes used. Although more pleasing in an intuitive physical sense than the fixed stake per area concept, this philosophy of measurement confronts the investigator with the great problems of determining the density of his observation network.

Any practical method of field measurement of accumulation and ablation must be composed of an intuitive as well as a statistical methodology. The intuitive skill is obtained only by mush experience with the glaciers being measured, thus we cannot talk about it. The statistical aspects can be discussed, but one must bear in mind that in reality they must be combined with intuition in order to yield valid results.

The enclosed graph allows one to determine the number of observations necessary to obtain a representative mean, if the individual observations fit a normal probability distribution. First, the standard deviation of a number of observations, for example the ablation measurement of a number of stakes in a certain area of uniform ablation on a glacier, is computed. Alternatively, if an experiment is being planned, some information on the expected standard deviation might be obtained from other experiments. The standard deviation is defined

$$\sigma = \sqrt{\frac{(a - \bar{a})^2}{N}} \qquad \text{where a is}$$

the individual measurement value, $\bar{a}$ is the arithmetic mean of the observations, and N is the number of observations, or in this case the number of stakes. The arithmetic mean is considered to be representative if it differs, with a predetermined probability P, not more than x from the true mean. Generally x and P are fixed according to the requirements of the study, and σ may be fixed by the inherent dispersion of point-values on the glacier.

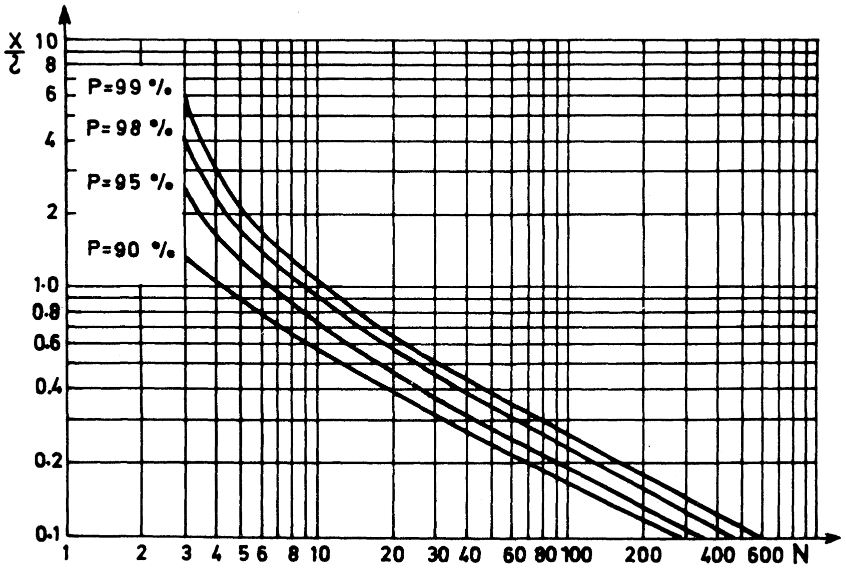
With a given σ and a chosen x the point on the chosen probability curve whose ordinate is x/σ can be found, and the abscissa of this point is then the number of observations, or stakes, necessary. Of course, this says nothing about the array of observations, but in order for the statistics to be valid it is necessary that the area in question on the glacier be covered. The array design demands intuitive insight, since it is probable that σ will not only vary considerably from glacier to glacier but will vary from one part of the glacier to another.

The graph may be used in two ways. As above it can be used to estimate the density of an observational network necessary for a desired accuracy. The graph can also be used to find the accuracy for a given set of observations.

For example, suppose 30 ablation stakes gave measurements with a standard deviation of 2. 0. Suppose also that one desired a probability of 99 percent that the arithmetic mean was representative of the true mean. The point on the 99 percent P-curve whose abscissa is 30 is then located and the ordinate is read as 0. 5. The accuracy of the determination of the mean value is then

$$x = \ell(0.5) = 2(0.5) = 1 \text{ centimeter}$$

This method affords an objective way of estimating the accuracy of one's measurements as well as a check on the density of the observation network. Of course, it is useful only after some observations have been made, thus it is of little help in the initial design of an observational network. However, it can be most helpful in the modification of existing networks to make these more accurate.



Graph for determination of number of single values (N) necessary to obtain a representative arithmetic mean.

OFFICE PROCEDURES

1. General

To allow of direct comparison between glaciological results obtained at various glaciers, it is necessary that all data should be tabled, plotted and presented in a uniform manner. Furthermore, it is obvious that standard units should be used when results are published. However, experience has shown that, even when the same units have been used by different authors, their graphs cannot be directly compared, as they may use different units for divisions on co-ordinate axes, so that slopes of curves and the visual impressions of graphs will be greatly influenced. In the following sections, standard types of graphs and tables are proposed for future data presentation. The proposed formats have been used for several years in Canada, Norway, Sweden and other countries. See, for example, Østrem (1966), Schytt (1968), Liestøl (1967), Pytte (1967), and Kasser (1967).

2. Data presentation

Some results of glaciological investigations may be used by other scientists for further analysis etc. and others may be used directly in calculations of practical importance, for planning purposes, etc. If the data are to be used for further calculations it is necessary to present the figures in tables, but many results are more readily understood if they are presented in the form of graphs or plotted on maps. It is therefore recommended that all pertinent data (generally not the rough field data) should be published in tables and a selection of the results plotted on maps and in graphs. Those data that are to be shown in illustrations will generally be chosen from case to case, depending upon the main purpose of the investigation. A water-power institution will probably be more interested in the hydrological applications of mass balance studies than meteorologists, who will certainly be more interested in meteorological parameters. The proposals in the following sections must therefore be regarded as a guide only; deviations from this standard form will be made when necessary.

a) Stake and pit location

The glacier outline and the locations of the stakes and pits are best shown on a map. For digital computations a system of co-ordinates can also be used for all stake and pit locations. Such systems have been developed in connection with computer programs and will be described further below.

A map showing the pit and stake locations may be made relatively simple with only the glacier outline, a few contour lines (every 50 or 100 m) and some reference points, such as main triangulation points, the hut location, etc.

When the accumulation measurements are made in the field a great number of soundings are made on the glacier. It will be practically impossible to plot all these soundings on a map suitable for reproduction. Therefore, only the lines along which soundings were performed should be plotted on the map as "sounding profiles". A sample map showing stake and pit locations and sounding profiles is shown among the illustrations.

b) Accumulation results

The "true" winter accumulation on a glacier can seldom be measured as some ablation will normally occur also in wintertime. For this reason the term "winter balance" was introduced. When the accumulation measurements are made in late spring, one normally obtains the final result of the winter accumulation minus the material that has disappeared through evaporation, wind removal, etc. during the winter. This measured result is termed "winter balance", and it will be slightly smaller than the "true" accumulation (see appendix).

The water equivalent of the winter balance will be obtained by sounding the snow pack in a large number of points (mostly along sounding profiles) and making a number of density measurements in pits dug down to the previous summer surface. Snow-depth measurements should, at least for valley glaciers, be made with a density greater than 10 points/km^2. Thus, it is not practical to present all depth measurements, in cm of snow or in cm of water equivalent. The original snow depths are therefore plotted on a working map along the sounding profiles. The location of each sounding profile must therefore be known. On this working map, with all single field data plotted, iso-lines must be constructed for selected water equivalent intervals. Example: Contours may be drawn for 50, 100, 150, etc. cm of water equivalent. The total amount of accumulation can be obtained by planimetring the areas between contours. The area between 50 and 100 cm is then given the mean value of 75 cm of water equivalent etc. When this planimetring is completed for the whole glacier, the total winter balance can easily be calculated. However, it is desired to obtain information about variations in winter balance in relation to altitude. Thus the planimetring must be carried out separately for each elevation interval, using the working map with 50-m or 100-m contours.

The results of this planimetry between the contour lines should be presented in a table that will show the winter balance within each height in-

BREIDABLIKKBREEN 1965
Winter balance

Elevation	100 - 150 cm		150 - 200 cm		200 - 250 cm		250 - 300 cm		300 - 350 cm		Total		Specific	
m	Area km^2	W.eq. 10^{6}m^3	Area km^2	W.eq. 10^{6}m^3	Area km^2	W.eq. 10^{6}m^3	Area km^2	W.eq. 10^{6}m^3	Area km^2	W.eq. 10^{6}m^3	Area km^2	W.eq. 10^{6}m^3	m	l/s km^2
1650-							0.221	0.608	0.014	0.046	0.235	0.654	2.78	86.3
1600-1650							0.436	1.199	0.309	1.004	0.745	2.203	2.96	91.9
1550-1600					0.268	0.603	0.814	2.239			1.082	2.842	2.63	81.7
1500-1550			0.325	0.569	0.453	1.019					0.778	1.588	2.04	63.4
1450-1500			0.442	0.774	0.226	0.509					0.668	1.283	1.92	59.6
1400-1450			0.271	0.474	0.314	0.707					0.585	1.181	2.02	62.7
1350-1400	0.061	0.076	0.291	0.509	0.155	0.349					0.507	0.934	1.84	57.2
1300-1350	0.196	0.245	0.204	0.357	0.029	0.065					0.429	0.667	1.55	48.1
1250-1300	0.001	0.001	0.105	0.184	0.091	0.205					0.197	0.390	1.98	61.5
1200-1250					0.004	0.009					0.004	0.009	2.25	69.9
1200-1650	0.258	0.322	1.638	2.867	1.540	3.466	1.471	4.046	0.323	1.050	5.230	11.751	2.25	69.9

