Environment Canada Environnement Canada

Study of Sentinel Glacier, British Columbia, Canada within the International Hydrological Decade Program

Procedures and Techniques

O. Mokievsky-Zubok

TECHNICAL BULLETIN NO. 77
(Résumé en français)

INLAND WATERS DIRECTORATE,
WATER RESOURCES BRANCH,
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The author is grateful to Dr. A.D. Stanley, Glaciology Division, Inland Waters Directorate, and Dr. J.P. Johnson, Jr., Carleton University, Ottawa, Ontario, for their valuable comments and suggestions throughout this study.

Abstract

Sentinel Glacier, considered to be representative of many glaciers in the Mount Garibaldi area of British Columbia, is one of the glaciers studied as part of the Canadian contribution to the International Hydrological Decade (IHD) program. Situated in a maritime climate and subject to high winter precipitation, it presents many problems in obtaining the mass balance. Field work techniques and problems are discussed in this report.

Résumé

Le Glacier Sentinel est considéré comme étant représentatif de plusieurs glaciers situés dans la région du Mont Garibaldi en Colombie Britannique. Il est l'un de ceux qui ont été étudiés dans le cadre de la contribution canadienne à la Décennie Hydrologique Internationale (DHI). Le calcul de son bilan massique pose beaucoup de difficultés en raison du climat maritime dans lequel il se trouve et des précipitations importantes qu'il reçoit durant l'hiver. Ce rapport expose les techniques utilisées ainsi que les problèmes rencontrés durant cette étude.

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O. Mokievsky-Zubok

INTRODUCTION

Glaciers, as natural phenomena and convenient reservoirs and regulators of water, have received special attention in the last few decades. The need for glaciological research was emphasized by the General Assembly of the International Association of Scientific Hydrology (IASH), which was held in Helsinki in 1960 (IUGG/IASH, 1961). At that meeting more comprehensive work on glaciers was recommended to the Commission of Snow and Ice. The program subsequently prepared by the Subcommittee on Variation of Existing Glaciers, was a major step forward in international glaciological research and was accepted by the Commission of Snow and Ice at the Symposium of Obergurgl in 1962 (IUGG/IASH, 1962).

Research and planning of water resources require:

a) determination of the role of glaciers in the hydrologic cycle (recommended by the Subcommittee on Variation of Existing Glaciers, 1962).

b) evaluation of fresh water resources in the world for the proper management of the present balance (Resolution of the IHD Co-ordinating Council I-7, 1965).

When it became apparent that there was a need, at the international level, to standardize terminology and methods for glacier studies (Meier, 1962), special consideration was given to a fundamental aspect of glaciology, that is, the measurement of glacier mass balance (IUGG/IASH, 1962). This need for the study of glaciers, combined with purely hydrologic problems led the 1964 General Conference of the United Nations Educational, Scientific and Cultural Organization (Unesco) to implement the world-wide IHD program on glaciers in Resolution I-13 Unesco/NS/198.

The second major objective, the quantitative determination of fresh water in different forms (IHD Resolution I-7), implies rational planning of its use. Glaciers are an important element in any program because they store 3/4 of the earth's fresh water and cover 11% of the land surface. The Canadian portion of this is estimated by the author to be 40,486 km^3 of water in a frozen state, which is about 17,000 km^3 more than the amount of water stored in the Great Lakes.

In southwestern Canada, a chain of five glacier basins – Peyto, Ram River, Woolsey, Place, and Sentinel – were selected for a long-term detailed study of mass and water balance. This part of the Canadian contribution to the IHD program began in 1965. The study at Sentinel Glacier was started in 1966. Responsibility for carrying out these studies was given to the Glaciology Section, Geographical Branch, Department of Mines and Technical Surveys which is now the Glaciology Division, Water Resources Branch, Inland Waters Directorate, Department of the Environment.

Choice of a glacier for study depends on several factors: its size, distinctiveness of accumulation area, representativeness of the other glaciers in the area, topographic characteristics, and the nature of the meltwater channel. Sentinel Glacier has easy accessibility, and, although small, is very representative of other glaciers in the vicinity with a distinctive accumulation area.

Sentinel Glacier is the most westerly of the five glaciers and occupies a key position in the IHD glacial network (Kasser, 1967), because it is situated at a junction of the north-south chain running from Alaska to South America and the east-west chain of glacier basins in the Canadian Cordillera, Europe, and Asia.

The studies made on Sentinel Glacier include:

a) measurement of the accumulation of snow and the ablation of snow and ice;

b) recording of meltwater discharge and meteorological data;

c) relating glacier fluctuation to past and present climatic trends.

This study deals with the methods employed in obtaining mass balance and with the problems involved. Comparison and evaluation of results are dealt with in other reports (Mokievsky-Zubok, 1973a,b). The methods employed were: direct surface measurement, terrestrial photogrammetry, and hydrologic record of water discharge.

GENERAL DESCRIPTION

Site

Sentinel Glacier (49°54′ N latitude, 122°59′ W longitude) is located in Garibaldi Provincial Park, 70 km north of Vancouver, in the Coast Mountain Range of Western Canada (Fig. 1). The glacier is influenced by a maritime climate; it has a high winter precipitation with seasonal snow cover ranging from 4 m at its tongue to more than 9 m at higher elevations.

Figure 2. View of the lower part of Sentinel Glacier (photograph by Water Survey of Canada).

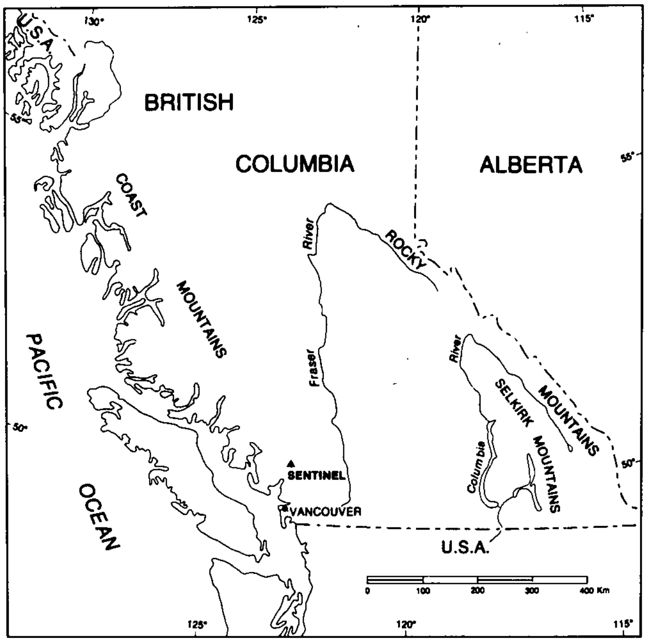

Figure 1. Sentinel Glacier, location map.

Figure 3(a). Crevasse near stake no. 60 in the upper basin of Sentinel Glacier (photograph by S. Bunge).

Topography

Sentinel Glacier occupies a basin facing north on the northeast side of Garibaldi Névé, which extends from the Glacier Pikes at 2158 m asl down to Garibaldi Lake at 1478 m asl. The ice cover is nearly 2 km^2, i.e., about 45% of the total basin above the stream gauge located approximately 700 m upstream from the lake at an elevation of 1500 m.

Glacier surface

Sentinel Glacier ranges in elevation from 1550 m to 2100 m asl with an average gradient of 17°. This steep gradient contributes to an irregular pattern of snow accumulation and uneven melt, and, in combination with high precipitation and extreme variability of surface topography (including a major ice fall and crevasses in many areas), accentuates the practical problems encountered in obtaining mass balance data.

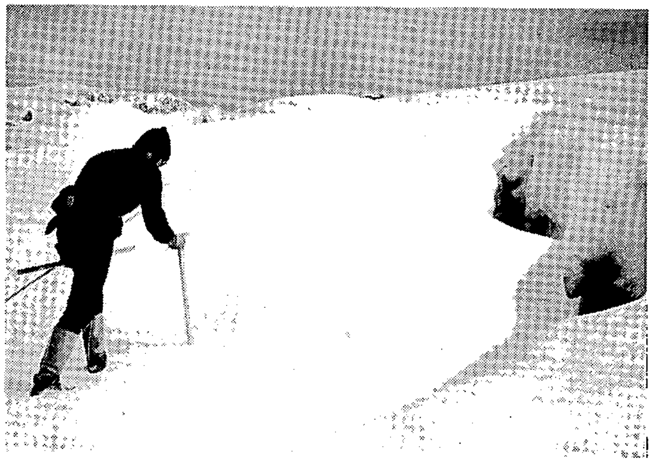

Figure 3(b). Crevasse near stake no. 90 in the upper basin of Sentinel Glacier.

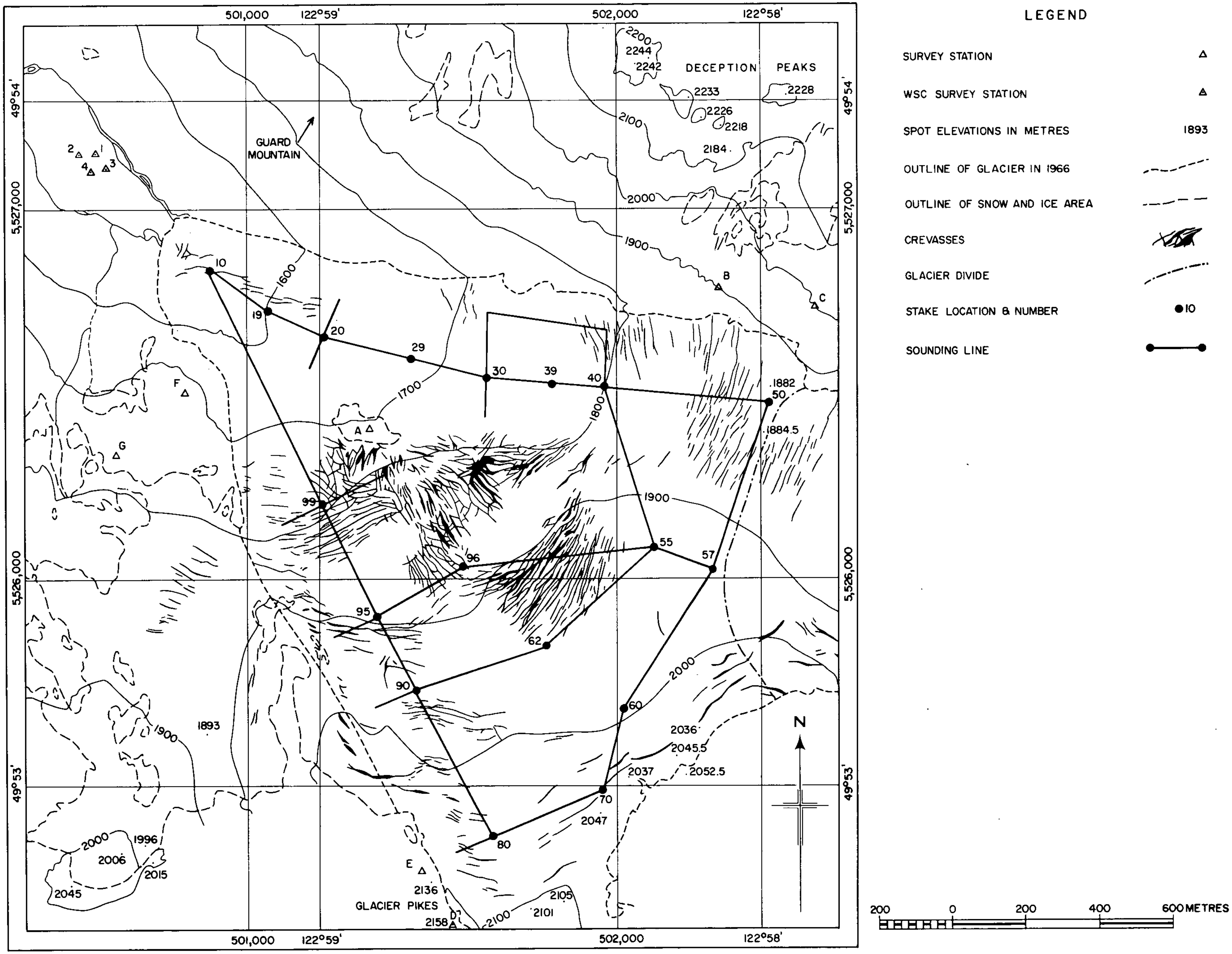

Figure 4. Map of provisional stake net, sounding profiles and survey points, Sentinel Glacier.