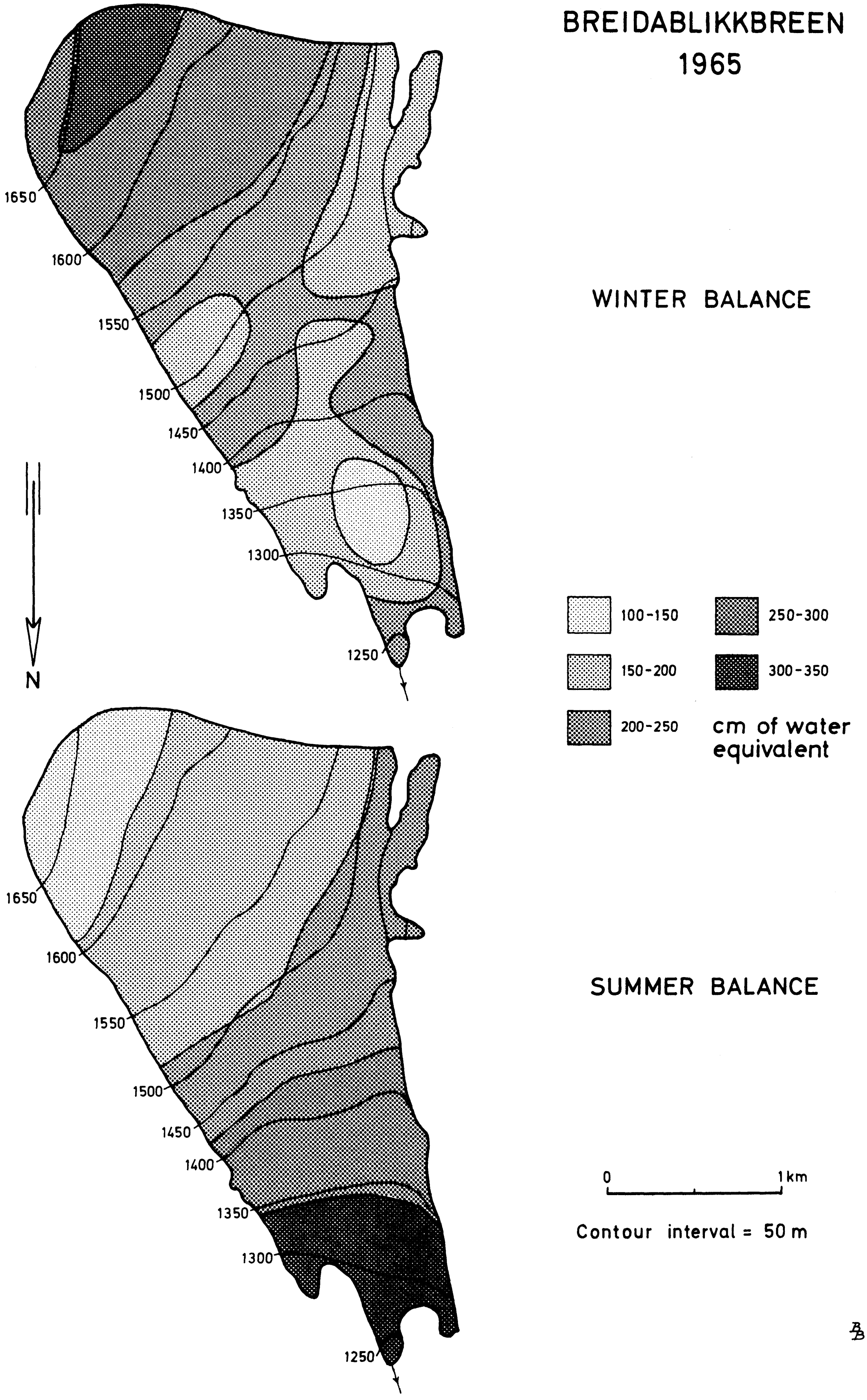
BREIDABLIKKBREEN 1968
Summer balance

Elevation	100 - 150 cm		150 - 200 cm		200 - 250 cm		250 - 300 cm		300 - 350 cm		Total		Specific	
m	Area km^2	W.eq. 10^{6}m^3	Area km^2	W.eq. 10^{6}m^3	Area km^2	W.eq.	Area km^2	W.eq. 10^{6}m^3	Area km^2	W.eq. 10^{6}m^3	Area km^2	W.eq. 10^{6}m^3	m	l/s km^2
1650-	0.235	0.294									0.235	0.294	1.25	38.8
1600-1650	0.414	0.518	0.331	0.538							0.745	1.056	1.42	44.1
1550-1600			1.082	1.764							1.082	1.764	1.63	50.6
1500-1550			0.620	1.163	0.158	0.356					0.778	1.519	1.95	60.6
1450-1500			0.009	0.017	0.659	1.483					0.668	1.500	2.24	69.6
1400-1450					0.382	0.860	0.203	0.558			0.585	1.418	2.42	75.2
1350-1400					0.022	0.050	0.485	1.333			0.507	1.383	2.72	84.5
1300-1350							0.054	0.149	0.375	1.219	0.429	1.368	3.19	99.1
1250-1300									0.197	0.640	0.197	0.640	3.25	101.0
1200-1250									0.004	0.013	0.004	0.013	3.25	101.0
1200-1650	0.649	0.812	2.042	3.482	1.221	2.749	0.742	2.040	0.576	1.872	5.230	10.955	2.09	64.9

BREIDABLIKKBREEN 1965
Mass balance

Elevation	Area	Winter balance			Summer balance			Net balance		
		Total	Specific		Total	Specific		Total	Specific	
m	km^2	10^{6}m^3	m	l/s km^2	10^{6}m^3	m	l/s km^2		m	l/s km^2
1650-	0.235	0.654	2.78	86.3	0.294	1.25	38.8	+0.360	+1.53	+48
1600-1650	0.745	2.203	2.96	91.9	1.056	1.42	44.1	+1.147	+1.54	+49
1550-1600	1.082	2.842	2.63	81.7	1.764	1.63	50.6	+1.078	+1.00	+32
1500-1550	0.778	1.588	2.04	63.4	1.519	1.95	60.6	+0.069	+0.09	+ 3
1450-1500	0.668	1.283	1.92	59.6	1.500	2.24	69.6	-0.217	-0.32	-10
1400-1450	0.585	1.181	2.02	62.7	1.418	2.42	75.2	-0.237	-0.40	-13
1350-1400	0.507	0.934	1.84	57.2	1.383	2.72	84.5	-0.449	-0.88	-28
1300-1350	0.429	0.667	1.55	48.1	1.368	3.19	99.1	-0.701	-1.64	-52
1250-1300	0.197	0.390	1.98	61.5	0.640	3.25	101.0	-0.250	-1.27	-40
1200-1250	0.004	0.009	2.25	69.9	0.013	3.25	101.0	-0.004	-1.00	-32
1200-1650	5.230	11.751	2.25	69.9	10.955	2.09	64.9	+0.796	+0.16	+ 5

BREIDABLIKKBREEN
1965



terval, expressed in 10^6 m^3 of water. A sample table is shown on a separate page among the illustrations. In the same table it is convenient to present the mean specific values (i.e. the mean figure for each elevation interval), given in cm of water equivalent.

For publication, this table together with a map of reduced size showing the contour lines and the iso-lines for water equivalent, should be given. To stress the various areas on the map they may be marked with different colours or shading made by using various screens. See the sample maps among the illustrations.

Information about snow densities is generally used in connection with the data processing in the office (converting snow depth figures to water equivalent values) and will normally not be published. Only for unusual snow conditions will it be of interest to publish a diagram showing the density variations with depths.

c) Ablation results

As in the winter season, it may happen that the glacier will receive material during the summer. This so-called "summer accumulation" has previously been handled differently by different glaciologists. However, according to the definition of the new term "summer balance" (see appendix), the "ablation" measurements should include summer snow falls, so that the final result will represent a difference between the ablation and the accumulation during the summer. In most cases, the ablation is far larger and the glacier will normally lose material during the entire melt season.

Ablation measurements are obtained from stake readings on the glacier. The number of stakes is far smaller than the number of soundings made at the end of the accumulation season. Thus, when the total ablation (or more correctly, the summer balance) is to be calculated, the calculation will be based upon a limited number of stake readings. Generally, glacier melt decreases fairly regularly with altitude, so that iso-lines for equal melt will more or less parallel contour lines on the glacier, but there are local deviations from this general rule. For one and the same glacier these deviations will normally occur in the same areas from year to year. It is thought that they originate from local topography, winter snow distribution, etc.

On the basis of the figures for the total summer balance at each stake, a summer balance map can be constructed, showing iso-lines for selected ablation intervals. Example: Lines may be drawn for 100, 200, 300, etc. cm of water equivalent and the areas between these lines coloured or shadowed.

As on the accumulation map (see above), these areas should be planimetred. After some simple multiplications the total summer balance should be obtained. However, as it is necessary also to know the variations in summer balance with height, each elevation interval (preferably each 100 m) must be processed separately and the results given in a table similar to that described in the previous section. The specific values, i. e. the mean ablation expressed in cm of water equivalent, may be given in the same table.

The stakes should preferably be evenly distributed on the glacier surface so that observations are obtained from all parts of the glacier. It is, however, difficult to insert and observe stakes in heavily crevassed areas. It may even be impossible or at least very dangerous to travel across the crevassed areas and in that case glaciological information cannot be obtained. It is therefore necessary to make some kind of interpolation, based upon the measurements made below and above the crevassed area. Assuming a linear variation, such an interpolation can easily be made. However, in the crevasses more ice is exposed to the atmosphere per km^2 than in other parts of the glacier. Thus a higher ablation rate may be expected in a highly crevassed area. A study made by Karlén (1965) indicates as much as 17% more ablation in the crevasses than on adjacent horizontal ice surfaces.

A map showing the total summer balance (corresponding to the "accumulation map") will normally not be published, as the ablation pattern is generally simple. A more interesting illustration will be a diagram showing the summer balance vs. elevation. Such curves can easily be constructed from tables giving all ablation results. The plotting of this curve will be further described in the next section.

d) The mass balance

The difference between the glacier "income" (winter balance) and "expenditure" (summer balance) will give the net balance for one year. If the difference is positive, the glacier has increased its total mass; when it is negative, it has decreased. In hydrological terms this means that the glacier stream has obtained less water or more water, respectively, than it would have obtained if all the winter snow had melted in the basin and there had been no influence from the glacier. It is therefore of practical concern to obtain good information about the mass balance of glaciers in certain areas where the river water is utilized by man. In a wider sense mass balance studies are of scientific interest for several reasons. The results of mass balance studies should therefore be published in a form that will satisfy both the engineering hydrologists and the glaciologists. It is anticipated that the proposed tables, graphs, etc. will prove suitable for glaciologists, engineers, hydrologists, meteorologists, and other scientists.

The tables described in the two previous sections show the winter balance and the summer balance for each elevation interval (generally 50 or 100 m), both as a total water volume expressed in 10^6 m^3 and as specific figures expressed in cm of water equivalent. Thus, the mass balance for each elevation interval can easily be obtained as a difference between corresponding figures. Such a table should always be published for all glaciers where mass balance studies have been performed. The table should include, for each elevation interval, the area, the winter and summer balance (both total and specific) and finally the mass balance. Figures for the entire glacier can easily be obtained by simple addition of corresponding data in the table.

In addition to this important final table, a special mass balance diagram should be constructed. In this diagram the specific winter balance, summer balance and mass balance are plotted vs. elevation. In the same diagram the area distribution can also be plotted. Finally, the total net mass balance can be shown as histograms. If the histograms are shadowed, the completed diagram will give a good impression of the conditions on the glacier for that year. Two examples are shown among the illustrations.

To make the diagrams easily comparable and to ensure that the slopes of curves will always be the same for the same conditions, the following rule should be used for divisions on the axes: the X-axis is divided into metres of water equivalent. The length of the axis representing 1 m is arbitrary, but is should equal the length of the Y-axis representing 100 m of elevation. In other words, the divisions on the co-ordinate axes should be in the ratio 1:100. When the diagram is eventually reduced for publication, the slopes and general appearance of the curves will remain the same and diagrams from various glaciers (especially net balance curves) can be directly compared. The slope of the net balance curve at the equilibrium line was originally termed "energy of glacierization" by Shumskiy (1947)* and it is important to present this slope in a standardized manner.

In certain cases it may be of interest to follow the variations in mass balance continuously throughout the season. For this purpose a special stake form has been designed. On this form all observed data can be plotted

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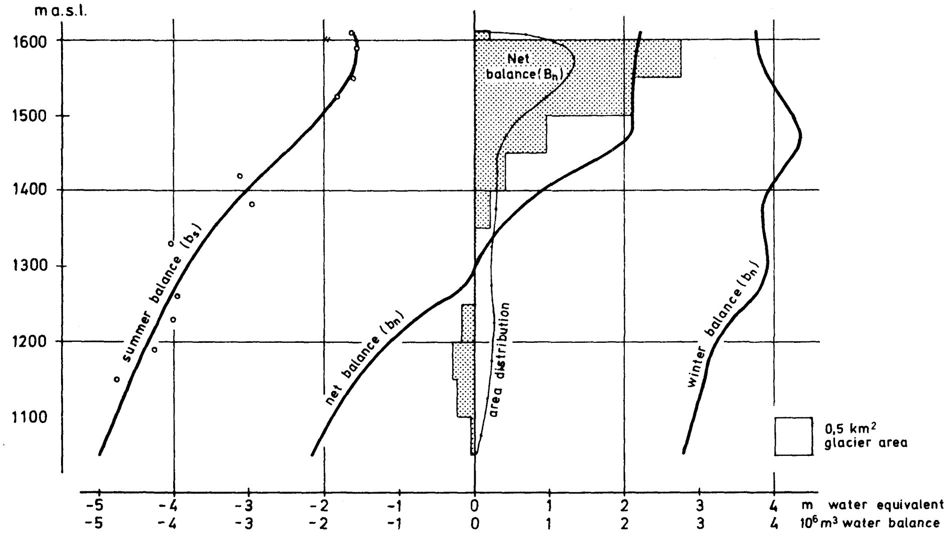
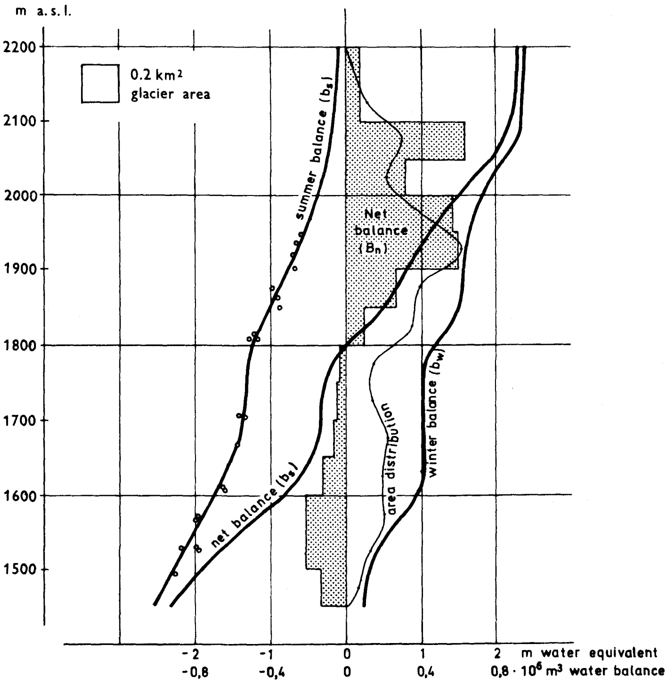
*This concept was later "translated" by Meier (1961) to "activity index". Haefeli (1962) introduced the term "ablation gradient" which is also discussed by Schytt (1967).

Folgefonni 1967
Eastern part



Hellstugubreen 1967



In these standard mass balance diagrams, the winter, summer and net balance curves are plotted vs. elevation. Note the ratio of 1:100 for the divisions on the axes.

Glacier area distribution is also shown, and the resulting areal values of net balance given as histograms. In both cases the glacier gained mass (i. e. had a positive balance) during the glaciological year 1966/67.

for each stake and the mass balance calculated for any time of observation. If a stake form is completed for every stake on the entire glacier, it will be possible to calculate the ablation (for example, variations in summer balance) for any given time period, provided that complete stake readings have been made at least at the beginning and at the end of this period. The stake form also proved useful for general mass balance studies, for it allows a check of all observations made during the summer. A disadvantage of the stake form may be that it looks formidable and it may be difficult to complete it properly. The following rules should be used as a guide in this work when the Canadian form is used. (The Norwegian form has a slightly different design).

i. Fill in all details requested at the top of the form. One form to be used for each stake. If duplicate stakes or replacement stakes are used, measurements must be recorded on separate forms.

ii. Column 1 shows the date of the readings.

iii. Column 2 and 3 show the visible length of the stake. If ice is exposed, only column 3 is filled in; if the spot is still snow-covered, only column 2 should be used.

iv. Columns 4-7 are for recording snow depths at stakes which still have some of the last winter's snow present. Consequently, if the stake length was placed in column 3 (see iii. above) nothing should be put in columns 4-7, as no snow exists at the location.

If the snow depth is actually sounded (see description of stake readings in the chapter about ablation measurements), the mean value of the three soundings should be placed in column 4. From knowledge of the snow density given in Column 6 (obtained by pit studies at the stake or in the same part of the glacier) the water equivalent of the snow cover can be calculated and the figure placed in column 7. Column 5 is used only when soundings are not taken and the snow depth is calculated from the stake reading alone. This may occur when there is not time available for the measurement or when a snow probe is not available, so that only stake readings can be made. The use of column 5 should therefore be restricted as far as possible.

v. Column 8 is used for incidental notations, for example for a check of totals of figures shown in columns 2 and 4. This sum should be a constant but if great variations occur it is necessary to investigate more closely conditions at the stake to determine whether the depth to the summer surface has been miscalculated or the stake has sunk, or for stakes on the tongue, whether superimposed ice has formed.

STAKE OBSERVATIONS

Peyto Glacier
1968 Year
48 Stake No.
2120 m Elevation

Wire [✓ 5m]
[✓ Al] 4m
Steel 2m
Bamboo

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
DATE	TOP TO		SNOW					DIFFERENCE					ABL.	Cum. Acc.	w.eq. Abl.	NET w.eq. (+) (-)	REMARKS
								SUPER ICE			ICE						
	Snow	Ice	Sound	Calc.	Dens.	w.eq.		cm	w.eq.	Snow	cm	w.eq.					
9/4	180		120	40		40	(300)									+ 40	Stake inserted
23/4	190		110			36	(300)			4			4		4	+ 36	
3/5	225		(88)	75		30				6			6		10	+ 30	
12/5	240		50			20	(290)	10	8	10			2		12	+ 28	
24/5	270		21			9	(291)			11			11		23	+ 17	
10/6		303							8	9	3	3	20		43	- 3	Bare ice
13/6		307									4	3	3		46	- 6	
-11-		105															Stake reset
30/6		135									30	27	27		73	- 33	

vi. Columns 9-13 are used for calculations and should not contain any observed figures. The thickness of superimposed ice found by variations in stake length above the ice surface should be put in column 9 and its water equivalent placed in column 10 (assume a density of 0.7 - 0.8). Superimposed ice is regarded as accumulation, and this figure should be marked as positive.

The variation in water equivalent of the snow pack between two readings (compare column 7) should be placed in column 11. Strictly speaking, this will normally be a negative figure, as snow disappears during the melting season, but any observed additional snowfall in the summer should be considered positive.