The glacier surface has two distinct units separated by the firn line at an approximate altitude of 1800 m. Below the firn line, the tongue area (Fig. 2), is ice and is an area relatively simple in configuration. There are few crevasses and moulins near the tongue; therefore snow soundings are easier to take and more reliable. Above the firn line, in the glacier's catchment basin, the surface is irregular. The surface topography and the ice falls suggest that a large bedrock knob protrudes into the ice at the centre of the glacier, just above the snow line. From there the undulating snow surface rises steeply against the valley walls. The western part of the glacier has an assemblage of concave and convex areas with numerous crevasses probably overlying an uneven surface. Crevasses vary in size but the more prominent are more than two meters wide (Fig. 3).

During the accumulation period snow is blown from ridges and exposed areas to fill depressions both on and off the glacier. Concave and convex areas are levelled so that the slopes become uniform. The underlying glacier's surface is responsible for major difficulties in determining the true depth of snow cover, however, because, within a distance of 100 m to 200 m, winter snow depths may vary by as much as 5 m. This is a common occurrence around ablation stakes 50, 55, 57, 60, 80, 95, and 96 (Fig. 4). Uncertainty in identifying a former summer's surface, owing to the presence of ice lenses (which may be mistaken for either glacier ice or firn), may lead to an underestimation of winter accumulation in the area.

Nonglaciated part of the basin

Sentinel Glacier is surrounded by several prominent peaks and high ridges, whose steep slopes contribute runoff waters to the glacier's meltwater stream. Snow avalanches occur on steep slopes on both sides of the valley, from Guard Mountain (2186 m) to and along Deception

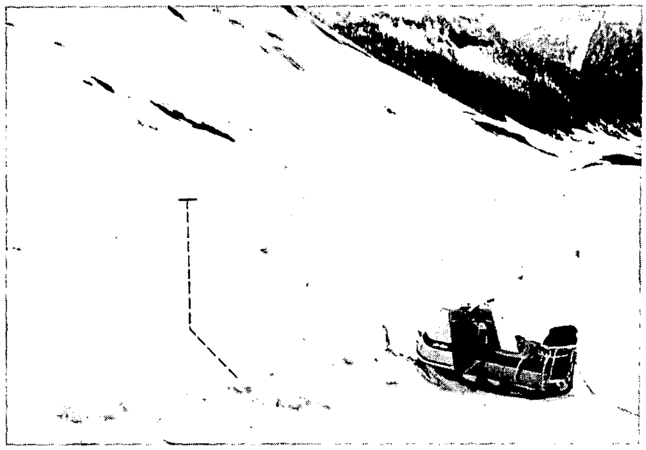

Figure 5(a). Avalanche path, Sentinel Glacier.

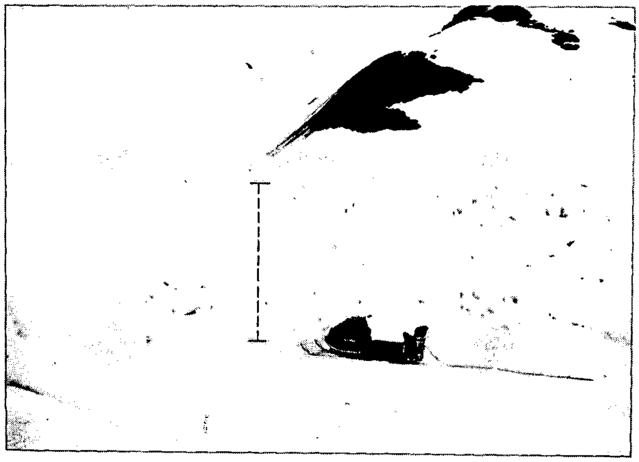

Figure 5(b). Avalanche terminus on the tongue of Sentinel Glacier.

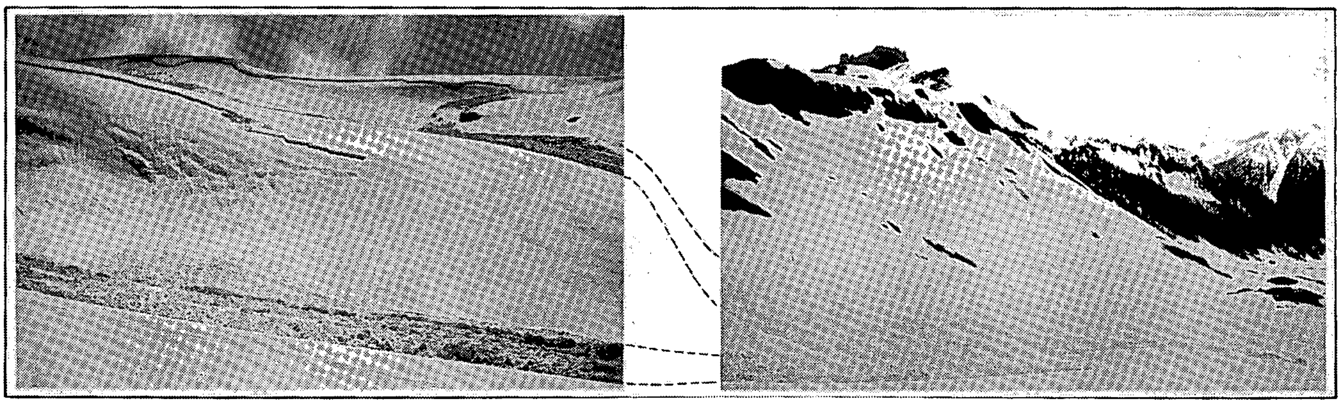

Figure 5(c). Avalanche area on western slopes, Sentinel Glacier.

Peaks (2231 m) on the eastern side; and from Glacier Pikes (2158 m and 2136 m) to survey point G (Figure 4) on the western side.

Nonglaciated slopes are stable on the eastern side of the valley. Kame terraces and the lower slopes, recently freed of ice, are still covered with loose morainic material. Sparse vegetation covers the upper portion, but diminishes with elevation, or towards the wind exposed areas.

Western slopes which are much steeper and less stable, are covered with loose material eroded by runoff water. Vegetation is found only above these slopes on a plateau. The rumbling of small and large boulders down the slopes often disrupts the peacefulness of the area. Small mudslides are also common after heavy rains.

Avalanches do little to influence the mass balance: a few reach the glacier on the eastern side. (In 1967 a base camp located 400 m below the glacier was partly destroyed.); on the western side, however, they originate in the inaccessible upper parts of the basin, a short distance above the ice, and, on their way down, redistribute snow to the lowest part of the tongue (Figures 5a,b,c,d). At the southern limits of the basin above Sentinel Glacier's bergschrund only a narrow nonglaciated band is snow-free in summer.

HISTORY

Fluctuations

Despite heavy snowfalls the glacier is steadily retreating. This action may be a reflection of a relatively warm trend of the last four to five decades, as indicated by meteorological records (Powell, 1965). The ice front has retreated 1.6 km from the position at Garibaldi Lake shown in a photograph taken in 1923 (Fig. 6).

From the photograph taken in 1923 it is possible to estimate the location of the glacier terminus at that time. It coincides closely with remnants of prominent end moraines which extend across the valley at the southern end of Garibaldi Lake. The conclusion, therefore, is that the moraines were developed when the glacier was in a stationary position. However, this may not have been Sentinel Glacier's maximum extent. "Mountain glaciers attained a greater rise in the eighteenth and nineteenth centuries than at any time since the waning of the Late Wisconsin ice sheet . . ." says Mathews (1950, p. 369). As Sentinel Glacier lies within a triangle of glaciers investigated by Mathews (Lava, Sphinx, and Warren), it is most likely that its maximum extent would be in close agreement with the maximum extent of these three in the first half of the eighteenth century. It seems reasonable to assume that Sentinel Glacier reached the lake and was calving ice into lake waters prior to the beginning of its retreat at that time.

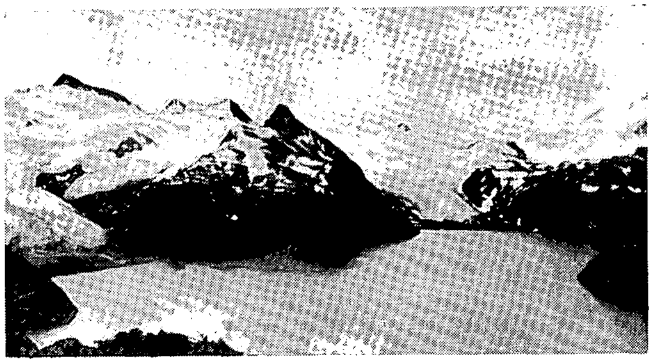

Figure 6. Glacier terminus in 1923 (photograph by W. Crane).

The retreat did not proceed at a constant rate, and the moraines were probably formed during a stationary period that coincides with the cold spell around 1880. A warming trend started at the beginning of this century; by 1923 when the photograph (Fig. 6) was taken, the tongue had thinned and the glacier began an accelerating retreat that still continues. The average retreat from 1923 to 1966 was 32 m/yr. For the last six years, from 1966 to 1972, the rate of horizontal retreat was 24 m/yr.