The actual melting of glacier ice is recorded in column 12. This figure will always be negative. The difference in stake reading between the last two observation occasions should be noted, and the water equivalent calculated and placed in column 13 (assuming a density of 0.9).

vii. Column 14 shows the total ablation between the previous two readings. The figure in this column will be the algebraic sum of figures shown in columns 10, 11 and 13. For practical reasons however, it can be shown without an algebraic sign.

viii. The cumulative value of figures in column 14 should be noted in column 16. If, however, it appears that accumulation has occurred (generally summer snow fall) between the two readings, column 15 will be used.

Column 17 shows the present situation at the stake, starting with the amount of snow accumulation (the winter balance), as observed in the spring (being a positive value). During the melt season this value will diminish according to figures shown in column 16. At the end of the season the figures in column 17 might be very small or even negative (on the lower part of the glacier) if figures in column 16 exceed the original accumulation (i.e. all winter snow cover and some of the ice has melted). At the end of the season there will always be negative figures in column 18 for stakes in areas where the glacier ice is exposed. At the equilibrium line, however, the final figure approaches zero, indicating zero net accumulation and zero net ablation.

e) Movement studies

Although movement studies are not necessary to obtain the mass balance for a glacier, they may be of general interest. Because stakes are inserted in a fixed position on the glacier surface, they will serve as good reference points for movement studies. Difficulties of identification can be overcome by using various markers on the stakes; experience has shown that a combination of small and large flags attached to the stake is a good aid in identification from a distance. Stake positions must be determined by triangulation from fixed points on the adjacent ground. The reverse procedure, i. e. to place the theodolite at the stake and read angles to the fixed points may also be used but the resulting computations are more complicated.

The approximate position of each stake can be found graphically on a large-scale glacier map by simple intersection from the known fixed points but the accuracy of graphical methods is poor and is generally insufficient to determine stake movements.

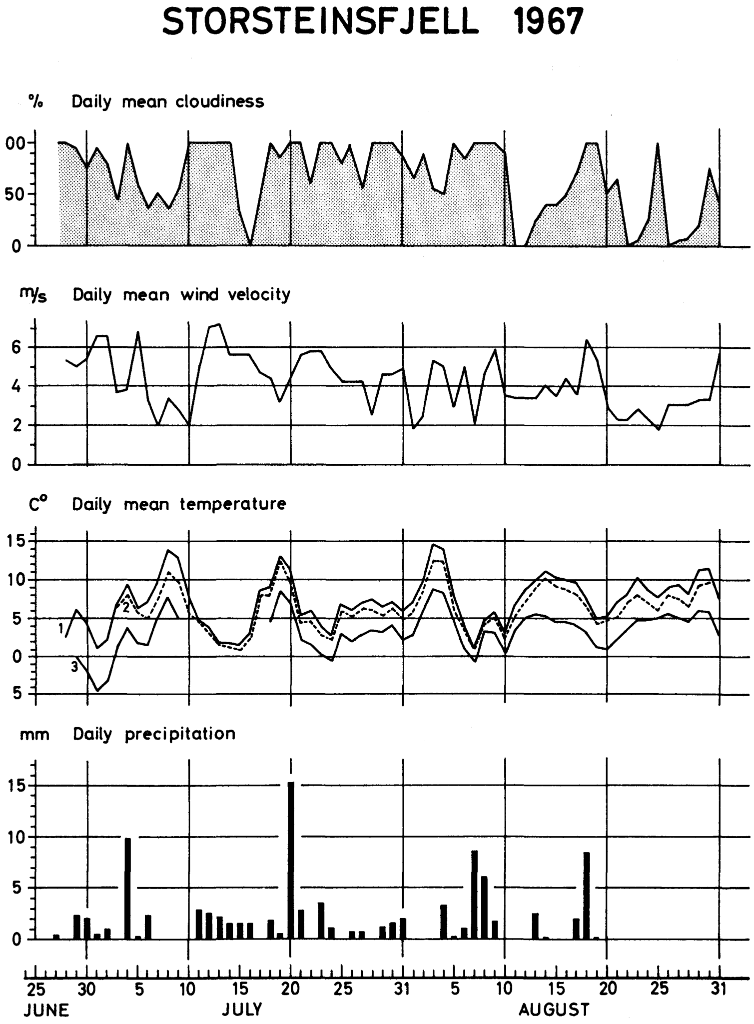
A more accurate determination will be obtained by using a right-angle co-ordinate system. The co-ordinates for each fixed point must then be known and the stakes' positions calculated by trigonometry. When the next survey is done, another set of stake posstions will be obtained and the movement of each stake can be plotted on the map or found by further computation.

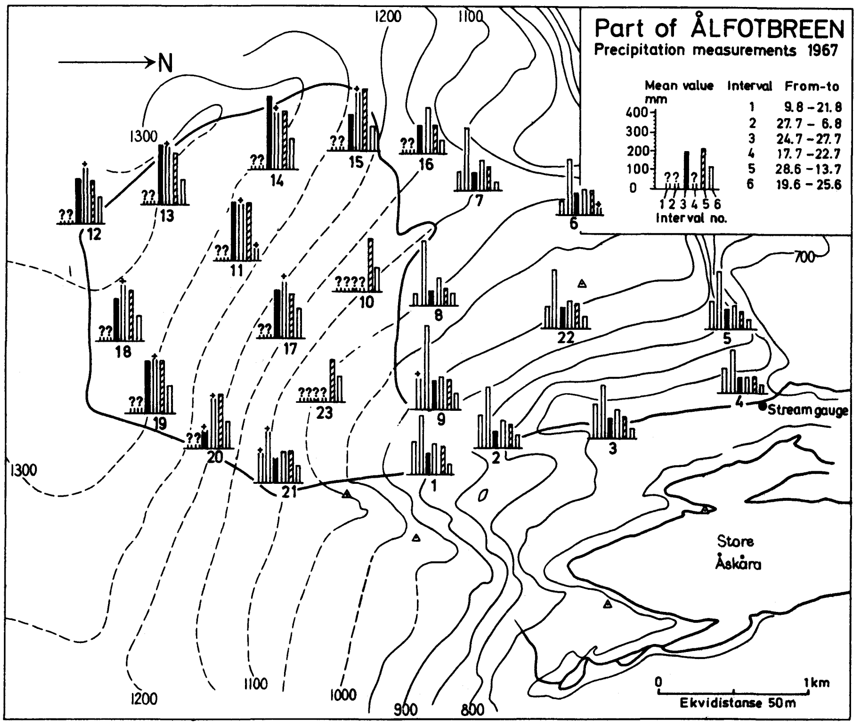
If the stake has been relocated between the two surveys, it is important to note this "artificial" movement of the stake. Distance and direction of the new position relative to the previous location must be recorded.

The movement studies can be presented either in a table in which all movements are indicated by direction and distance or the movement can be plotted on a map. The movement is shown as arrows, pointing in the direction of movement with the length proportional to the displacement between surveys. The time interval between the surveys should also be given.

f) Meteorological results

The meteorological results obtained at each glacier will normally be presented or published in the form of tables or a diagram showing the daily variations in various meteorological parameters. If precipitation is measured at a great number of locations (see about "Pluvius" network in the chapter describing meteorological observations) these observations are better shown if the results are plotted on maps, see below. The main diagram will normally contain observations made at the observation hut and for some areas also at locations on the glacier. To make the result easily comparable it is advisable to follow the format shown among the illustrations or to visualize the results in a similar manner. The recommended illustration consists of 4 (or more) separate diagrams, all of them having a common





Examples showing various methods of presenting meteorological results (see text).

X-axis with divisions for each day during the whole observation period. Each single curve in the diagram has its own Y-axis; the divisions are selected for each particular case.

For the daily mean cloudiness, which is normally observed in tenths, it is practical to divide the Y-axes in tenths. A completely clear day will then be plotted as 0 cloudiness, an overcast day be presented by 10 cloudiness. (In the example the cloudiness is shown in per cent).

For the daily mean wind velocity the divisions on the Y-axis must be selected according to the highest wind speed observed. In the example this maximum mean wind speed was some 7 m/sec and the Y-axis is divided accordingly.

Similar conditions will govern the Y-axis' divisions for the graph showing daily mean temperature. In the illustration observations from three various locations at the same glacier were plotted in the same graph.

The daily precipitation will normally be shown in the form of a histogram or as vertical columns. Where possible the scales should be uniform for glaciers including humid areas and for glaciers in a continental climate. Note that the daily precipitation shown in the graph demonstrates observations in one single point and may not be representative for the whole basin. To show the regional variations in precipitation (e.g. rain) it is proposed to plot results on a map. This can be done either by plotting the total amount of rain collected at each rain gauge or by constructing a precipitation map which will be comparable with an accumulation map. Examples are shown among the illustrations.

The construction of the above-mentioned diagrams etc. should be based upon daily mean values. It is therefore necessary to calculate daily means from field observations. In most cases the field crew can do this during days of bad weather. For the precipitation the daily inspection of the rain gauge will directly give the wanted figure. For cloudiness an estimation or rough calculation can be readily and easily made in the field. Wind velocity must be calculated from the total wind distance as read on the anemometer (see the previous chapter about Meteorological Observations). The daily mean temperature can be obtained from the thermograph chart by reading off the temperature for every hour each day and the total divided by 24 to obtain the daily mean. If the thermograph had no mechanical defects it should record the "true" air temperature, i.e. the air temperature read on the standard mercury thermometer. However, many instruments will deviate slightly from the mercury thermometer and some calibration will be necessary. The corrections are based upon differences between the thermograph reading and a reading made simultaneously on a standard thermometer placed within the same Stevenson screen. Such readings should be made at least twice a day. To facilitate the calculations of a corrected daily mean temperature, a special form has been developed on which temperature registrations for one week should be processed. A sample form is included in the appendix.

If more meteorological parameters are observed at the glacier they could, of course, be shown in the same large diagram. For the benefit of further scientific data processing it may be advisable also to give all data in tables. The construction of such tables is not dealt with in this manual.

g) Stream discharge

The water discharge in glacier streams is observed for three main reasons:

(1) To serve as a check of ablation measurements and to form a base for a statistical study of the relationship between discharge variations and meteorological parameters (rainfall, radiation, air temperature, wind, etc.). See a following section about computer programs.

(2) To serve as a base for sediment transport studies. Sediment samples are taken at various intervals and to obtain the total sediment transport (per hour, per day or for the whole season) it is necessary to know the discharge variations. For this purpose daily values will be insufficient, because short-term variations have a great influence on the sediment transport. See the following section.

(3) To give general hydrologic information about discharge conditions in glacierized catchment areas.

Provided a rating curve is established for the measuring site, the stream discharge may be calculated for selected periods during each day (see the previous chapter about field techniques in the water discharge measurements). It is anticipated that the field crew has made such calculations so that the daily values expressed in 10^6 m^3 of water volume are plotted on summary forms. The office work will then be limited to a simple plotting of the daily discharges in the form of a histogram. This histogram may be presented separately or it may be included in the diagram of various meteorological observations. If the data are expected to form the base for mathematical studies, the daily figures should also be given in a table.

h) Sediment transport

The study of the sediment transport is based upon a number of relatively small samples (generally 1 litre) taken at regular times in the glacier

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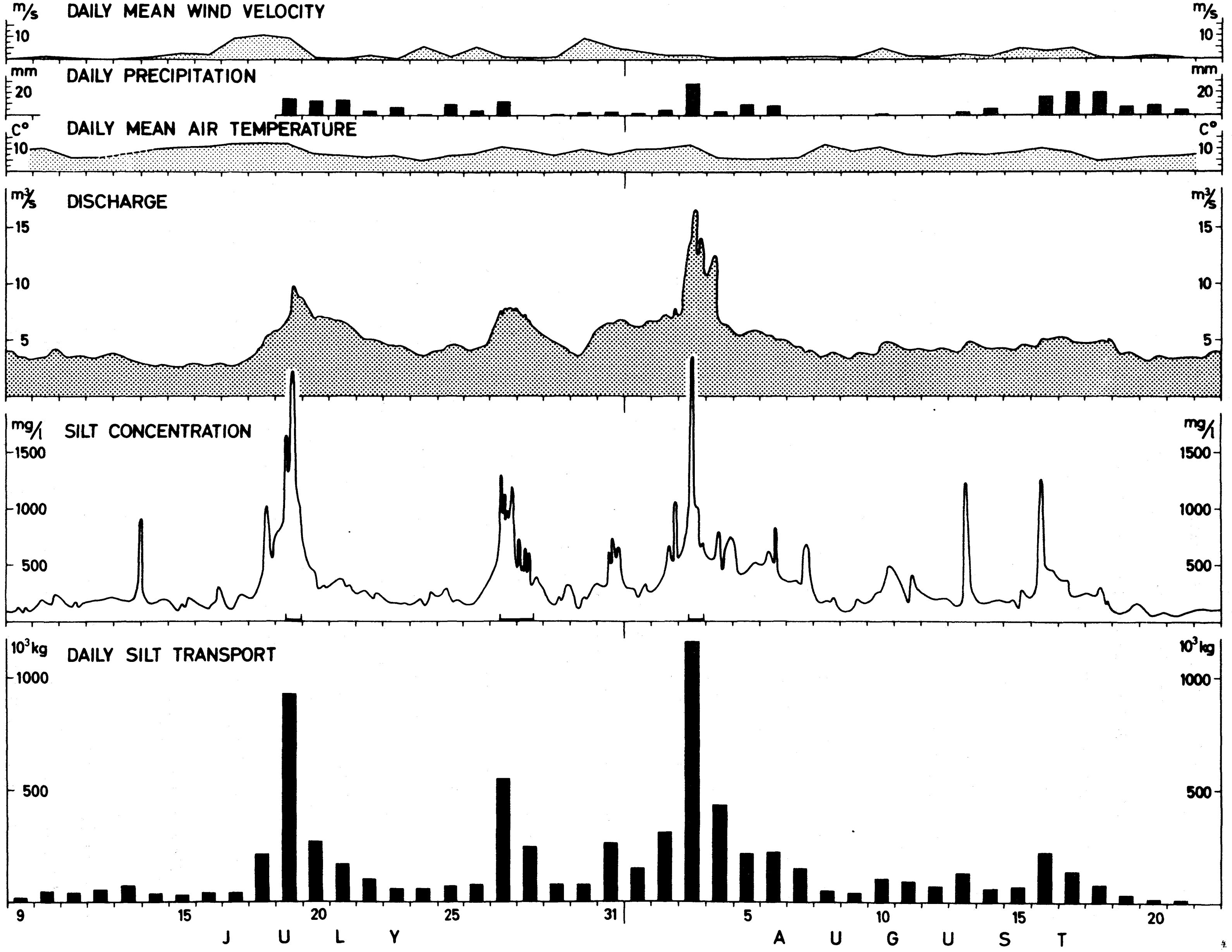


stream. The laboratory analysis of each sample gives the sediment concentration at the time of sampling. To calculate the amount of transported sediment in a given time interval it is also necessary to know the discharge. If the sample is regarded representative for a given time interval the figure for the sediment concentration should be multiplied by the total discharge in this interval.

If discharge variations are very small it may be sufficient to take two samples a day, each being representative for a 12-hour period. However, if rapid or large discharge variations occur samples must be taken frequently; each of them representing a relatively short time period. In practice, this means one hour or even half an hour. When the water stage is rising it is important to take samples frequently. When the results are published it will be of interest to show not only the size of the daily sediment transport but also a diagram showing variations in sediment concentration and water discharge variations.

It is therefore proposed that three graphs are constructed.

(1) The water discharge variations shown as detailed as possible during the entire melt season.

(2) The results of all sediment sample analyses in the form of a sediment concentration graph.

(3) The total sediment transport for each day plotted as a histogram or as single vertical columns for each day of the observation period.

If the sediment concentration diagram shows extremely rapid variations during certain periods it may be necessary to make special diagrams for these periods to avoid generalisation in the main diagram.

To demonstrate the main reasons for variations in river discharge, it may be of interest to plot also daily precipitation, air temperature, etc. in the same diagram. A sample diagram is shown among the illustrations.

3. Computer programs

During recent years many computer programs have been developed to facilitate complex calculations and office procedures. As this field is developing rapidly and continuously it is impossible to give an up-to-date revue of programs or procedures suitable for glaciological work. The following sections only indicate some possibilities that should be checked by the leader of a glaciological mass balance project before time-consuming calculations are started.

a) Water discharge

In the chapter about water discharge measurements it was shown how to calculate the discharged water volume from gauge readings and the rating curve. During recent years computer programs have been developed both to construct the rating curve from a number of discharge measurements (and simultaneous gauge readings) and to "read" charts from automatic gauges and transform the information directly to water volumes. The rating curve is then anticipated to be a linear function in a logaritmic system. Its mathematical expression is given by the formula $Q = k\ (h + \Delta h)^n$ in which

Q is the water discharge (m^3/sec),

k is a constant,

h is the gauge reading (on a vertical scale),

Δh is a constant directly connected with the vertical scale. It will be 0 if zero of the scale has exactly the same elevation as the lowest part in the river profile that controls the water level at the measuring site. In all other cases it will be a positive or negative figure showing the difference in elevation.

n is an exponent.

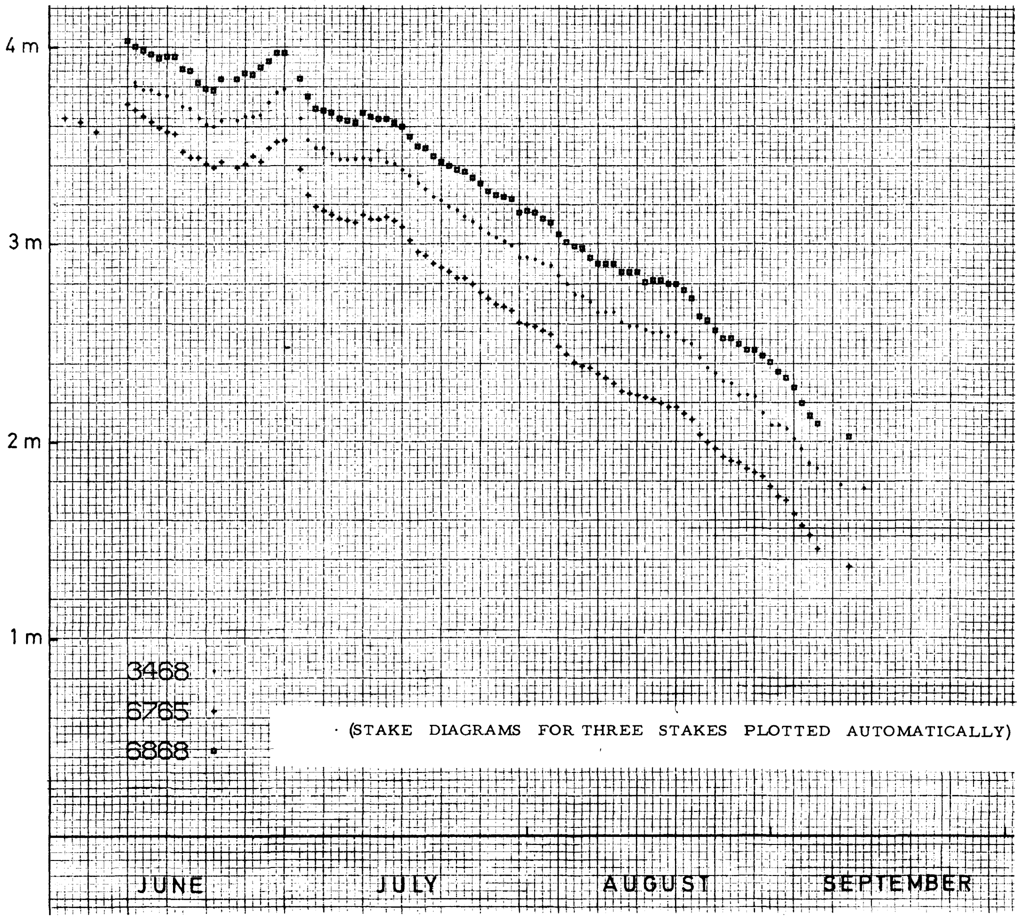
The computer input will be a series of observations of water discharge (Q), the corresponding gauge readings (h) and information about the zero point of the gauge relative to the lowest point of the "controlling profile". The computer will then calculate k and n.