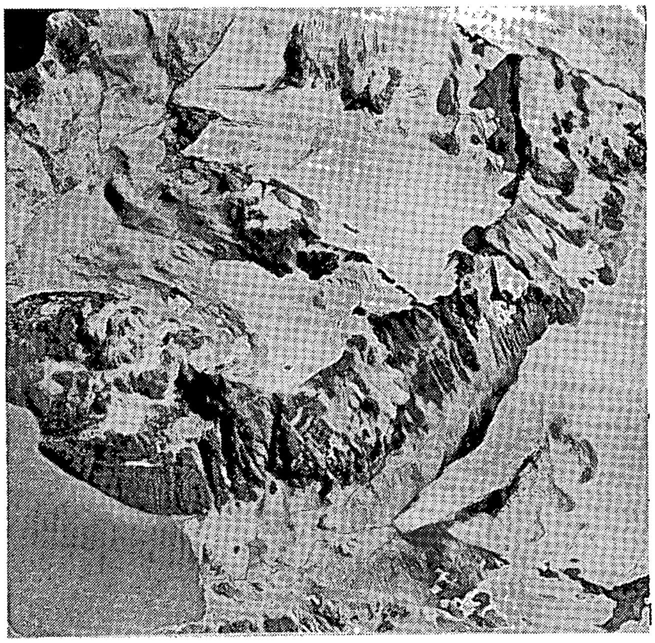

Figure 7. Aerial photograph of Sentinel Glacier Basin showing position of ice front (Flight No. 19219, August 7, 1965, Department of Energy, Mines and Resources).

The Age of Sentinel Glacier – Radiometric Dates

During the Hypsithermal period in Post-Wisconsin times the whole Sentinel Glacier Basin became clear of ice and was subsequently covered by a thick forest of large fir trees (*Albies sp.*). In the summer of 1970 retreating ice exposed numerous fragments of wood that had been preserved in a sheltered area below a rock face. The ends and sides were worn off most of them thereby indicating transport by ice or subglacial water.

The author found one piece of wood, apparently the outer part of a much larger log, embedded in a moraine approximately 2000 m from the glacier's known maximum extent, and 400 m above the 1970 position of the terminus. The site is 400 m lower in elevation than the glacier summit and 1200 m distant from it. The Radiocarbon Laboratory of the Geological Survey of Canada (GSC) dated it at 6170 ± 150 years B.P. (4220 B.C.). The information (GSC 1477, Radiocarbon dates) indicates that a forest probably covered the entire basin at that time and that Sentinel Glacier has developed in the last 6000 years. Other finds in the Mount Garibaldi area confirm this deduction. Thus, GSC 760 Radiocarbon Dates VII and Y-140 (Yale V, Radiocarbon) show that fragments of wood found, exposed by retreating glaciers, were of the ages 5950 ± 140 (4000 B.C.) and 5260 ± 200 (3310 B.C.), respectively.

FIELD WORK, MEASUREMENTS, AND PROBLEMS

Field Activities

Each summer, since the initiation of studies in 1966, the field season at Sentinel Glacier has begun about the middle of May.

The base camp at Sentinel Glacier consists of two huts, originally A-frame shaped and suitable for two persons each. One of the huts was destroyed by a snow avalanche in the winter of 1967. Due to a shortage of lumber and because an A-frame construction proved to be very restrictive, the hut was rebuilt so as to eliminate one slanted wall of the A-frame (Fig. 8a,b,c).

On the day of arrival the camp is converted into livable quarters and tents are raised for storing everything needing protection from inclement weather. Meteorological instruments intended for use at the base camp are installed the same day.

Glaciological measurements begin the next day: A provisional stake net is set up on the glacier and the first density pit dug. After four or five days the base camp is in full operation and initial glaciological measurements are

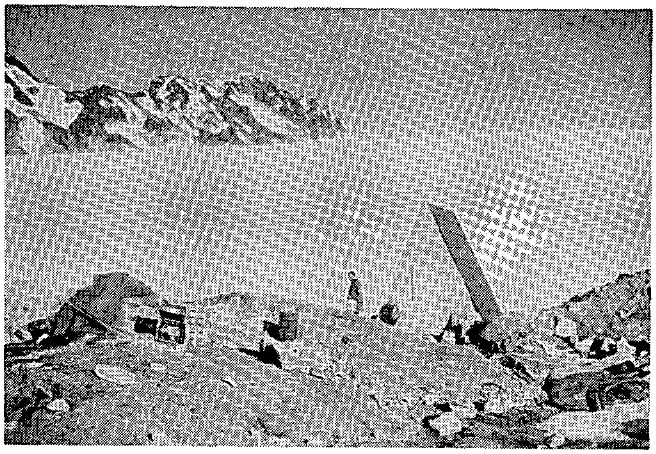

Figure 8(a). A-frame hut at the base camp (original structure).

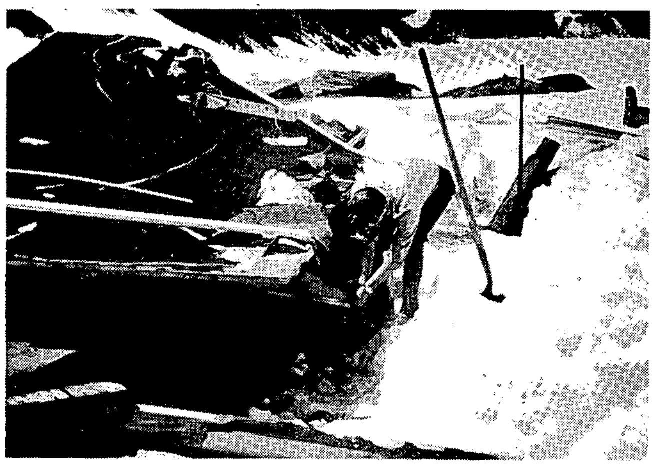

Figure 8(b). A-frame hut crushed by snow avalanche in 1967.

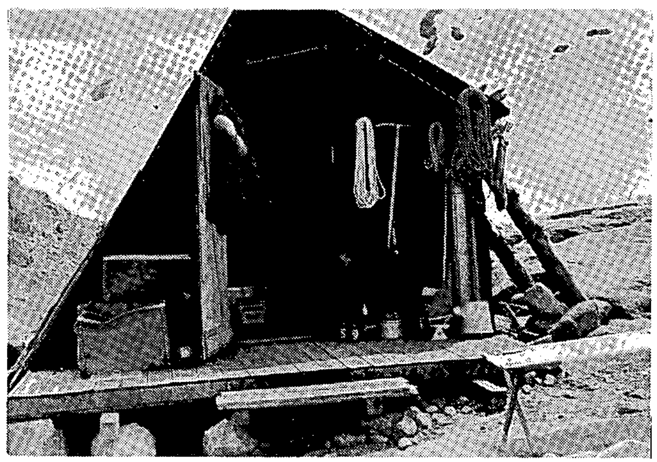

Figure 8(c). A-frame hut after rebuilding in 1968.

taken. After completion of work on Sentinel Glacier, Place Glacier, located approximately 80 km NE, is set up in a similar manner. Sentinel Glacier is manned throughout the ablation season. From there, visits to Place Glacier are made once a month to take glaciological measurements and to carry out surveying.

Unpredictable weather, characteristic of the West Coast maritime climate, often disrupts schedules. The distruption is most pronounced when helicopter flights are involved.

The ablation season ends when the first major snowfall covers the entire glacier, usually, the end of September or the beginning of October. After this time no further records are kept to provide data on winter conditions (see "Meteorological Instrumentation" Sumner Long Period Recorder).

Glaciological methods

Standard mass balance measurements (Østrem and Stanley, 1966) were carried out to obtain data in compliance with recommendations made by the Subcommittee on Existing Glaciers to the Commission of Snow and Ice of IASH and accepted in a resolution at the Symposium of Obergurgl, 1962 (pp. 306-309).

The methods employed at Sentinel Glacier were:

1. Two surface balance methods: a) Method 1, in which the difference between net accumulation and net ablation was obtained. Field measurements closely followed procedures outlined by Østrem and Stanley (1966). b) Method 2 (alternate method), where mass balance was determined by subtracting the remaining snow cover from ice and firn ablation. Number 2 is similar to the methods employed on Hintereisferner Glacier by Hoinkes and Rudolf (1962).

Results of both methods were compared each year to determine which one was more accurate and to see whether methods of measurement could be improved.

2. Geodetic method (terrestrial photogrammetry), in which the change in the volume of the glacier was calculated from the measured change in absolute surface elevation. (In this report it will be referred to as the "photogrammetric method").

There is another method for determination of mass balance, the hydrologic one, in which hydrologic measurements provide the amount of melt calculated as the difference between precipitation and runoff. A comparison of the ablation determination by any other method with this one was not made, however, because the research on discharge components of the monitored meltwater stream from Sentinel Glacier Basin has not yet been completed.

Equipment and techniques

Mass balance determination at Sentinel Glacier could not have been performed without the seemingly unimportant but essential auxiliary equipment like shovels, tapes, mallets and hammers, wrenches, 50-m long measuring rope; basic tools like saws, screwdrivers, files, and safety equipment including ice screws, carabiners, climbing ropes, crampons, etc.

The basic glaciological equipment consisted of:

1. Various snow augers including the SIPRE coring drill and a Mt. Rose sampler. They were tried in determining snow density, which is an integral part of any mass balance measurement, but neither proved satisfactory for Sentinel Glacier snow conditions. The SIPRE coring drill rarely recovered a full core and the Mt. Rose sampler was unable to penetrate ice lenses.

The most common technique for determining density involved the manual excavation of snow using a snow density kit consisting of: a steel tube sampler 7.27 cm in diameter (cross-sectional area 41.5 cm^2), a rubber mallet, a small spring balance of 1 kg capacity, a scale, and a small bag in which to weigh snow samples.

As a snow pit was deepened, one side was cut evenly so that a surface was left undisturbed for sampling (Fig. 9). Sampling began from the surface when the depth of the pit reached approximately 2 m. At a depth slightly less than the length of the sampler a steel plate was pushed or hammered horizontally into the pit wall. The cylindrical sampler was then pushed downward until it reached the steel plate. The length of the snow sample was determined by subtracting the length of the empty part of the sampler from its total length.

The snow sample was cut from the snow surrounding it and slid along the plate to the edge and into a small bag. Normally the sample would slide out of the tube into the bag, and both the bag, of known tare weight, and the sample were weighed on a spring balance. This procedure was repeated for snow samples down to the ice or, if the pit was in the firn area, to 50 cm below the previous summer's surface. Density was determined by dividing the weight of the sample by its volume, and the water equivalent by multiplying density by the length of the sample.

2. A snow sounding rod to measure the total thickness of winter snow cover over the glacier by probing. The type employed was made of aluminum tubing, 1 cm in diameter and with 1-m extensions. A steel point on the end of the probe had a diameter slightly larger than the rest of the rod to facilitate pushing the rod into the compacted snow. This was screwed onto the first extension. The extensions were marked at 1-cm intervals with particular markings every 10 and 50 cm from the ends.

Accumulation measurement at Sentinel Glacier often required probes 10 m long. If the probe was more than 5 m long, it became progressively difficult to keep the rod vertical owing to its flexibility, especially in gusty winds. Owing to hard snow and working in the wind, sounding rods soon became bent. Once the rods were bent it was difficult to straighten them and keep them straight. A stronger type of sounding equipment is needed for glaciers with accumulation values similar to those for Sentinel Glacier.

The technique used to obtain snow depth readings was very simple: the rod was pushed into the snow perpendicular to the slope to reduce deflection by ice lenses. The measurement shown on the rod was read to the nearest centimetre.