Due to topographical conditions at each measuring site, a rating curve may be divided in several sections, each of them being a straight line in a logaritmic system. The computer program will be able to indicate various sections to obtain best possible fit for the initial water discharge observations. It will also print a complete table so that any gauge reading can be transformed directly into discharge.

Charts from automatic recording gauges can be "read" by various machines (coordinatographs, or more or less automatic tracing instruments) that will digitalize any graph. Some gauge recorders print their observations on tape that can be directly read by a computer. The tapes can be also combined with the rating curve so that water discharge figures are printed out in tables.

b) Mass balance

The construction of accumulation and ablation maps and the measurement of areas to obtain the total winter and summer balance are very time-consuming. Computer programs are now developed by the Glaciology Section of the Norwegian Water and Electricity Board to calculate the winter balance directly from the snow depth soundings and the density information obtained by pit studies. The computer will be able to construct accumulation and ablation maps and to give the complete table of balance variations vs. height. An



· (STAKE DIAGRAMS FOR THREE STAKES PLOTTED AUTOMATICALLY)

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         6550.02 VESLEDALSBREEN.                         DATE  250269


                   TABLE OF BALANCE


 HEIGHT      AREA     WINTER BALANCE       SUMMER BALANCE          MASS BALANCE
INTERVAL      S       BBW       BW        BBS       BS          BBN       BN
M A.S.L.     KM2    MILL.M3  M  L/S KM2 MILL.M3  M  L/S KM2 MILL.M3  M  L/S KM2
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
1700-   HST    .015    .048  3.25  103     .031  2.12    67     .017  1.12   36
1600-  1650    .119    .385  3.25  103     .252  2.12    57     .133  1.12   35
1550-  1600    .190    .621  3.26  103     .404  2.12    67     .217  1.14   36
1500-  1550    .712   2.289  3.22  102    1.512  2.12    67     .777  1.09   35
1450-  1500    .518   1.681  3.25  103    1.100  2.12    67     .581  1.12   36
1400-  1450    .459   1.611  3.29  104    1.039  2.12    67     .571  1.17   37
1350-  1400    .730   2.455  3.36  107    1.314  2.48    79     .641   .88   28
1300-  1350    .714   2.094  2.93   93    1.976  2.77    88     .118   .17    5
1250-  1300    .416   1.260  3.03   96    1.278  3.07    97    -.018  -.04   -1
1200-  1250    .122    .360  2.94   93     .405  3.30   105    -.045  -.36  -12
1150-  1200    .143    .333  2.33   74     .528  3.70   117    -.195 -1.37  -43
1100-  1150    .053    .118  2.21   70     .213  4.00   127    -.096 -1.79  -57
 LST-  1100    .016    .036  2.25   71     .066  4.12   131    -.030 -1.87  -59
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
1100-   HST   4.236  13.289  3.14   99   10.618  2.51    79    2.671   .53   20
= = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = = =
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COMPLETE MASS BALANCE TABLE CALCULATED AND PRINTED BY THE COMPUTER

```
              NVE NIGARDSBRETUNGEN  BD6424-04          DATE  050268  PAGE   11


POLARE STIKNINGSDATA  FRA STASJON:,   W3766

        PUNKT      RETNV.       VINKEL      AVSTAND
       W3767    188.0979        .0000      80.9322

                                                     -- * --


POLARE STIKNINGSDATA  FRA STASJON:,   W3666

        PUNKT      RETNV.       VINKEL      AVSTAND
       W3667    190.7248        .0000      78.9703
```

STAKE MOVEMENT DATA (ANGLES AND DISTANCES) FOR TWO STAKES ON NIGARDSBREEN 1966-67 example of such a table and a stake diagram plotted by the computer are shown among the illustrations. The programs have not been fully completed yet, so no further details can be given.

c) Movement

The movement of a stake can be readily calculated by means of a computer program that gives the co-ordinates for a stake location directly from the angle observations made in the field. The field triangulation can be made from fixed points with known co-ordinates or by resection using known stations. The movement of the stake is directly computed when two sets of field data are given. The distance and the direction of movement is printed out for each stake (see example among the illustrations).

This program is a further development of programs used in terrestrial triangulation.

d) Correlation calculations

The discharge in a glacier stream can be correlated with various independent variables (precipitation, wind, air temperature, etc.).

A visual inspection of diagrams showing daily mean air temperature, precipitation, etc. and water discharge from a glacier can give a subjective impression of the relationship between discharge and various meteorological parameters. Such a study was done for Canadian glaciers (Østrem 1966a) and later discussed by Paterson (1966) and Østrem (1966b).

Based upon this discussion, a method was developed for correlation studies of river discharge in highly glacierized basins and various meteorological parameters.

There is a certain correlation between daily water discharge in the glacier stream and the energy balance (e.g. daily mean air temperature, radiation, precipitation and wind speed on the same day or one or two days before).

A stepwise regression analysis (for details in the special program used in this study, see Wøien 1966) selects the most significant parameters to describe the variation in discharge, and separate equations are given for one, two, or more independent variables included in the regression.

The program will give correlation co-efficients between the variables and their significance and, finally, the resulting regression equations with partial and multiple co-efficients.

It is assumed that studies carried out for the same glacier for a number of years with variable meteorological conditions will form a base for future discharge prediction, and will become vital in the study of the relationship between glacier variations and climate.

APPENDIX

1) Standard forms

At the end of this manual there is included a sample collection of forms that are used by the field parties in their work at the glaciers. The collection is given to show examples of various design; several other solutions are naturally possible.

The following forms are included:

Snow pit measurements
Core auger measurements
Norwegian stake reading form ("Stakemåling")
Norwegian stake redrilling form ("Omboring av staker")
Norwegian stake form ("Stakeprotokoll", mainly used in office work)
Daily meteorological observations
Temperature corrections and daily means (Norwegian form)
Summary of meteorological observations
Stream gauge record
Norwegian silt sample data form ("Slamprøver")
Norwegian photo record form ("Fotojournal")

2) Conversion table

For hydrologic engineering purposes, for example to calculate the expected water yield from a given catchment area, it has proved practical to transform mass balance data into specific discharge figures. The metric unit for mean annual specific discharge is "litres per second per square kilometre" (One l/skm^2 equals approximately 66 acre-feet per sq. mile).

A conversion table that can be used to transform centimetres of water equivalent to l/skm^2 is included at the end of this book.

3) Glacier mass balance terms

Various glaciologists have used slightly different terms in their mass balance studies and this may make comparisons difficult for results obtained in various countries. At a meeting in the International Association for Scientific Hydrology in Berne 1967 it was agreed to standardize glacier mass balance terms. This agreement can be considered as the final result of discussions over several years. One of the most active glaciologists to co-ordinate and standardize mass balance terms has been Dr. M. F. Meier, Tacoma, Washington. His "Proposed definitions for glacier mass budget terms" (see Meier 1962) have been modified but many of them are now included in the standardized system which is published by UNESCO (see Meier 1969).

Accumulation includes all processes that increase the glacier's mass; ablation includes all processes that remove mass from the glacier. This definition is the same as given by Ahlmann, 1948 (p. 15 and 26) and others.

The measurements of glacier mass balance are performed at a great number of points on the glacier surface from which the total values are calculated by integration over the glacier area. At each point the change in glacier mass is measured relative to last year's summer surface; all point measurements are symbolized with small letters. The balance (b) is at any time the change in mass as measured in a point. It can be positive or negative.

One balance year is the time period between the formation of two consecutive summer surfaces*. In the first part of the balance year a curve demonstrating the balance vs. time will show an increasing trend. In the last part of the balance year it will show a decreasing trend. The maximum balance value during the one balance year is called the winter balance (b_w). The time when this maximum value is reached (i.e. the end of the accumulation period) will divide the year into a winter season and a summer season. These seasons were earlier named accumulation season and ablation season.

The winter balance was earlier termed total accumulation (at least by some glaciologists) but it is obvious that some more snow have fallen on the glacier during the winter than will be found at the end of the winter season. A part of the fallen snow may have been removed again by evaporation, wind action, etc. Thus, the "true" total accumulation (c_t) will in most cases be slightly larger than the winter balance but it will be almost impossible to observe.

Changes in mass during the summer season is called summer balance (b_s). This was earlier termed total ablation which strictly speaking was generally larger. Snow that falls during the summer will change the summer balance and make it different from the "total ablation". Such accumulation during the summer was accounted for in a number of ways by different scientists. If the snow melted immediately, it was generally regarded as rain that drained off the glacier, or it was included in the accumulation figures and termed "summer accumulation". It would then be included also in the ablation figures, which made the total ablation correspondingly larger.