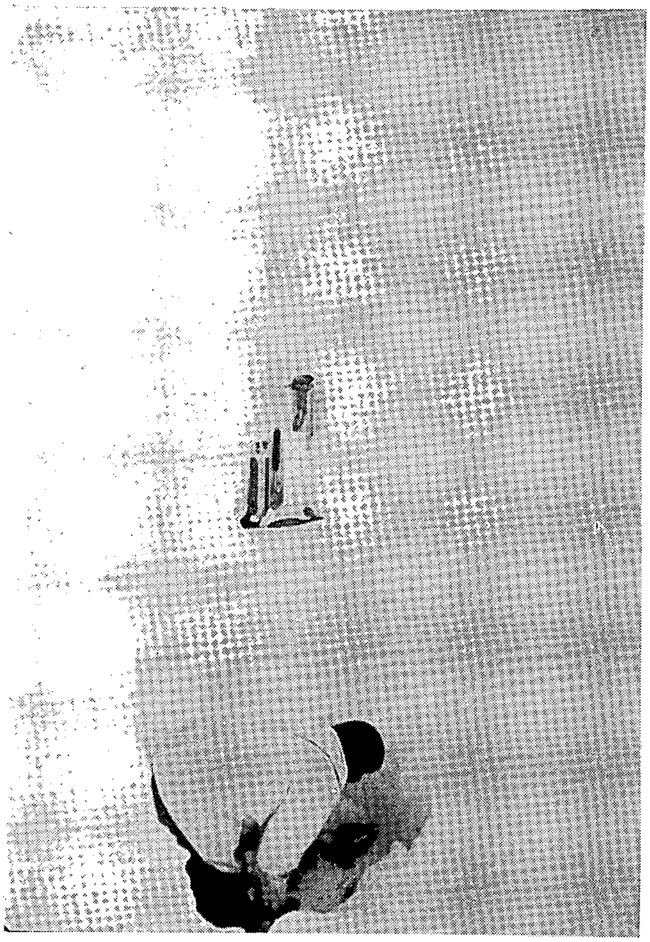

Figure 9. Digging a snow pit for density measurements.

3. Standard ablation stakes used on all Canadian IHD Program glaciers. The stakes were made of aluminum alloy tubing, (Alcan "65ST6") 31.75 mm (1.25 in) in outer diameter and with a wall thickness of 1.651 mm (0.065 in) (Østrem and Stanley, 1966). Ablation stakes were used to measure the lowering of the snow or ice surface. In fog they also served well for orientation of crew working on the glacier. The stakes generally survived snow creep and rarely were they snapped off. However, most of those placed on a slope were found bent by early summer.

Ablation stakes were distributed across the glacier to cover all representative topography points. The density of the distribution was approximately 17/km^2; this coverage compared well with the recommended density of 10-20/km^2 (Schytt, 1962; Hoinkes and Rudolf, 1962; Keeler, 1964).

Two techniques were used to insert stakes; one for snow and firn, the other for ice. The first was used at the beginning of the season when the entire glacier was covered by snow, and later on, in the firn area of the upper part of the glacier. A hole was drilled in the snow with a SIPRE coring drill to a depth of 4-5 m. A SIPRE coring auger kit consists of a steel core barrel, several extension rods, and a modified carpenter's brace. The steel barrel produces a 72.2-mm (3 in) diameter core. The overall length is 91.44 cm (36 in). The barrel has a welded double helix flight configuration and a large flange at the top to allow passage of the cuttings and recovery of the core. A cutting shoe is attached to the bottom of the barrel.

Drilling holes for stakes was a fatiguing process as the drill did not always recover the full core and frequently jammed before the desired depth was reached. The stake was then inserted with an empty can taped to the bottom of the stake to prevent it from sinking further into the snow. The stake and can were lowered into the drill hole and snow was tramped around the stake to keep it vertical. Stakes were marked with dymo-taped numbers; the length of stake protruding above the snow was measured and recorded together with soundings of the snow depth.

4. A hand-operated ice drill was used to insert stakes into the ice and reset stakes that melted out of the ice. Although there are several other mechanical ways to insert stakes (e.g., hot-point drill, motorized auger), the hand-operated ice drill proved to be practically the most acceptable for the work on Sentinel Glacier. The use of this drill eliminated the transporting of heavy and cumbersome equipment; only manual skill was required to operate it in the predominantly wet ice conditions. Holes into which stakes were inserted were drilled only to a depth of 3-4 m as it was difficult to reach greater depths.

A complete ice drill consisted of a 1-m long steel tube with four teeth bent inwards, aluminum extension 1 m long, and a handle for rotating the set. As teeth break, the tube is shortened to allow room for a new set of teeth to be sawn. In two to four field seasons the cutting tube may be shortened by 30-40 cm.

Drilling was a difficult time-consuming operation for two reasons:

i) the teeth bent and broke easily and it was difficult to set them at the proper angle for cutting;

ii) water collected in the drill hole during the drilling operation melted or washed down the ice chips before they could be retrieved at the surface, thus slowing the operation.

5. Other equipment:

a) Masonite plates – Plates of masonite were placed on the stakes at the end of the ablation season to facilitate identification of the previous summer's surface (Østrem and Stanley, 1966); they were not useful at Sentinel Glacier because the accumulated snow was too deep. By the end of winter neither stakes nor plates could be located.

b) Magnets – Another technique that did not work was an attempt to detect stakes within the snow cover by placing commercial magnets, 10 cm long and 3 cm in diameter, on the stakes in the fall. The magnets could not be detected with a magnetometer through 5 m of snow.

An alternative, the installation of a provisional stake net, proved to be satisfactory. Fifteen to 17 stakes were placed into the snow at points that best represented the surrounding area. These stakes were located along the longitudinal profile of the glacier, preferably close to the existing permanent stakes covered by winter snow. Provisional stakes were inserted in late spring concurrently with winter balance measurements. The purpose of the provisional stake net was to serve in measuring snowmelt until the previous year's ablation stakes appeared. Melt data were transferred to the nearest permanent stake, as it was assumed that the melt, to that date, was similar for both. Ablation measurements were carried on until the end of the melt season.

Observations and Measurements

As part of the basic work on mass balance, meteorological observations and hydrologic measurements were carried out during the ablation season from mid-May to October. They varied from simple visual observations to continuous records of automatic instruments.

Meteorological observations

The relationship between climatic parameters and glacier melt is a very important factor in studying glacier behaviour and mass balance. For glaciers in the Canadian IHD program, considerable attention is paid to collections of meteorological data. On Sentinel Glacier data were collected daily; observations and readings of instruments were taken four times a day for temperature, relative humidity, wind direction and wind velocity, radiation, precipitation, sunshine hours, and minimum temperature in snow. Visual observations of visibility, fog, cloud cover in tenths, height and type of clouds, and present weather were also recorded.

Collected data were reduced and analyzed and also tabulated in graphic form for visual examination. Graphs for 1966 to 1972 are presented in Appendix I.

Meteorological instrumentation

Each summer from 1966 until October of 1971, short term recorders were used to measure climatological and hydrological parameters relevant to the glaciological studies. There were two stations: one at the base camp (elev. 1540 m asl) and the other in the upper basin (elev. 2030 m asl).

The base camp station was equipped with: thermohygrograph, totalizing anemometer, sunshine recorder, solarimeter, barograph, and simple precipitation gauge (Pluvius type).

In the upper basin the following instruments were installed: thermohygrograph, pyrheliograph, and simple precipitation gauge (Pluvius type).

In addition seven precipitation gauges were distributed across the glacier. All Pluvius-type gauges were replaced in 1971 by the larger MSC-type (Meteorological Services of Canada) rain gauges. The need for the latter was dictated by frequent losses due to overflow from the Pluvius-type gauges during heavy rains. In the autumn of 1970, two MK11 Sumner Long Period Recorders were installed at the base camp to record temperature, relative humidity, wind direction, and wind velocity during the winter months.

Hydrologic observations and instruments

Meltwater from Sentinel Glacier flows into two separate channels for approximately 800 m before joining into one stream that runs into Garibaldi Lake. The site for hydrological measurements is located approximately 30 m below the channels' confluence and discharge measurements (Appendix II) were made each year to determine the rating curve. Both Gurley current meter and chemical (salt

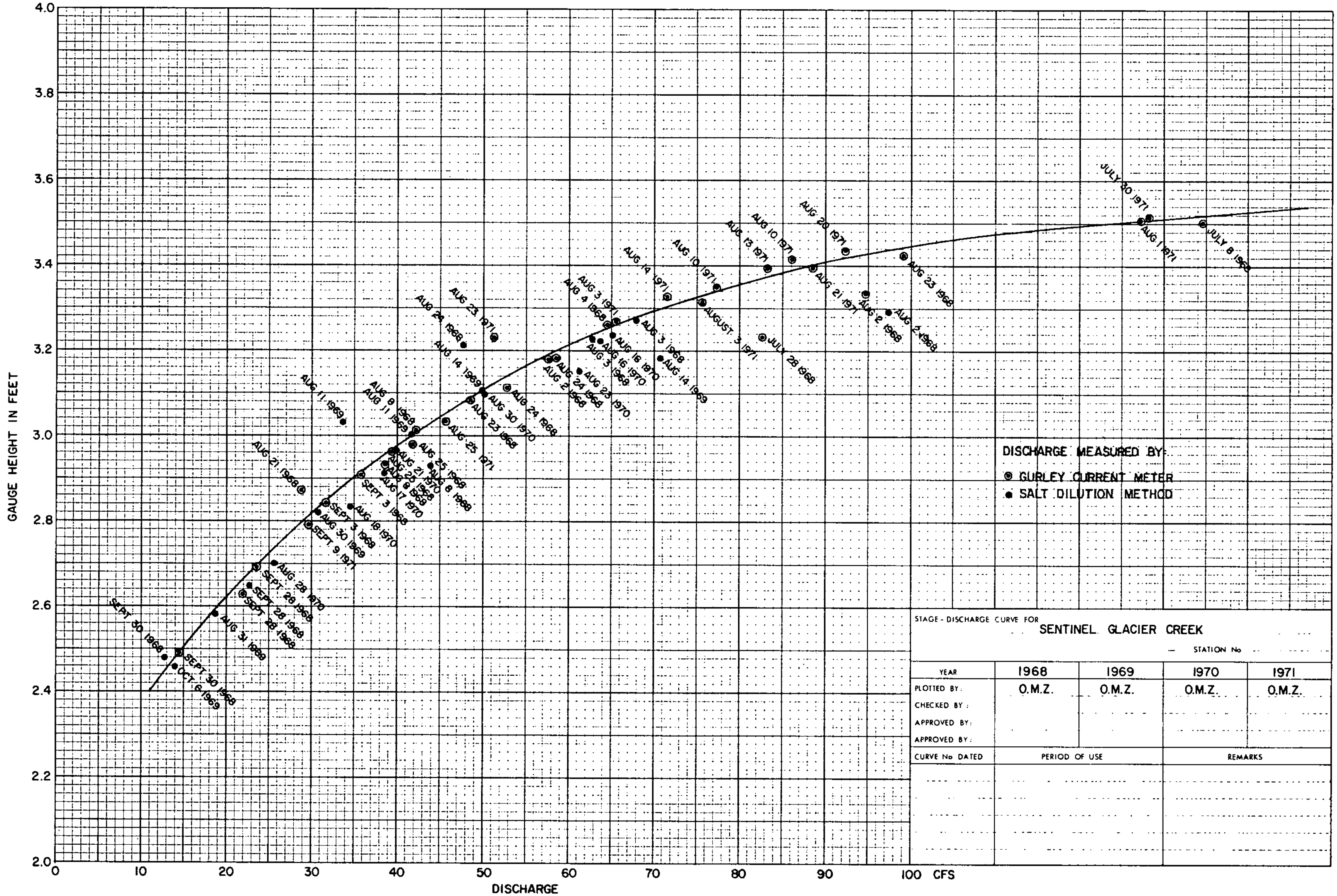

Figure 10. Rating curve for Sentinel Creek.

dilution) methods were employed for the first 3 years. Recordings of the water level were made with a Stevens A-35 automatic stage recorder. As agreement was usually close, the chemical method was discontinued (Fig. 10).

The discharge at the gauging site is not the actual meltwater discharge from the glacier. Some distance ahead of the point of confluence of the two channels, several small creeks and groundwater from the unglaciated part of the basin join the meltwater streams, thus increasing the actual meltwater volume at the recorder site. To determine the contribution of non-glaciated parts of the basin, a separate project is currently underway to determine the meltwater component alone. V-notch weirs were constructed on four prominent side creeks and water recorders installed. Because of the shallow flows a Pigmey current meter was used to measure discharge and to establish a rating curve.

If winter flows and the amount of groundwater entering the glacier creek could be determined, hydrological studies on the glacier would be improved. Therefore, studies including installation of a new water recorder, protected during the winter months from snow, freezeups, and flood waters, and the construction of an artificial channel bed were planned for the summer of 1973.

Irregularities Affecting Measurements

Sentinel Glacier's topography and its location in a maritime climate are responsible for creating practical problems in the measurements of true snow depth and in other glaciological and hydrological measurements. These problems were a direct result of wind accumulation pattern, ice layers, and sudden releases of meltwater.

Wind and accumulation pattern

Accumulation patterns at Sentinel Glacier vary from year to year. Changes in the direction of prevailing winds give pattern variations to snow distribution on the glacier. Precipitation increases with elevation during the summer. Table 1 shows the precipitation distribution for both summer and winter. In 1971, the summer precipitation was collected on the glacier by using, for the first time on Sentinel Glacier, the large MSC rain gauges.

In winter the distribution of precipitation is controlled by wind, but there appears to be no definite pattern of accumulation; from year to year, nevertheless, some areas of the glacier surface can be predicted to have higher amounts of snow. For example, the area around stake no. 70 (Table 1) shows less accumulation than the areas at lower elevations between stakes 39 and 60, except for the year 1969 when the pit site was moved further down from stake no. 70. In contrast, the area at stake no. 80, behind a ridge slightly higher and about 300 m west, always has very high accumulation, as illustrated in the first two lines of the winter precipitation part of Table 1. Sounding values at stake no. 70 are given for comparison; both stakes are in the upper part of the catchment basin, one having nearly the lowest and the other nearly the highest snow depth values. These snow depth values, however, relative to other areas with high accumulation, change from year to year as a result of prevailing winds, which are normally from west or southwest. Whenever this is the case, snow from Glacier Pikes slopes fills in the gully where stake no. 80 is located. If the wind direction is from the south or southeast a little extra snow is accumulated in this area because winds sweeping over the col have only a small area for deposition. On the other hand, wind from the same direction would deposit blowing snow around stakes no. 57 and no. 60 from the surrounding ridges, including the area of no. 70.

Changeable wind directions in the Sentinel Glacier basin during winter storms influence accumulation patterns

TABLE 1. Precipitation patterns on Sentinel Glacier.

SUMMER PRECIPITATION

Elev. (m)	Stake no.	Total (mm) Sept. 24
2030	70	700.1
1950	90*	918.6
1920	55	679.1
1880	50	659.3
1810	99*	582.7 to Sept. 4
1700	30	626.2
1570	10	438.1 to Sept. 4
1540	Base Camp	443.9

*Locations of stakes no. 90 and no. 99 are on the leeward side of the ridges.

WINTER PRECIPITATION (Initial snow depth, cm)

Elev. (m)	Stake No.	1968 May 26	1969 June 1	1970 May 18	1971 May 21	Remarks
2060	80	589	712	628	912	Sounded at stake
2030	70	602	500	452	525	Sounded at stake
2020	70	512	629	395	581	Pit measur. 50 m away from no. 70
1920	55				658	According to pit measurement
1880	50			501		"
1720	39	621		390		"
1700	30		515			"
1640	20	481			569	"
1570	10		320	314		"

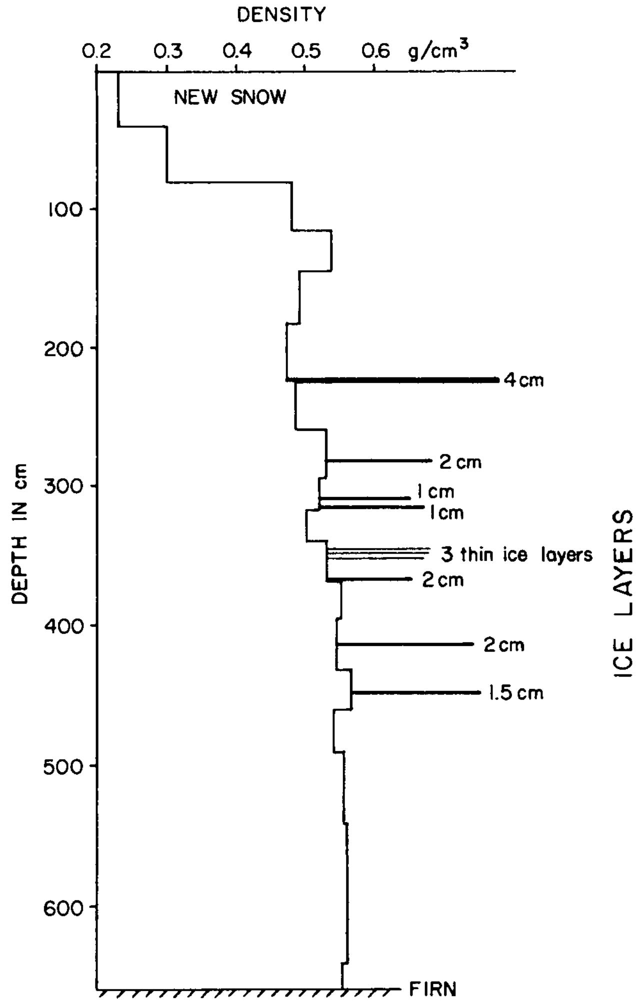

Figure 11. Sentinel Glacier: density profile and frequency of ice layers on 21 May, 1971. Snow pit location at stake no. 55.

over the glacier surface and render an accurate assessment of total winter accumulation difficult.

Ice layers

To obtain an accurate evaluation of the snow volume collected between the end of one ablation season and the start of another, it is essential to find the correct position of the previous summer's surface. In some years warm spells in the autumn may melt the new snow, and, when this happens, water percolates through the snowpack to freeze at the ice surface and form ice lenses in the firn area as well as superimposed ice in the tongue area. Ice layers can also form by melting during warm periods in October, November, and later in winter during periods of winter ablation. Such ablation periods are confirmed by the nearest Meteorological Station at Alta Lake 22 km north and 665 m lower in elevation.

When the temperature drops, after each warm spell, the snow surface freezes forming an ice crust. This may become thicker if there is more new snow, which in turn is melted by another warm spell. The water which percolates downwards reaches the ice crust and freezes thereby increasing the thickness of that layer. Indications of winter melt periods are found during the following field season when snow is probed or pit dug. Figure 11 shows a density profile and the frequency of ice layers. Ice layers, 3-4 cm thick, are encountered in various sections of the glacier each summer. The areal extent is indicated by probing and may vary from small patches to the entire glacier surface. If the layer is thick and impenetrable to snow sounding rods, is constant over a large area, and is located approximately one m above the previous summer's surface, it may be mistaken for the last summer's surface; thus winter accumulation could be erroneously underestimated.

To determine the thickness of the snowpack, pits are dug at about the same time as probing of the entire glacier takes place. Due to the glacier's topography, changeable

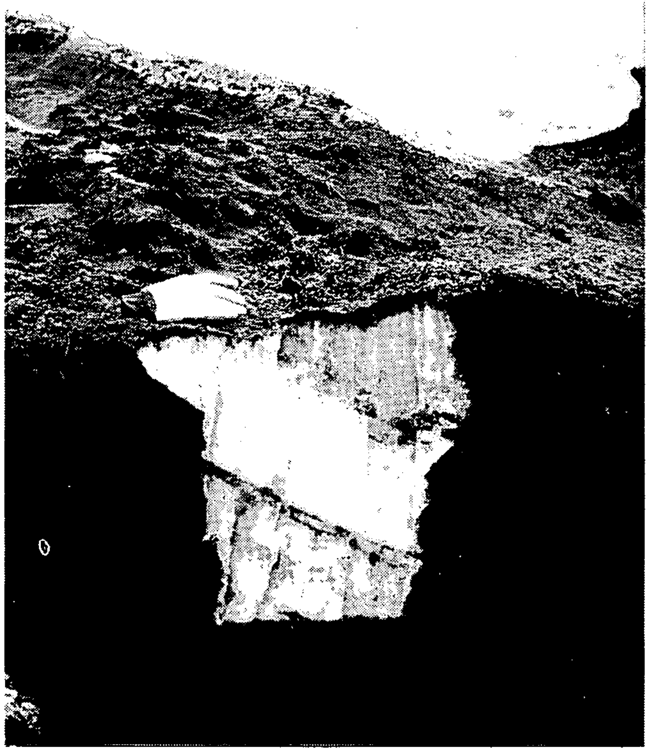

Figure 12(a). Effects of winter flooding: brown snow under sediments.

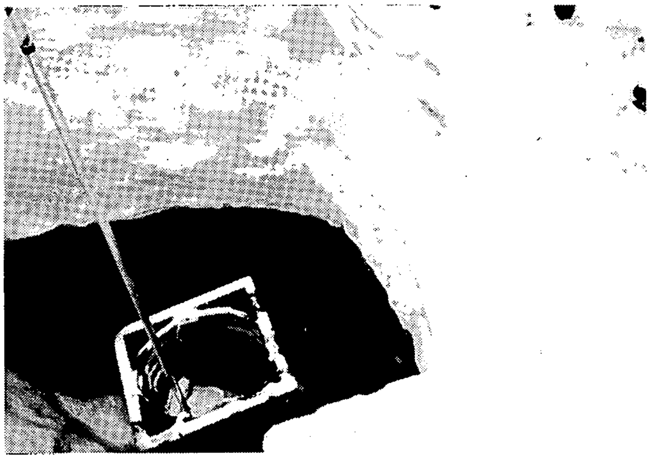

Figure 12(b) Effects of winter flooding: tilted water-recorder well and differentiation in snow colours.

accumulation patterns, and several ice layers in the profile, however, it is a difficult task to determine snow depth in the areas away from pit sites, especially in the firn area.