The net balance (b_n) is the change in balance during one balance year

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*A balance year according to this definition (the stratigraphic system) will seldom be equal to a calender year. A balance year may also be defined in the "fixed date" system. Its length must then be stated in each case.

and it can be expressed as the algebraic sum of winter balance and summer balance or the sum of total accumulation and total ablation:

$$b_n = b_w + b_s = c_t + a_t$$

Summer balance and total ablation are normally negative, winter balance and total accumulation positive. Net balance may be positive or negative depending upon conditions in the particular balance year. All values are given in m of water equivalent.

Processes that will change the mass of a glacier are generally taking place in a relatively thin surface layer on the glacier. However, as mass balance investigations intend to study the variations in the total mass of a glacier, the sub- and englacial processes should also be studied. These processes are difficult to observe and they will seldom be directly measured. For temperate glaciers the results of subglacial and englacial accumulation and ablation are very small compared with the processes taking place at, or near the surface. The most important process that is taking place under the surface is the vertical mass transport connected with the warming of the glacier in the beginning of the summer season. Snow is then melting at the surface and the melt water percolates down to areas where snow temperatures are still below the freezing point. When this melt water freezes it will release a large amount of heat (80 calories per gram freezing water). Within a short period (from a few days to a couple of weeks) the entire snow pack may become isothermal ($0^\circ C$).

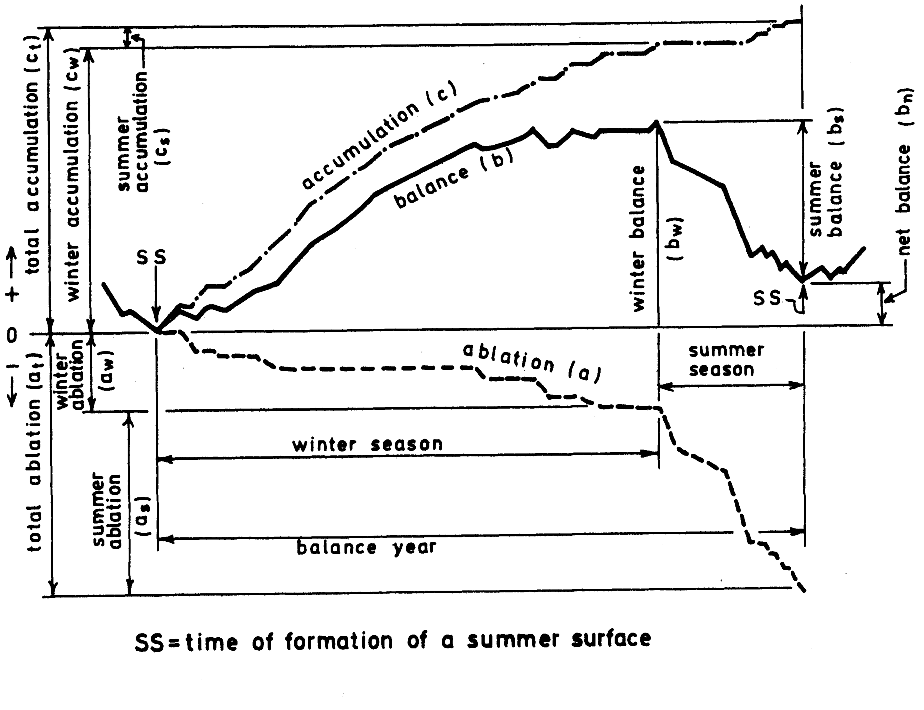
Most of the vertical mass transport will thus stay within the snow pack originating from one and the same winter season. However, a small part of the percolating water may penetrate through the summer surface and freeze within the firn if the firn has negative temperatures. According to the definition (Ahlmann, 1935) temperate glaciers are at the melting point and therefore the firn layers would normally allow percolating water to penetrate down to the glacier bed and leave the basin without refreezing. However, at the end of the summer season part of the firn may be cooled so that negative temperatures occur within the firn. This would cause some refreezing which, in turn, would result in a movement of mass through the summer surface. Thus, some material, i.e. the mass of the percolating water that refreezes in the firn, would not be accounted for in a balance year. To avoid such miscalculations it is necessary to dig pits for snow density measurements beyond the summer surface to check if the density of the firn has changed during the first part of the summer season. Experience has shown that these density measurements should be continued some 50 cm down into the firn. As soon as the firn becomes iso-thermal there is little chance for refreezing of any percolating water.

The amount of refrozen melt water, as calculated from observed variations in the firn density, must be regarded as a part of the glacier's accumulation.

The winter balance (b_W) and the summer balance (b_S) as observed in single points must be integrated for the entire glacier. The terms referring to the entire glacier are analogous with those for single points but they are symbolized with capital letters (B_W, B_S, B_N). They are normally expressed in 10^6 m^3 of water. In many cases it is practical to report average values for the entire glacier or for selected parts. Mean values ($\bar{b}_w$, $\bar{b}_s$, $\bar{b}_n$) are expressed in m of water equivalent. For hydrological calculations they may also be expressed as a specific discharge, using a unit such as litres per second per km^2 (commonly used in Scandinavia). The specific discharge is calculated as a mean for one year.

The balance year is normally of different length on various parts of the glacier and the integration therefore cannot be clearly defined with regard to time. The winter balance is observed as close to the end of the winter season as possible but before any ablation has taken place. During the time period when the snow becomes iso-thermal several ice layers may form in the snow pack (see above) so that snow depth soundings referring to the summer surface will be difficult or impossible to make. It is therefore most important to make the snow survey before the summer season has started. The small increase in winter balance after this survey can be directly measured, at selected points or it may be estimated from meteorological data.

The procedures involved in the integration of point measurements to obtain the winter balance, summer balance and net balance for the entire glacier is described in the chapter concerning office procedures.



SS=time of formation of a summer surface

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A description of the
"SNOW PILLOW"

A CONVERSION TABLE

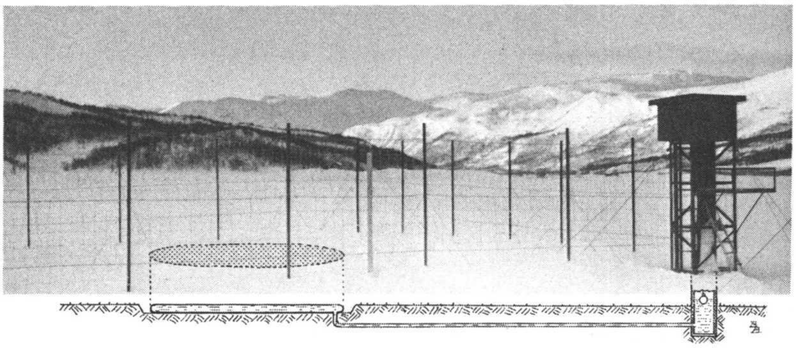
and

SAMPLE COLLECTION OF FORMS

are found in the
following pages.

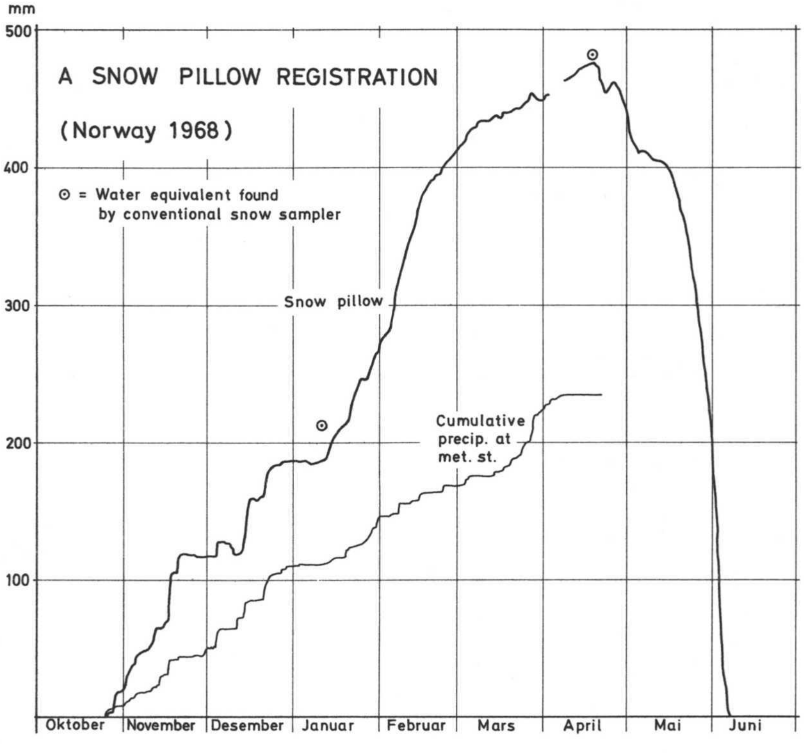
THE "SNOW PILLOW"

The snow pillow is briefly described on p. 27 - 28, being an instrument for snow accumulation studies. Permanent installations of snow pillows were made during recent years in various countries. For Canada the data from a snow pillow on the Blackwall Mountain in Southern British Columbia are regularly published in the B. C. Snow Survey Bulletin. In Norway a snow pillow[*] was first installed in the I. H. D. representative basin on Filefjell (61° N, 8° E) in October 1967. The principle of its installation and the first year's record are shown in the illustrations.



The snow pillow installation on Filefjell, Norway, was protected by a 2-m high fence to avoid damage or disturbances from skiers or animals. The antifreeze liquid level in the vertical stilling well is recorded by a conventional gauging instrument (limnigraph) located in a wooden shelter.

Wind action did not change snowconditions significantly at the pillow except during the first few days of accumulation when some snow was swept away from the pillow's extremely smooth surface.