Determination of the old firn surface is a problem even without ice lenses within the snow. The interface of compacted new snow and firn may not be well defined and,

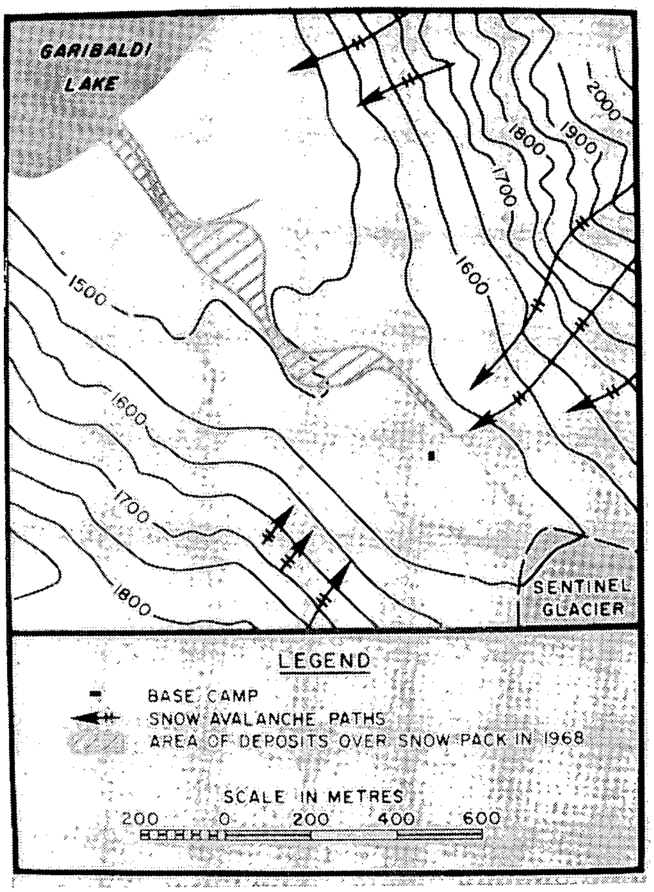

Figure 13(a). Location of deposits of debris on snow pack.

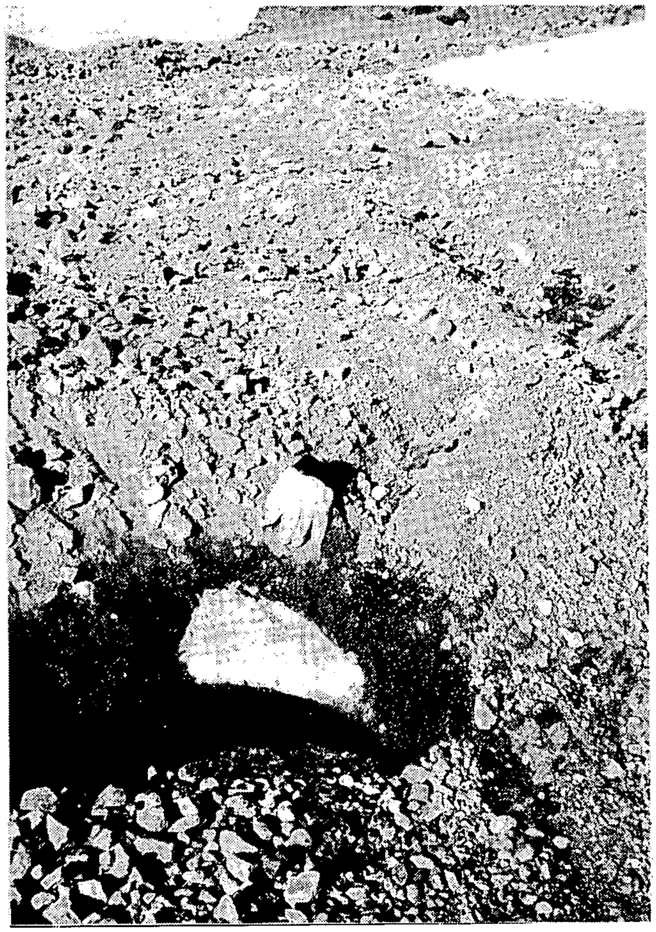

Figure 13(b). Mixed sediments on snow pack.

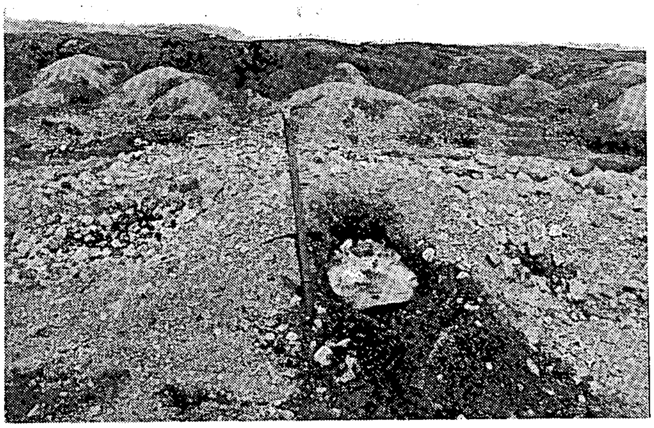

Figure 13(c). Sorted sediments (background) on snow.

after the probe is passed through several crust surfaces or ice lenses, it becomes difficult to recognize the true firn. To overcome difficulties of this nature the best solution remains to have more pits dug.

Winter flooding and sudden discharge of meltwater

Hydrological studies of melt flow at Sentinel Glacier were affected by sudden discharges of accumulated glacier meltwaters. The only outburst reported on Sentinel Glacier, previous to this study, was noted by Mathews in 1946. Based on his observations that the water burst forth near the firn line, leaving a trail of sediment on the snow and cutting a deep trench (6 m) into the glacier ice, Mathews (1949) assumed that the source of water was within the glacier.

A similar outburst occurred in the proglacial zone; the author noted it in May 1968 while digging through 6 m of snow to free the stream gauge located 800 m downstream from the glacier tongue. The upper part of pit wall was composed of white snow whereas the lower part consisted of brownish snow with numerous crust surfaces and brown ice layers (Figs. 12a, b).

During the period May-June, melting snow revealed a layer of sediments comprised of silt, sand, gravel, and rock fragments, generally well sorted, incorporated within the snowpack (Figs. 13a,b,c). A comparatively small area had mixed sediments overlain by rock fragments up to 15 cm long.

This debris was deposited by one or more large flows of water and covered level areas beginning 350 m downstream from the glacier. It closely followed the course of the meltwater channel and was as much as 100 m wide and approximately 1.0 km long. Its estimated volume was $6.6 \times 10^3 m^3$.

Sedimentation occurred while the ground was covered with snow several metres thick. Meteorological records from the nearest meteorological station at Alta Lake and preliminary research (Mokievsky-Zubok, in preparation) indicate that sedimentation took place in January of 1968, at a time when winter stream flow was negligible. It was determined, however, that some rock fragments must have been transported by water, moving with a velocity of not less than 3.2 m/s, that flooded the area (average river velocity in summer is 0.69 m/s).

This flooding had unfavourable consequences on the initial stages of discharge measurements at the beginning of the field season. The stage-recorder well was silted up and tilted owing to snow creep caused by the increased density of the snow saturated by flood waters. Resurveying of the position of the well and consequent adjustments in discharge measurements as well as in the rating curve were necessary. Apart from that, the flow of water in winter months may be a partial explanation for the disagreement in figures correlating river discharge and glacier melt.

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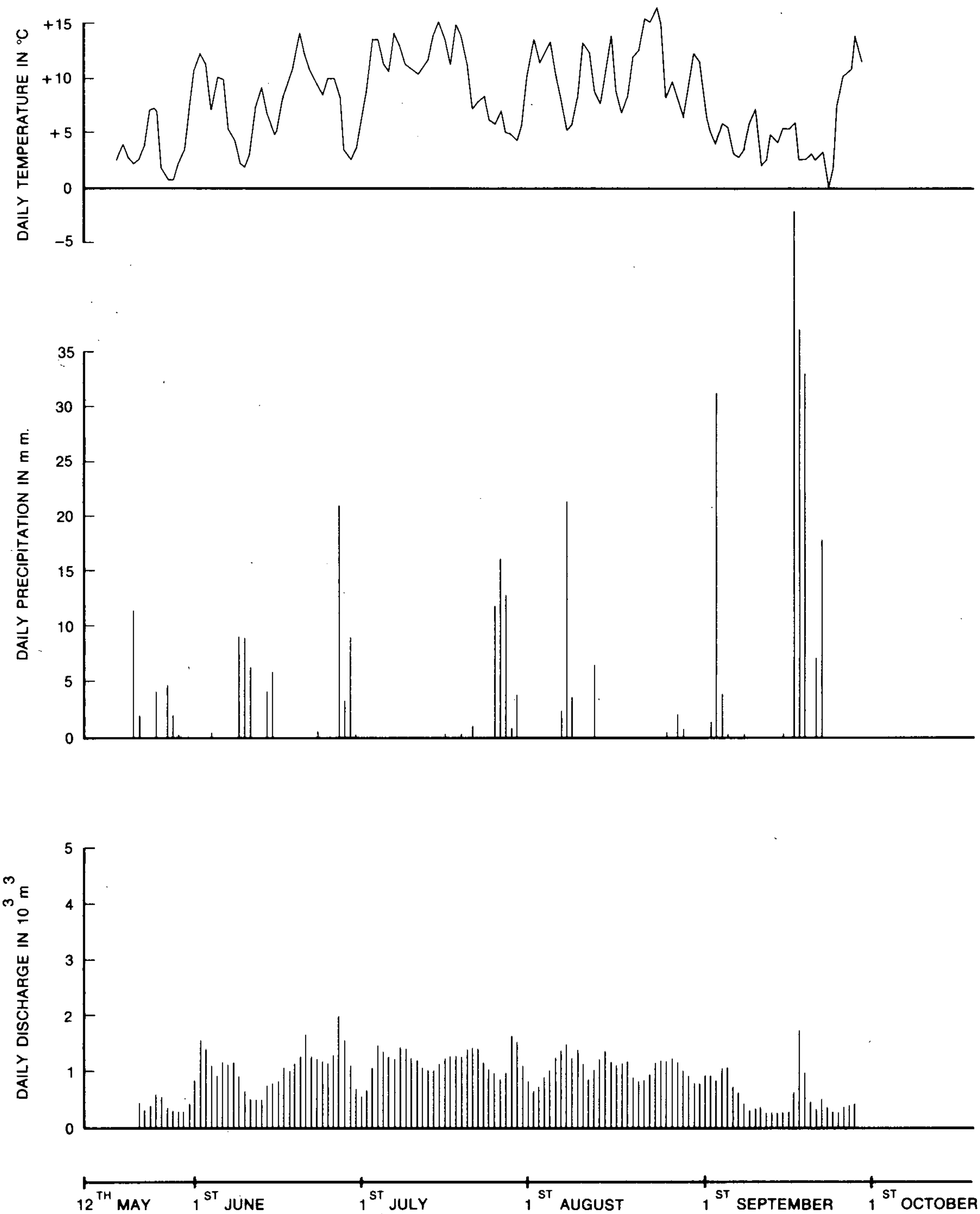
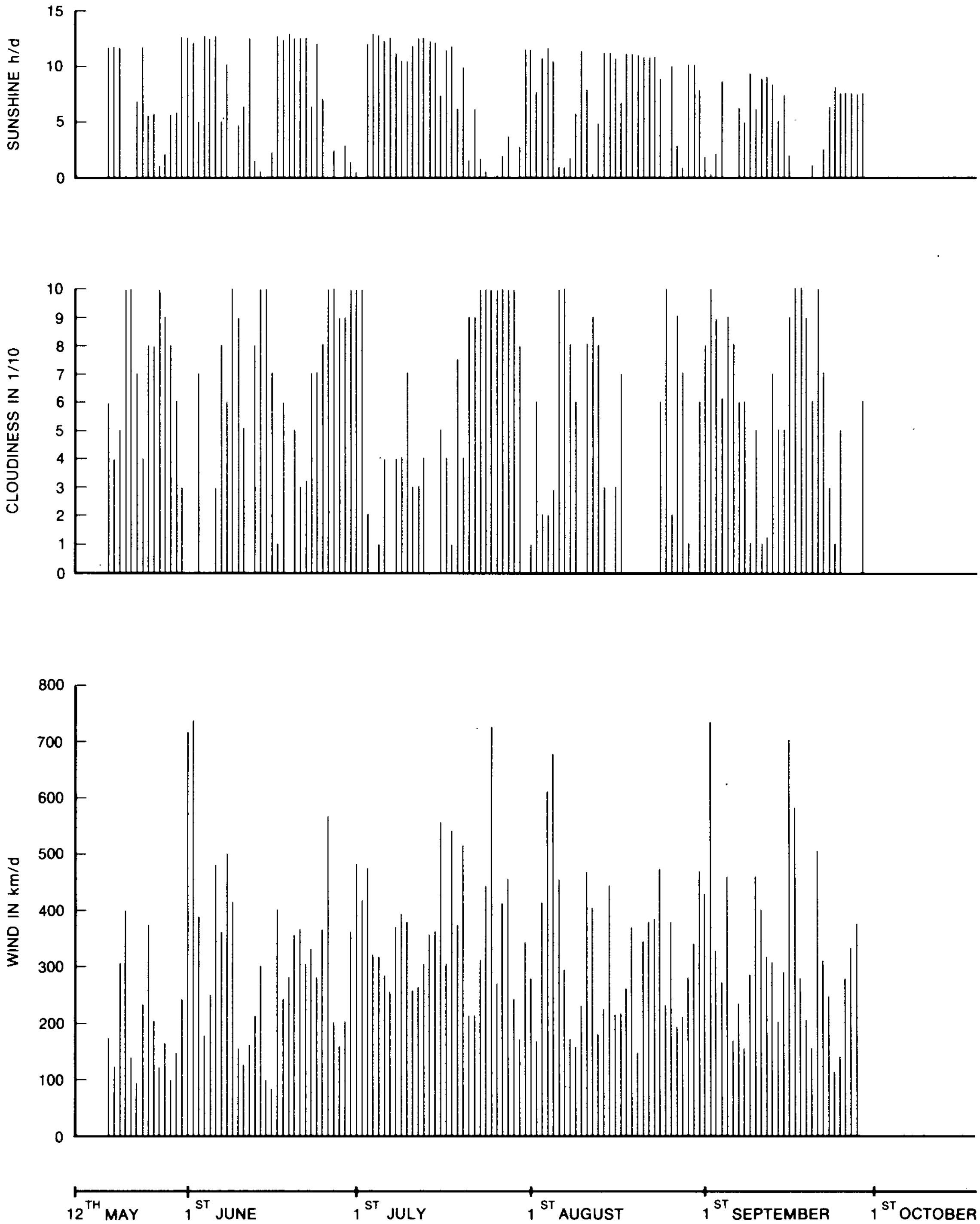
Appendix I

Samples of Summarized Meteorological Parameters and of River Discharge



DAILY TEMPERATURE IN °C
+15
+10
+5
0
-5
DAILY PRECIPITATION IN m m.
35
30
25
20
15
10
5
0
DAILY DISCHARGE IN 10³ m³
5
4
3
2
1
0
12TH MAY
1ST JUNE
1ST JULY
1ST AUGUST
1ST SEPTEMBER
1ST OCTOBER


15
10
5
0
SUNSHINE h/d
10
9
8
7
6
5
4
3
2
1
0
CLOUDINESS IN 1/10
800
700
600
500
400
300
200
100
0
WIND IN km/d
12TH MAY
1ST JUNE
1ST JULY
1ST AUGUST
1ST SEPTEMBER
1ST OCTOBER

Appendix II (a)

Samples of Discharge-Measurement Computations Made in the Field (Gurley Current Meter)

DEPARTMENT OF NORTHERN AFFAIRS AND NATIONAL RESOURCES

WATER RESOURCES BRANCH

DISCHARGE MEASUREMENT NOTES

Date August 10 19 71 No. of Meas. 6

Sentinel Cr. River at W.L.R.

Width 18' Area 23.7 sq.ft Mean vel. 3.63 Cor. M.G.H. 3.42

Party Jordan and Gray Disch. 85.95

Gauge, checked with level and found ..

Measurement began at 1725 Measurement ended at 1750

First reading of gauge 3.41 ft. at 1715 | Meter No. 1-190

Gauge 3.41 ft. at sta. at 1725 | Date rated

" " at | Method of meas.

" " at | No. meas. pts. Coef.

Last reading of gauge 3.42 ft. at 1750 | Av. width sec. Av. depth

Weighted mean gauge height Correct mean gauge height 3.42

Meas. from cable, bridge, boat, wading; Meas. at 10 ft. above, below gauge.

If not at regular section note location and conditions

Date of Standard Soundings used

Method of suspension Stay wire Approx. dist. to W.S.

Arrangement of weights and meter; top hole; middle hole; bottom hole

Gauge inspected, found; Cable inspected, found

Distance apart of measuring points verified with steel tape and found

Wind - upstr., downstr., across. Angle of current

Observer seen and book inspected

Examine station locality and report any abnormal conditions which might change relation of G. Ht. to discharge, e.g., change of control; ice or debris on control, backwater from; condition of station equipment none

Sheet No. 1 of 2 sheets.

DEPARTMENT OF ENERGY, MINES AND RESOURCES

0·00 0·10 0·20 0·30 0·40 0·50 0·60 0·70 0·75

R. 19
(9-67)

INLAND WATERS BRANCH - WATER SURVEY OF CANADA

CURRENT METER NOTES

Date Aug. 30 19 69 A.M. P.M. Stream Sentinel

Party O.M.-Z Locality Gage Site

Meter No. 1-528 Gauge height, beg. 2.82 end 2.82 mean 2.82

Total Area 15.25 Mean Velocity 2.02 Discharge 30.78 cfs = /0.87m³/se

OBSERVATION					COMPUTATIONS				
Dist. from initial point	Depth	Depth of observation	Revolutions	Time in seconds	Velocity At point	Velocity Mean in vertical	Area	Width	Discharge
0	LB		16	; 55					
2	0.5	0.3	10	52.5	0.44		1.25	2.5	0.55
3	0.7	0.4	15	52.5	0.65		0.7	1.0	0.46
4	1.2	0.7	20	42.5	1.04		1.2	1.0	1.25
5	1.2	0.7	30	55	1.21		1.2	1.0	1.45
6	1.3	0.8	80	42	4.18		1.3	1.0	5.44
7	1.2	0.7	80	53	3.30		1.2	1.0	3.96
⊙ 8	1.3	0.8	60	49	2.69		1.3	1.0	3.50
9	1.2	0.7	60	44	2.99		1.2	1.0	3.59
10	1.1	0.7	60	48	2.74		1.1	1.0	3.02
11	0.9	0.5	60	50	2.64		0.9	1.0	2.38
12	0.8	0.5	60	59.5	2.22		0.8	1.0	1.78
13	0.8	0.5	40	63	1.40		0.8	1.0	1.12
14	0.8	0.5	30	58	1.15		0.8	1.0	0.92
15	0.6	0.4	20	41.5	1.07		0.6	1.0	0.64
16	0.6	0.4	15	42	0.80		0.9	1.5	0.72
17	RB		17:	20			15.25	17.0	30.78

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DEPARTMENT OF NORTHERN AFFAIRS AND NATIONAL RESOURCES

WATER RESOURCES BRANCH

DISCHARGE MEASUREMENT NOTES

Date Aug. 30 1969. No. of Meas. 5

Sentinel Cr. River at Garibaldi L.

Width 17.0 Area 15.25 Mean vel. 2.02 Cor. M.G.H. 2.82

Party O.M.-Z P.J. Disch. 30.78 cfs = 0.87 m³/sec

Gauge, checked with level and found O.K.

Measurement began at 16⁵⁵ Measurement ended at 17²⁰

First reading of gauge 2.82 ft. at 16⁵⁵ | Meter No. 1-528

Gauge 2.82 ft. at sta. ... at ... | Date rated ...

" ... " ... at ... | Method of meas. Wading

" ... " ... at ... | No. meas. pts. 15 Coef. ...

Last reading of gauge 2.82 ft. at 1720 | Av. width sec. ... Av. depth ...

Weighted mean gauge height ... Correct mean gauge height 2.82

Meas. from cable, bridge, boat, wading; Meas. at 10 ft. above, below gauge.

If not at regular section note location and conditions ...

Date of Standard Soundings used ...

Method of suspension ... Stay wire ... Approx. dist. to W.S. ...

Arrangement of weights and meter; top hole ...; middle hole ...; bottom hole ...

Gauge inspected, found O.K.; Cable inspected, found ...

Distance apart of measuring points verified with steel tape and found ...

Wind ... upstr., downstr., across. Angle of current ⊥

Observer seen and book inspected ...

Examine station locality and report any abnormal conditions which might change relation of G. Ht. to discharge, e.g., change of control; ice or debris on control, backwater from; condition of station equipment O.K.

Sheet No. 1 of 2 sheets.

DEPARTMENT OF ENERGY, MINES AND RESOURCES

0·00 0·10 0·20 0·30 0·40 0·50 0·60 0·70 0·75

R. 19
(9-67)

INLAND WATERS BRANCH—WATER SURVEY OF CANADA

CURRENT METER NOTES

Date August 10 1971 A.M./P.M. Stream Sentinel Cr.