A diagram showing snow pillow data compared with cumulative precipitation data from a conventional gauge in the vicinity. The results from two direct water equivalent measurements made in January and April are also shown.
The snow pillow recorded less accumulation than the precipitation gauge only during a short period in October (on account of wind action); in April the total snow pack on the ground proved to contain 100 % more water equivalent than was collected in the conventional precipitation gauge during the corresponding time period !

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[*] Manufactured by Trelleborgs Gummifabriks Aktiebolag, Trelleborg, Sweden. The price was approx. $ 550 f. o. b. for the plastic pillow proper.

CONVERSION TABLE

From cm of water equivalent to specific discharge in litres per second pr km^2

1 hydrologic year = $31{,}56 \cdot 10^6$ seconds

1 metre of water equivalent = 31,56 l/s km^2

cm	l/s km^2	cm	l/s km^2	cm	l/s km^2	cm	l/s km^2	cm	l/s km^2
2	0.6	102	32.2	202	63.8	302	95.3	402	126.9
4	1.3	104	32.9	204	64.7	304	95.9	404	127.5
6	1.9	106	33.5	206	65.0	306	96.6	406	128.1
8	2.5	108	34.1	208	65.6	308	97.2	408	128.8
10	3.2	110	34.7	210	66.3	310	97.8	410	129.4
12	3.8	112	35.3	212	66.9	312	98.5	412	130.0
14	4.4	114	36.0	214	67.5	314	99.1	414	130.7
16	5.1	116	36.6	216	68.2	316	99.7	416	131.3
18	5.7	118	37.2	218	68.8	318	100.4	418	131.9
20	6.3	120	37.9	220	69.4	320	101.0	420	132.6
22	7.0	122	38.5	222	70.1	322	101.6	422	133.2
24	7.6	124	39.1	224	70.7	324	102.3	424	133.8
26	8.2	126	39.8	226	71.3	326	102.9	426	134.4
28	8.9	128	40.4	228	72.0	328	103.5	428	135.1
30	9.5	130	41.0	230	72.6	330	104.1	430	135.7
32	10.1	132	41.7	232	73.2	332	104.8	432	136.3
34	10.7	134	42.3	234	73.9	334	105.4	434	137.0
36	11.4	136	42.9	236	74.5	336	106.0	436	137.6
38	12.0	138	43.6	238	75.1	338	106.7	438	138.2
40	12.6	140	44.2	240	75.7	340	107.3	440	138.9
42	13.3	142	44.8	242	76.4	342	107.9	442	139.5
44	13.9	144	45.4	244	77.0	344	108.6	444	140.1
46	14.5	146	46.1	246	77.6	346	109.2	446	140.8
48	15.1	148	46.7	248	78.3	348	109.8	448	141.4
50	15.8	150	47.3	250	78.9	350	110.5	450	142.0
52	16.4	152	48.0	252	79.5	352	111.1	452	142.7
54	17.0	154	48.6	254	80.2	354	111.7	454	143.3
56	17.7	156	49.2	256	80.8	356	112.4	456	143.9
58	18.3	158	49.9	258	81.4	358	113.0	458	144.5
60	18.9	160	50.5	260	82.1	360	113.6	460	145.2
62	19.6	162	51.1	262	82.7	362	114.2	462	145.8
64	20.2	164	51.5	264	83.3	364	114.9	464	146.4
66	20.8	166	52.4	266	83.9	366	115.5	466	147.1
68	21.5	168	53.0	268	84.6	368	116.1	468	147.7
70	22.1	170	53.7	270	85.2	370	116.8	470	148.3
72	22.7	172	54.3	272	85.8	372	117.4	472	149.0
74	23.4	174	54.9	274	86.5	374	118.0	474	149.6
76	24.1	176	55.5	276	87.1	376	118.7	476	150.2
78	24.6	178	56.2	278	87.7	378	119.3	478	150.8
80	25.2	180	56.8	280	88.4	380	119.9	480	151.5
82	25.9	182	57.4	282	89.0	382	120.6	482	152.1
84	26.5	184	58.1	284	89.6	384	121.2	484	152.8
86	27.1	186	58.7	286	90.3	386	121.8	486	153.4
88	27.8	188	59.3	288	90.9	388	122.5	488	154.0
90	28.4	190	60.0	290	91.5	390	123.1	490	154.6
92	29.0	192	60.6	292	92.2	392	123.7	492	155.3
94	29.7	194	61.2	294	93.8	394	124.3	494	155.9
96	30.3	196	61.9	296	93.4	396	125.0	496	156.5
98	30.9	198	62.5	298	94.0	398	125.6	498	157.2
100	31.6	200	63.1	300	94.7	400	126.2	500	157.8

SNOW PIT MEASUREMENTS

.... Glacier
.... Year
.... Location

Date........................
Elevation...................
Snow Sampler type...........
" " X Section Area ....

1	2	3	4	5	6	
Depth	SAMPLE		W. E. wt/area	CUMULATIVE WATER EQUIVALENT	DENSITY	REMARKS
	Length cm.	Weight grams.				

Mean density g/cm^3 Signature____________

CORE AUGER MEASUREMENTS

.......................GLACIER
........19............YEAR
.......................LOCATION

Date..............................
Elevation.........................
Auger type........................
Auger X Section...................

1	2	3	4	5	6	7	8	9	10
Depth (cm)	Penetration, calculated (cm)	Length of sample (cm)	Weight of sample (grams)	Volume of Sample (cm^3)	Sample density (g/cm^3)	Length repr. by sample	Water Equivalent	Cumulative water equiv.	Remarks

Mean Density g/cm^3 Signature..................

Dato-år

NVE-Vassdragsdirektoratet

STAKEMÅLING

Bre

Observatør

Stake nr.	Lengde cm	Sond. cm	Merknader	Stake nr.	Lengde cm	Sond. cm	Merknader

År

NVE-Vassdragsdirektoratet

OMBORING AV STAKER

Bre

Dato	Kl.	Stake nr.	Gammel stake				Ny stake				Ny stake sett fra gammel stake		Årsak til omboring	Merknader
			Al.	Wire	Stål	Total lengde	Al.	Wire	Stål	Total lengde	Avstand	Retning		

STAKEPROTOKOLL

BRE: Stake Al / stål / wire Dim.: Nr: Utsatt: H.O.H.:

Dato	Tid	Topp til			Snötetthet	Snödyp				pål. is		Differens mellom fortlöp. mål.				Sommer-akk.				Sum			St. tot. lengd	Anm.
						sondert		beregnet				snö	is		abl.	snö	ρ	vv	Σvv	Akk.	Abl.	Bal.		
		is	snö	s.o.		snö	v.v.	snö	v.v.	is	v.v.	v.v.	is	v.v.	v.v.					v.v.	v.v.	v.v.		
		cm	cm	cm	g/cm^3	cm	cm	cm	cm	cm	cm	cm	cm	cm	cm	cm	g/cm^3	cm	cm	cm	cm	cm	cm	

DAILY METEOROLOGICAL OBSERVATIONS

........................GLACIER
19..........YEAR
SCREEN ELEVATION..............
SCREEN LOCATION..............

TIME ZONE GMT, MOUNTAIN, PACIFIC
TYPE OF RECORDER.................

DAY	DATE	SUNSH. HRS.	SOLARIMETER READING	DAILY max/min	TIME CHECK	TEMP.		PPT. mm's.	WIND		WEATHER	VIS.	TOTAL	CLOUD-give in 1/10 listing ht. (low, med, high) & a description of type 1/10th ht. and type	REMARKS & OBSV.
						Hg.	Graph		m/sec	direction					

NVE-Vassdragsdirektoratet

GMT ☐
Norsk normaltid ☐

Termogram

År

Stasjon

Dato	Tid	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Sum	T_m	Merknader
	T diagram																											
	T Hg																											
	T korr.																											
	T beregnet																										☐	
	T diagram																											
	T Hg																											
	T korr.																											
	T beregnet																										☐	
	T diagram																											
	T Hg																											
	T korr.																											
	T beregnet																										☐	
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SUMMARY OF METEOROLOGICAL OBSERVATIONS

......................GLACIER
.........19...........YEAR

MONTH......................
MET SCREEN ELEVATION.........
MET SCREEN LOCATION.........

Day	Date	max/min	Temp °C	Sub Totals	Degree days	Sub totals	Hrs. sunsh.	Sub totals	Pp m.m.	Sub totals	Cloud 10th	Other
	1											
	2											
	3											
	4											
	5											
	6											
	7											
	8											
	9											
	10											
	11											
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	22											
	23											
	24											
	25											
	26											
	27											
	28											
	29											
	30											
	31											

Signature..............................

................GLACIER
19..........YEAR

STREAM GAUGE RECORD

TIME ZONE.....................
GAUGE TYPE....................
GAUGE LOCATION................

DRAINAGE AREA GLACIER..........km^2 Basin................km^2

DAY	DATE	HOUR	GAUGE HT.		DISCHARGE m^3/Sec.	DAY	DATE	HOUR	GAUGE HT.		DISCHARGE m^3/Sec.	DAY	DATE	HOUR	GAUGE HT.		DISCHARGE m^3/Sec.

År

NVE - Vassdragsdirektoratet

SLAMPRØVER

Sted for prøvetagningen

Nr. (dato - tid)	Prøvens volum (ml)	Vann-stand (cm)	Vass-føring (m^3/s)	Været da prøven ble tatt	Prøvetakerens navn	Filter	Merknader

BL M-6071

Måned - år

NVE-Vassdragsdirektoratet

FOTOJOURNAL

Film nr.

Bre

Eks. nr.	Dato	Tatt av	Tid	Blender	Motiv og evt. kommentarer	Fotoretn.	Fotopunkt

Bl. M-6060