Party Jordan and Gray Locality Garibaldi Lake

Meter No. 1-190 Gauge height, beg. 3.41 end 3.42 mean 3.42

Total Area 23.7 Mean Velocity 3.63 Discharge 85.95 cfs

OBSERVATION					COMPUTATIONS				
Dist. from initial point	Depth	Depth of observation	Revolutions	Time in seconds	Velocity: At point	Velocity: Mean in vertical	Area	Width	Discharge
0	R.B.								
1'	1.0	0.60	40	50		1.79	1.0	1.5	1.79
2'	1.2	.72	50	50		2.24	1.2	1.0	2.69
3'	1.1	.66	60	43		3.11	1.1	1.0	3.41
4'	1.3	.78	50	42.5		2.62	1.3	1.0	3.41
5'	1.6	.96	80	50		3.56	1.6	1.0	5.70
6' ⊙	1.9	1.14	100	48		4.62	1.9	1.0	8.78
7'	1.9	1.14	100	45		4.93	1.9	1.0	9.37
8'	1.9	1.14	150	61		5.45	1.9	1.0	10.35
9'	2.0	1.20	100	42		5.28	2.0	1.0	10.56
10'	2.0	1.20	150	55		6.04	2.0	1.0	12.08
11'	1.8	1.09	150	67.5		4.93	1.8	1.0	8.87
12'	1.7	1.02	50	49		2.28	1.7	1.0	3.88
13'	1.4	.84	40	47		1.91	1.4	1.0	2.67
14'	1.1	.66	30	57		1.19	1.1	1.0	1.31
15'	0.9	.54	15	42.5		.81	0.9	1.0	0.73
16'	0.5	.30	10	49.5		.48	0.5	1.0	0.24
17'	0.4	.24	5	46		.27	0.4	1.5	0.11
18'	L.B.						23.7		85.95

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DEPARTMENT OF NORTHERN AFFAIRS AND NATIONAL RESOURCES

WATER RESOURCES BRANCH

DISCHARGE MEASUREMENT NOTES

Date Sept. 3 19 68 No. of Meas. 15

Sentinel River at Garibaldi L.

Width 15 Area 18.0 Mean vel. 1.76 Cor. M.G.H. 2.84

Party O.M.-Z. PR Disch. 31.57 cfs = 0.89 m^3/sec

Gauge, checked with level and found O.K.

Measurement began at 09:50 Measurement ended at 10:10

First reading of gauge 2.84 ft. at 9:50 | Meter No. 1-227

Gauge ..... ft. at sta. ..... at ..... | Date rated 25.4.68.

" ..... " ..... at ..... | Method of meas. Wading

" ..... " ..... at ..... | No. meas. pts. 14 Coef. .....

Last reading of gauge 2.84 ft. at 9:50 | Av. width sec. ..... Av. depth .....

Weighted mean gauge height ..... Correct mean gauge height 2.84

Meas. from cable, bridge, boat, wading; Meas. at 15 ft. above, below gauge.

If not at regular section note location and conditions .....

Date of Standard Soundings used .....

Method of suspension ..... Stay wire ..... Approx. dist. to W.S. .....

Arrangement of weights and meter; top hole .....; middle hole .....; bottom hole .....

Gauge inspected, found O.K.; Cable inspected, found .....

Distance apart of measuring points verified with steel tape and found .....

Wind ..... upstr., downstr., across. Angle of current ⊥

Observer seen and book inspected .....

Examine station locality and report any abnormal conditions which might change relation of G. Ht. to discharge, e.g., change of control; ice or debris on control, backwater from; condition of station equipment .....

Sheet No. 1 of 2 sheets.

DEPARTMENT OF ENERGY, MINES AND RESOURCES

R. 19 (9-67)

INLAND WATERS BRANCH—WATER SURVEY OF CANADA

CURRENT METER NOTES

Date Sept. 3rd 19 68 A.M. P.M. Stream Sentinel

Party O.M-Z. PR Locality 20' below gage

Meter No. 1-227 Gauge height, beg. 2.84 end 2.84 mean 2.84

Total Area 18.0 Mean Velocity 1.76 Discharge 31.56 cfs /=0.83 m^3/sec

OBSERVATION							COMPUTATIONS		
Dist. from initial point	Depth	Depth of observation	Revolutions	Time in seconds	Velocity At point	Velocity Mean in vertical	Area	Width	Discharge
0	LB	9	:50						
3	0.4	0.2	5	54	0.22		1.4	3.5	0.31
4	0.9	0.5	10	47	0.99		0.9	1.0	0.89
5	1.3	0.8	30	49	1.37		1.3	1.0	1.78
6	1.4	0.8	40	41	2.02		1.4	1.0	2.83
7	1.5	0.9	40	41	2.17		1.5	1.0	3.25
8	1.7	1.0	50	49	2.27		1.7	1.0	3.86
9	1.8	1.1	50	45	2.57		1.8	1.0	4.47
10	1.5	0.9	60	45	2.95		1.5	1.0	4.42
11	1.3	0.8	40	44	2.02		1.3	1.0	2.63
12	1.2	0.7	40	53	1.67		1.2	1.0	2.00
13	1.1	0.7	30	45	1.49		1.1	1.0	1.64
14	1.0	0.6	30	45	1.49		1.0	1.0	1.49
15	0.9	0.5	25	45	1.25		0.9	1.0	1.12
16	0.7	0.4	20	51	0.88		1.0	1.5	0.28
17	RB	10	:10						
17							18.0		31.57

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Appendix II (b)

Samples of Discharge Measurement Computations Made in the Field (Salt Dilution Method)

Sentinel Creek – Salt Dilution Test No. 3, 7 September 1967

Primary solution (Østrem, 1964) – 25 *l* creek water + 4 lbs salt.

Gauge Height	Start 2.87 ft (87.5 cm)	Finish 2.88 ft (87.8 cm)	Average 2.88 ft (87.8 cm)

Water temperature: 5.8°C

Time – 1200 PST. Conductivity of creek water in creek: 165

Time* (Seconds)	Conductivity† Readings	Time (Seconds)	Conductivity Readings
0	Start	65	245
5	240	70	225
10	275	75	210
15	520	80	200
20	585 peak	85	195
25	575	90	170
30	520	95	185
35	465	100	183
40	400	105	180
45	345	110	180
50	320	115	178
55	285	120	175
60	255	125	172
		130	170

*Time from beginning of passage of salt wave.
†Readings of conductivity units, directly on instrument scale.

Salt Dilution Test No. 3—Calibration

Secondary solution: 100 ml primary salt solution + 900 ml creek water = 0.1 relative strength.

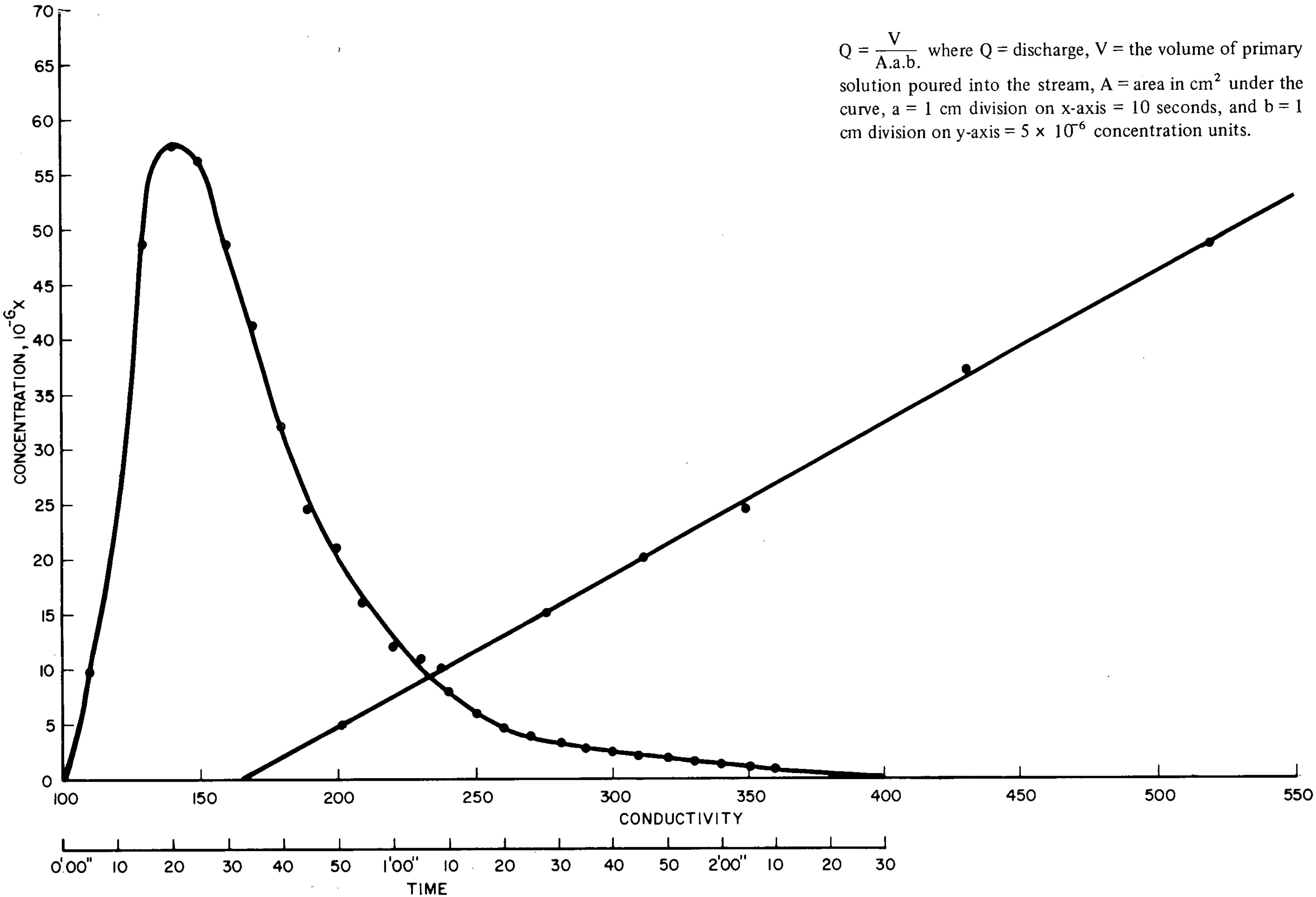
20 *l* creek water in tank.

Conductivity of creek water in tank 180.

Correction factor $= \frac{165}{180} = 0.917$

Secondary solution added to tank (ml)	Relative salt concn. (ml)	Conductivity readings	Corrected conductivity readings*
0	0.000000	180	165
10	0.000050	220	202
20	0.000100	260	238
30	0.000150	300	275
40	0.000200	340	312
50	0.000249	380	348
75	0.000374	470	431
100	0.000498	570	523
125	0.000621	675	619
150	0.000744	780	715

$^*\frac{\text{conductivity of creek water in creek}}{\text{conductivity of creek water in tank}} \times \text{conductivity of creek water with salt solution}$



$Q = \frac{V}{A.a.b.}$ where Q = discharge, V = the volume of primary solution poured into the stream, A = area in cm^2 under the curve, a = 1 cm division on x-axis = 10 seconds, and b = 1 cm division on y-axis = 5×10^{-6} concentration units.

Sentinel Glacier: salt dilution test no. 3, Sept 7, 1967.